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摘要

轴手性化合物广泛存在于天然产物和生物活性分子中，在不对称催化中也有着广泛的应用。因为其骨架的重要性，催化不对称构建轴手性化合物受到了科学家们的广泛研究。相比于得到迅速发展的轴手性联芳化合物，一类手性轴在烯烃和芳环之间的轴手性烯基芳烃却因为其比较低的翻转能垒而被忽视。与此同时，钯催化不对称碳氢键活化已经成为一种高效地合成手性分子的方法而受到广泛关注。基于此，本论文围绕钯催化不对称碳氢键官能团化来实现轴手性联芳和轴手性烯基芳烃化合物的构建，具体包括以下内容：

1. 钯催化硫醚导向不对称碳氢键烯基化和烯丙基化反应构建轴手性联芳

我们通过 DFT 计算和实验相结合，揭示出不同氧族原子在钯催化阻转选择性碳氢键官能团化反应中的导向能力，并成功实现钯催化硫醚导向不对称碳氢键烯基化和烯丙基化反应来构建轴手性联芳。反应使用钯(II)/手性磷酸催化体系，成功以高产率和高对映体选择性合成了一系列轴手性联芳化合物。该策略也可以用于合成具有多个手性轴的阻转异构体。此外，DFT 计算为反应条件的筛选提供了便利，同时对反应机理进行深入探究。

2. 钯催化不对称芳烃碳氢键官能团化构建轴手性烯基芳烃

我们使用廉价易得的 *L*-焦谷氨酸作为手性配体，通过钯催化不对称碳氢键烯基化和炔基化反应实现了具有开链式烯烃结构的轴手性烯基芳烃化合物的高效合成。这类烯烃轴手性产物可以通过简单衍生化反应合成一类轴手性酸，作为手性配体应用于钴催化的不对称二茂铁碳氢键的酰胺化反应。通过实验和计算，我们对反应的机理进行了研究。通过对反应速率的研究，我们发现反应存在一个配体减速效应(LDE)。基于 DFT 计算，证明了碳氢键活化步骤是反应手性诱导的决定步骤。

3. 钯催化硫醚导向不对称烯烃碳氢键烯基化反应构建含共轭烯烃结构的轴手性烯基芳烃

我们通过钯催化硫醚导向的烯基碳氢键烯基化反应策略实现了具有 1,3-二烯结构的轴手性烯基芳烃化合物的不对称合成。该反应操作简单，条件温和，有很好的官能团容忍性(69 个合成例子)，可以实现产物完全的 *Z*-选择性转化和优异的对映体选择性(up to 99% ee)。值得一提的是，我们利用该策略还可以实现含有两个不对称轴的轴手性烯基芳烃产物的高效合成。另外，反应可以实现规模放大，产物可以通过简单氧化合成具有高非对映体选择性的手性亚砜衍生物，并作为一类新型硫烯配体得到潜在的应用。

关键词：钯，轴手性联芳，轴手性烯基芳烃，不对称碳氢键活化，*L*-焦谷氨酸，手性

磷酸，硫醚导向

Abstract

Axially chiral compounds are widespread in natural products, biologically active compounds, and useful chiral ligands in asymmetric catalysis. Because of the importance of this structural motif, the catalytic enantioselective construction of axially chiral scaffolds has been intensively investigated by chemists. In distinct contrast to the well investigated axially chiral biaryls, axially chiral styrenes, which exhibit a chiral axis between a substituted alkene and an aromatic ring have been largely overlooked, results in relatively lower barriers to rotation compared to their biaryl counterparts. Meanwhile, Pd-catalyzed enantioselective C–H bond activation has received much attention as an important tool for the expedient synthesis of chiral molecules. Base on this context, the dissertation mainly focused on atroposelective synthesis of axially chiral biaryls and axially chiral styrenes via Palladium-catalyzed asymmetric C–H functionalization strategy. The main details were listed as follows:

1. **Atroposelective Synthesis of Axially Chiral Biaryls via Pd(II)-Catalyzed Thioether-Directed C–H Olefination and Allylation**

We present herein our experimental and DFT computational studies on the directing ability of chalcogenoether motifs in Pd-catalyzed atroposelective C–H functionalization. Both Pd-catalyzed enantioselective C–H olefination and allylation reactions were successfully developed to synthesis of axially chiral biaryls. A broad range of axially chiral biaryls in good yields with excellent enantioselectivities were successfully accomplished via a Pd(II)/chiral phosphoric acid catalytic system. This method could also be employed to access synthetically challenging atropisomers bearing two stereogenic axes with excellent enantioselectivities and diastereoselectivities. In addition, DFT calculation provided the convenience for reaction condition optimization and further enlighten the understanding of the reaction mechanism.

2. **Atroposelective Synthesis of Axially Chiral Styrenes via Pd(II)-Catalyzed Aryl C–H Functionalization Strategy**

We report herein the highly atroposelective synthesis of axially chiral styrenes with an open-chained alkene via Pd(II)-catalyzed C−H alkenylation and alkynylation using *L*-pyroglutamic acid as an inexpensive and catalytic chiral ligand. The potent application of the styrene atropisomers

is demonstrated by a Co(III)-catalyzed enantioselective C−H amidation of ferrocene using axially chiral styrene-type acid as chiral ligand. Experimental and computational studies were conducted to elucidate the reaction mechanism. Initial rate studies revealed a ligand deceleration effect (LDE) in this reaction. The chiral induction model of the enantioselectivity-determining C−H bond activation step was also provided based on DFT calculations.

3. Atroposelective Synthesis of Conjugated Diene-Based Axially Chiral Styrenes via Pd(II)-Catalyzed Thioether-Directed Alkenyl C–H Olefination

We report the highly atroposelective synthesis of axially chiral styrenes with a conjugated 1,3-diene scaffold via Pd(II)-catalyzed thioether-directed alkenyl C-H olefination strategy. This strategy features easy operation, mild reaction conditions, high functional group tolerance (69 examples), complete *Z*-selectivity, and excellent enantioselectivities (up to 99% ee). Notably, the highly enantioselective synthesis of atropisomers with two stereogenic axes were also achieved using this strategy. Moreover, the reaction could be scaled up and the resulting axially chiral styrenes could be easily oxidized into chiral sulfoxide derivatives with high diastereoselectivities, which showed great promise as a new type of sulfur-olefin ligand.

Keywords: Pd, axially chiral biaryls, axially chiral styrenes, asymmetric C–H bond activation, chiral phosphoric acid, *L*-pyroglutamic acid, thioether-directed

目录

第一章 绪论

1.1 不对称碳氢键活化简介

手性是一种自然界中普遍存在的现象，根据手性的表现方式不同可以将手性大致分成四大类[1](**图 1.1a**)：中心手性、轴手性、面手性和螺旋手性。手性骨架普遍存在于天然产物、药物和功能性材料中。因此如何利用最简单廉价的原料以高经济性和高选择性地合成手性分子一直以来是科学家们追求的目标。有机分子中几乎都含有碳氢键，因此选择性地实现碳氢键的官能团转化是一条极具步骤和原子经济性的合成复杂手性分子的路径[2]。然而一般情况下分子中的碳氢键是比较惰性的(键能高、酸度低)，想要实现碳氢键的断裂需要克服很高的键能(90 - 100 kcal/mol)。同时，有机分子中往往存在多个位置活性相似的碳氢键(**图 1.1b**)，如何实现高效选择性的碳氢键官能团化是极具挑战性的。

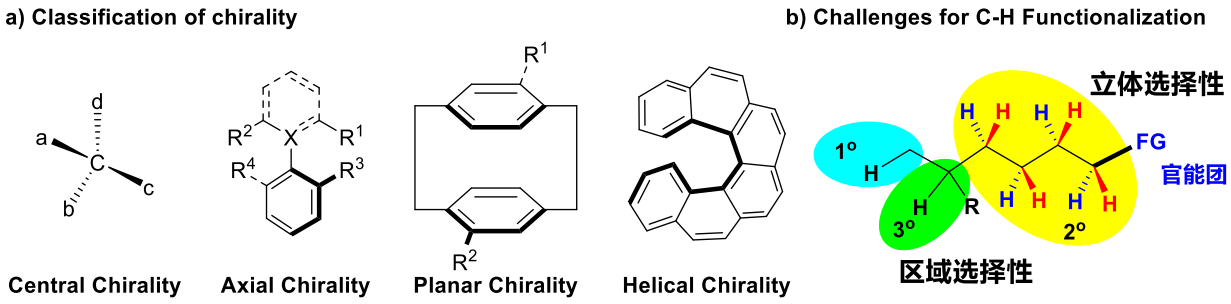


图 1.1 a) 手性的分类 b）碳氢键官能团化的挑战

经过几十年的探究，科学家们发展了一系列手段来实现立体选择性的碳氢键转化。其中金属参与的不对称碳氢键官能团化反应是一个实现高选择性碳氢键官能团转化的有效方法[3]。我们根据不同的反应机理，可以将金属参与的不对称碳氢键官能团化反应分为三类(**图 1.2**)：1）自由基参与的碳氢键断裂和重组反应[3a–d]；2）手性金属氮宾或卡宾化合物对碳氢键的插入反应[3e–g]；3）过渡金属催化的不对称碳氢键活化反应[3h, 4]。本论文中讨论的主要是第三种方法，也被称作“不对称碳氢键活化”(Enantioselective C–H Activation)。该过程在手性配体的作用下，过渡金属对特定碳氢键进行选择性活化，形成高活性的碳-金属中间体，再与各种官能团化试剂反应，生成多样化的手性产物(**图 1.2c**)[4]。

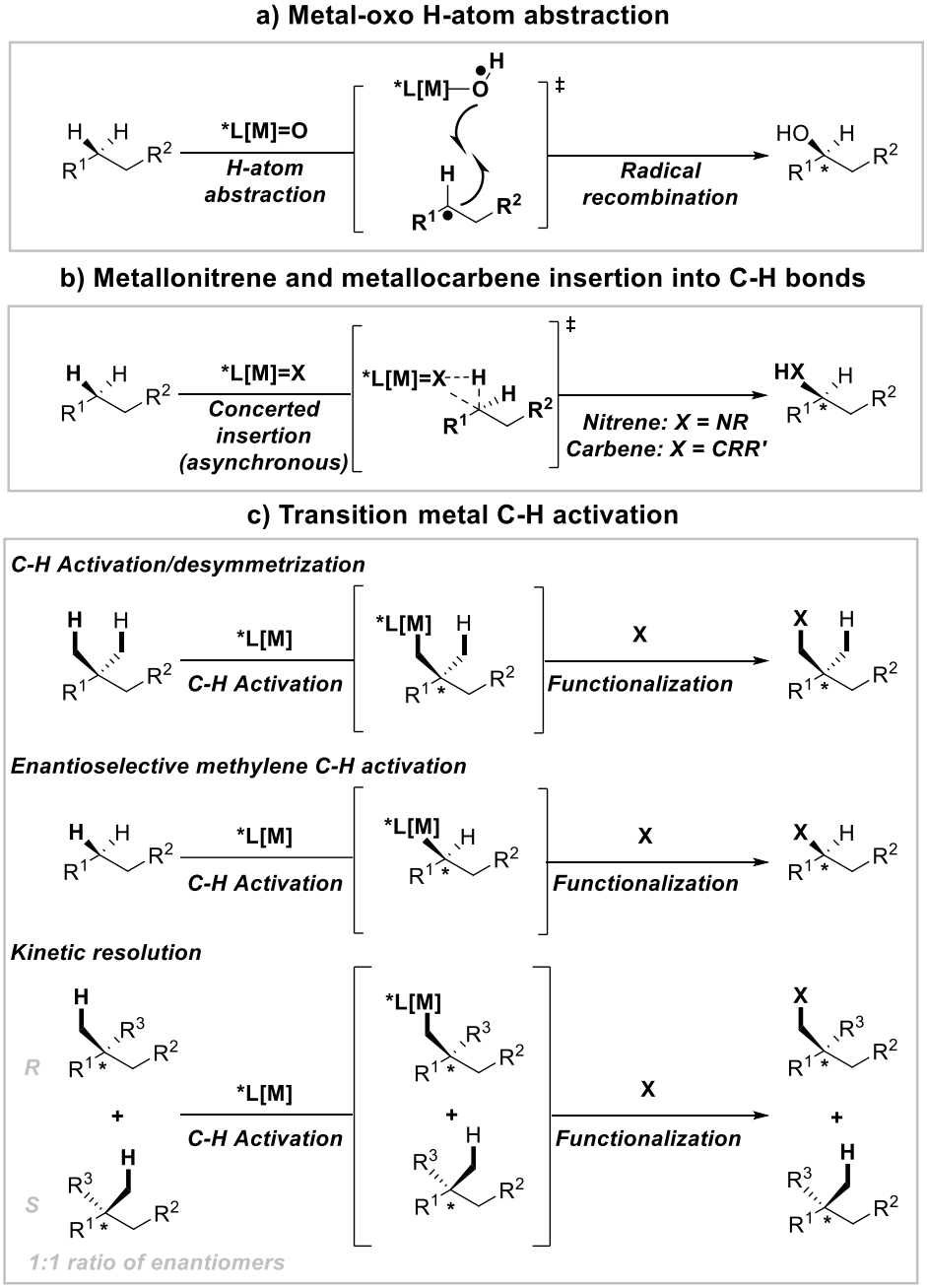


图 1.2 过渡金属催化不对称碳氢键官能团化分类

另外该策略根据反应底物的不同可以分为三种反应模式：对映体选择性碳氢键活化去对称化，不对称亚甲基碳氢键活化和动力学拆分。其中对映体选择性碳氢键活化去对称化又可以被细分成两种策略：一种是对底物中单原子中心的去对称化反应(**图 1.3a**)；另一种是对底物中面或者轴的去对称化(**图 1.3b**)[4f–g]。本人博士期间的工作主要是围绕钯催化不对称碳氢键活化去对称化(含轴底物的去对称化)反应来高效快速地构建轴手性化合物。下面将就相关邻域的发展和现状进行简单的综述。

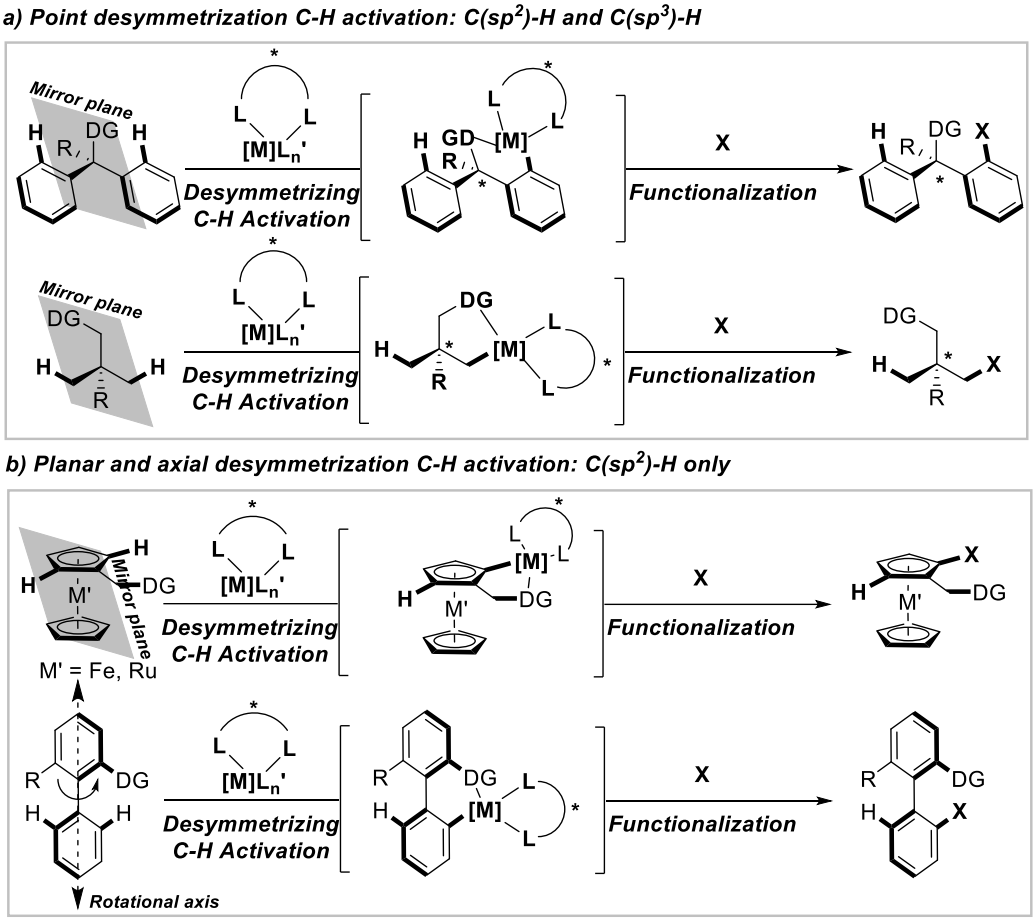


图 1.3 碳氢键活化去对称化反应

1.2 阻转异构体简介

与中心手性化合物不同，当化合物中的 σ-单键受取代基位阻或电子效应的影响而被限制自由旋转时，将会产生一对对映异构体，该对映异构体被称为阻转异构体[5]。根据 Oki[6] 对阻转异构体的早期研究，我们知道一对阻转异构体能在室温下稳定存在的最低翻转能垒需要达到 93 kJ/mol，相对应的半衰期为 1000 秒，这也是阻转异构体能被分离的前提。

阻转异构体拥有非常庞大的家族成员(**图 1.4**)[7]，我们根据其组成不同可以把它们分成两大类：联芳型阻转异构体和非联芳型阻转异构体。其中联芳型阻转异构体包含全碳骨架的联芳轴手性化合物和杂芳环轴手性化合物。而非联芳型阻转异构体的组成则更加的复杂。比如手性产生于非联芳类型 C-C 键的轴手性芳基酰胺和轴手性烯基芳烃,以及手性产生于 C-X(X = N, O, S)键的其他轴手性化合物。

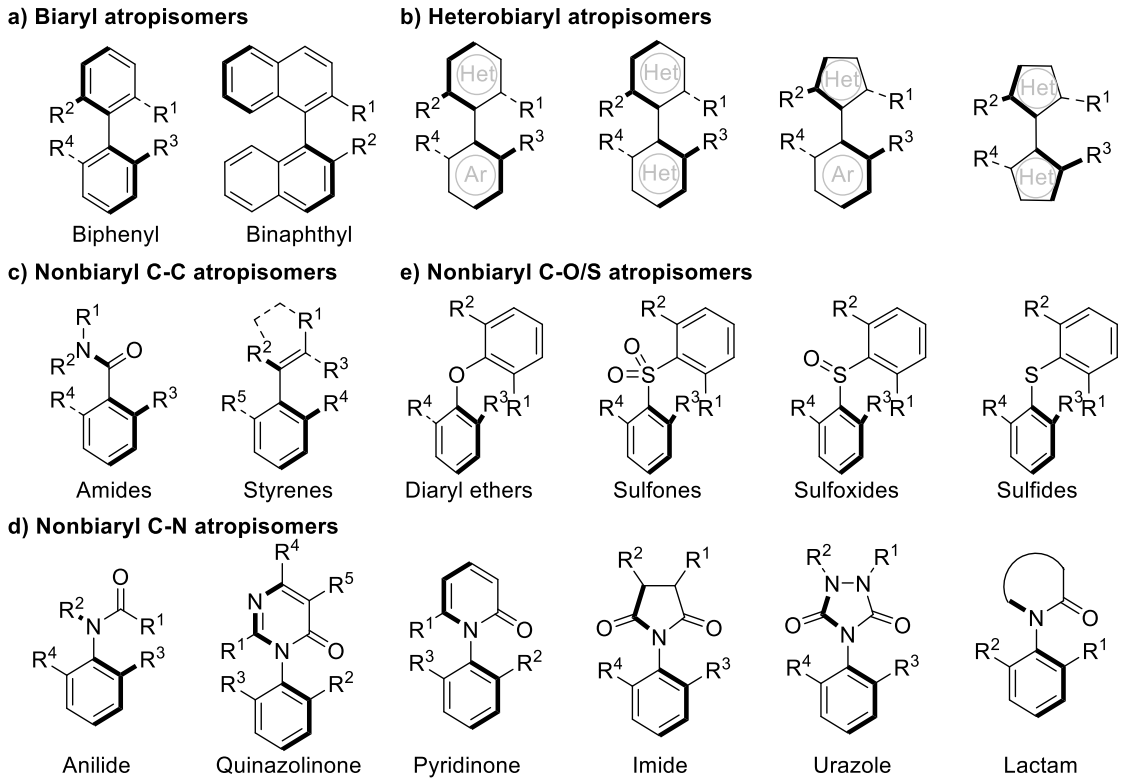


图 1.4 阻转异构体的多样性

1.2.1 传统方法构建联芳轴手性

轴手性骨架，尤其是联芳轴手性骨架广泛地存在于天然产物和药物分子中**(图 1.5a)**[8]。例如 Korupensamine A[8b]、Mastigophorene[8c]、Marinopyrrole[8d]和 Steganacin[8e]等天然活性分子的核心结构都是轴手性联芳骨架。其中 Korupensamine A 因表现出显著的抗疟性而被广泛研究。轴手性联芳骨架也被广泛应用于不对称催化反应中**(图 1.5b)**[9]。比如基于联萘骨架的 BINAP 已经被证实是铑催化不对称氢化反应中手性诱导的来源[10]。之后，基于该骨架衍生的 BINOL、NOBIN、BINAM 和 CPA 轴手性化合物均可以被应用于不对称催化反应中。这些轴手性配体和催化剂的应用极大地促进了不对称催化邻域的发展。轴手性联芳骨架在材料科学邻域也有着广泛的应用[11]。在荧光传感器[11b]、手性光学开关[11c]、主客体化学[11d–e]以及分子机器[11f–g]等方面都可以看到联芳轴手性化合物的身影。

鉴于联芳轴手性骨架在科学学科中的重要性，对联芳轴手性的构建得到了科学家们的重点关注[12]。经过几十年的迅猛发展，构建联芳轴手性的方法可以主要总结为以下四种**(图 1.6)**：1）通过金属参与的直接碳碳键偶联反应产生轴手性；2）通过中心手性向轴手性的传递产生轴手性；3）通过环加成反应直接构筑芳香环，从而产生轴手性；4）通过对已建

立轴的联芳化合物的去对称化或动力学拆分得到轴手性。

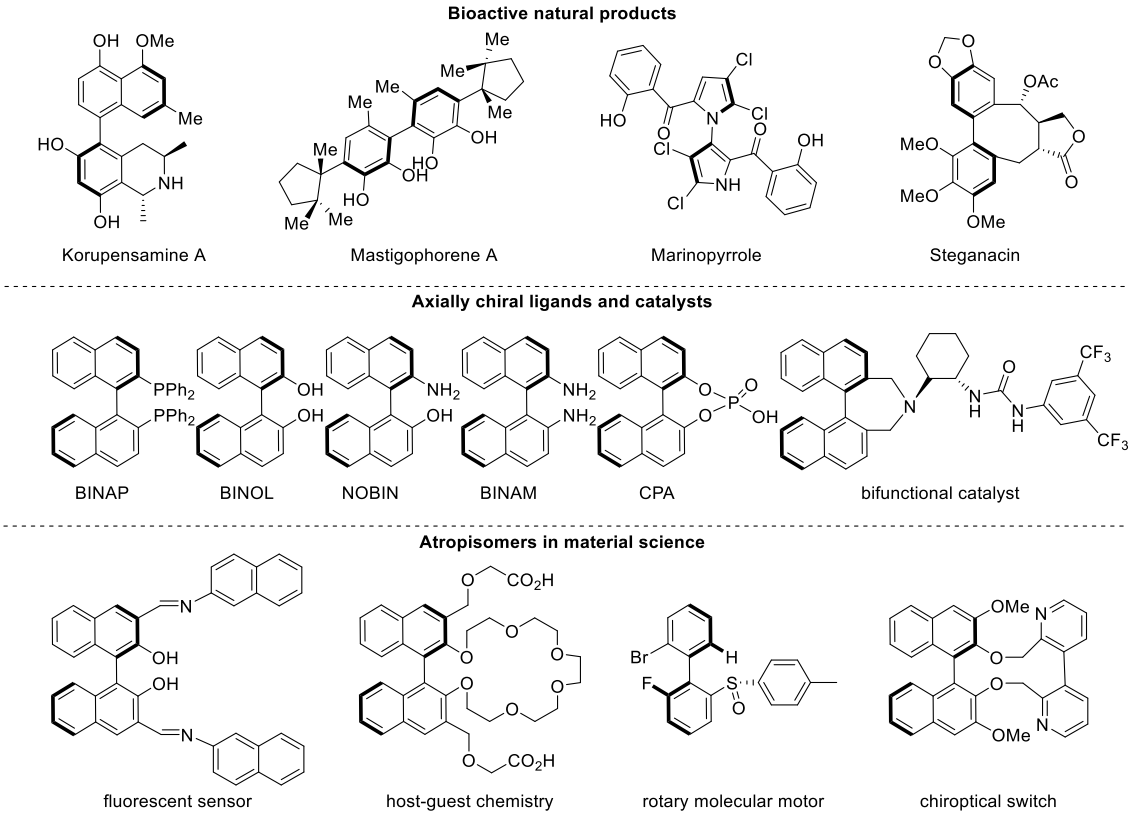


图 1.5 代表性的阻转异构体在科学学科中的应用

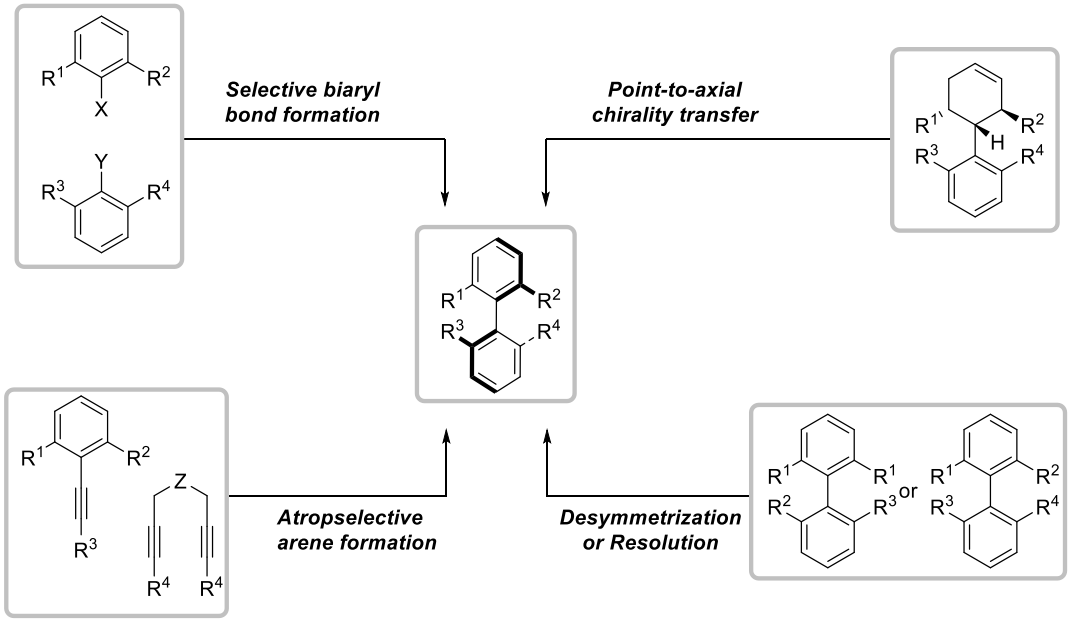


图 1.6 不对称合成轴手性联芳的策略

1.2.2 过渡金属催化不对称碳氢键活化构建联芳轴手性

近年来，过渡金属催化不对称碳氢键活化策略因为其步骤和原子经济性等优点，在高效构筑联芳轴手性骨架方面也取得了骄人的成绩[13]。过渡金属催化不对称碳氢键活化策略构建联芳轴手性可以总结为三种模式(**图 1.7**)：1）通过去对称化或动力学拆分的方式增大前手性轴的旋转位阻，从而构建联芳轴手性；2）手性金属催化剂对芳环邻位进行导向碳氢键芳基化反应，直接构建芳基-芳基键，产生轴手性；3）利用手性金属催化剂对芳环邻位进行导向碳氢键环加成反应，重新构建芳香环并产生轴手性。

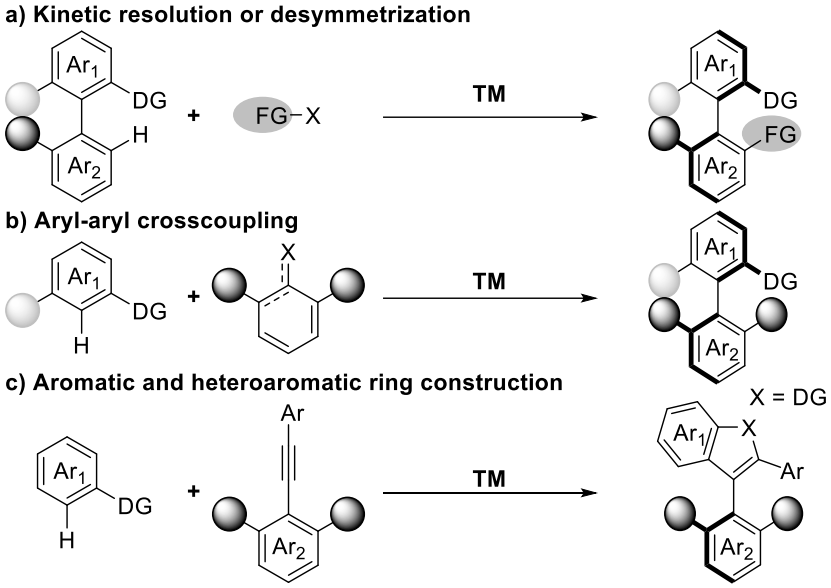


图 1.7 过渡金属催化不对称碳氢键官能团化反应构建轴手性联芳

1.2.2.1 动力学拆分或去对称化构建联芳轴手性

我们依据轴手性的来源不同可以将动力学拆分或去对称化构建联芳轴手性再细分为三类：1）轴手性由非手性金属催化剂和手性配体协同控制产生；2）轴手性由手性金属催化剂控制产生；3）轴手性由手性辅基参与导向控制产生。

1.2.2.1.1 金属和手性配体协同催化不对称碳氢键活化构建联芳轴手性

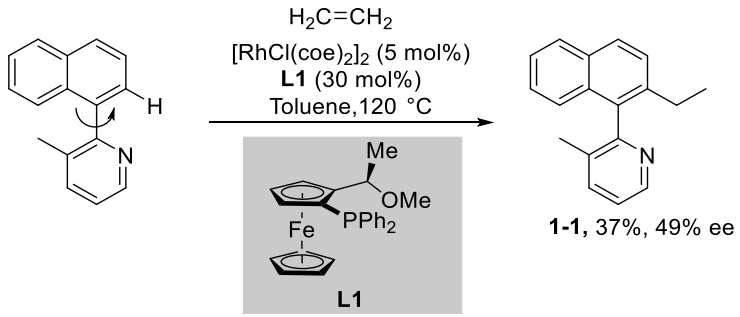


图 1.8 过渡金属催化不对称碳氢键活化烷基化反应构建轴手性联芳

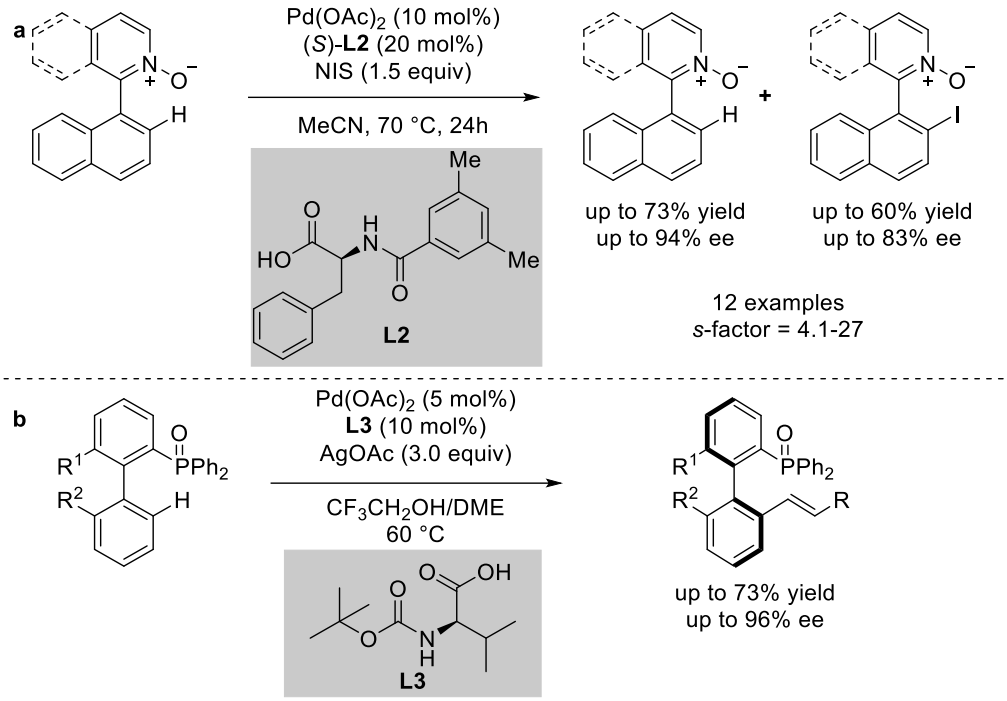


图 1.9 Pd(II)/MPAA-催化不对称合成轴手性联芳

2000 年，Murai 课题组[14]报道了首例通过 Rh(I)催化吡啶导向的不对称烷基化反应构建联芳轴手性的工作(**图 1.8**)。一价铑催化剂在手性二茂铁膦配体(*R*,*S*)-PPFOMe 的协同作用下，与底物结合并进行跨环碳氢键氧化加成反应，形成高价的手性 C-Rh(III)-H 中间体，再对乙烯发生插入反应和还原消除，得到轴手性化合物 **1-1**。该策略实现了对联芳基底物的动态动力学拆分。虽然反应的对映体选择性不高，底物范围也很局限，但是该工作为后续过渡金属催化不对称碳氢键活化构建轴手性的研究奠定了基础。

2008 年，余金权课题组[15]首次报道了 Pd(II)/MPAA 体系催化的不对称碳氢键活化反应。之后，Pd(II)/MPAA 催化体系不断在不对称碳氢键活化邻域做出重大突破[16]。2014 年，游书力课题组[17]使用 *N*-碘代丁二酰亚胺为碘代试剂，首次实现了 Pd(II)/MPAA 催化的不

对称碳氢键碘代反应。该反应通过廉价易得的单保护氨基酸配体**(L2)**，对 2-萘基异喹啉氮氧化合物进行动力学拆分，拆分因子 *S* 最高可以达到 27(**图 1.9a**)。2017 年，杨尚东课题组[18]使用同样的催化体系，实现膦氧导向不对称碳氢键烯基化反应，构筑了一系列轴手性联芳膦氧-烯烃化合物(**图 1.9b**)。

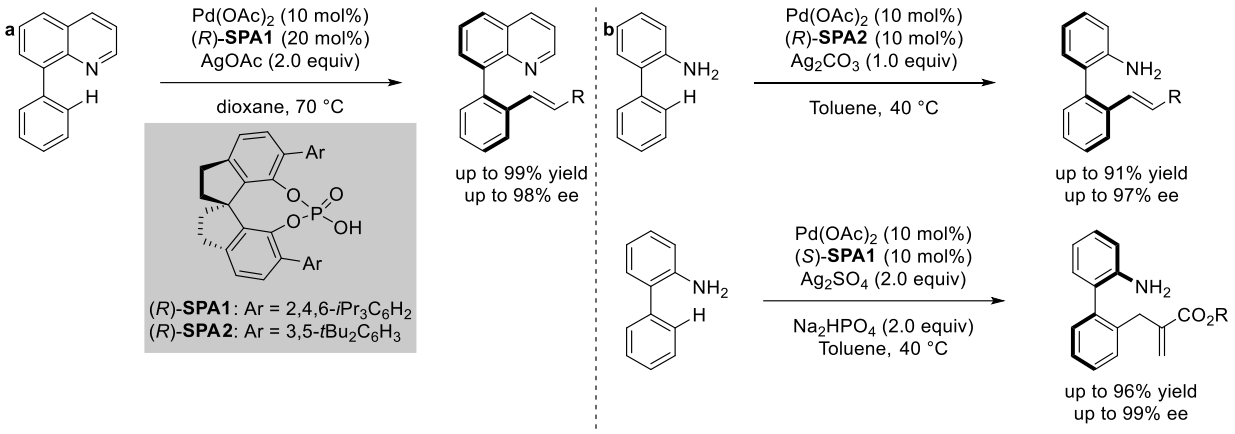


图 1.10 Pd(II)/SPA-催化不对称合成轴手性联芳

2019 年，史炳锋课题组[19]将催化体系扩展到了钯/手性磷酸催化体系，首次报道了喹啉导向钯催化不对称碳氢键烯基化反应构建联芳轴手性。反应通过螺环手性磷酸**(SPA1)**的手性诱导，一系列轴手性联芳喹啉-烯烃产物的对映体比率均可以达到 90%以上(**图 1.10a**)。此外，作者通过理论计算对螺环手性磷酸控制反应的对映体选择性机理进行了研究，揭示出大位阻的手性磷酸配体在反应中与金属钯结合，形成手性的反应空腔，迫使底物以特定构象进行反应，得到高专一选择性的结果。之后该课题组又使用更加活性的氨基作为导向基团，实现了裸露氨导向不对称碳氢键烯基化和烯丙基化反应(**图 1.10b**)[20]，构筑了一系列联芳氨基-烯烃轴手性化合物。裸露氨的存在为后续的合成应用提供了极大的可能性。

含五元杂环的轴手性化合物中转轴周围的位阻较六元联芳轴手性化合物要小，其翻转能垒也相对较低，因此对这一类型轴手性化合物的合成是更加困难的。2017 年，顾振华课题组[21]报道了钯催化分子内不对称碳氢键芳基化反应来构筑轴手性吲哚类化合物。反应使用 TADDOL 衍生的手性膦配体**(L4)**，可以有效的控制反应活性和对映体选择性，以最高 99%的产率和 91%的 ee 值得到产物(**图 1.11**)。

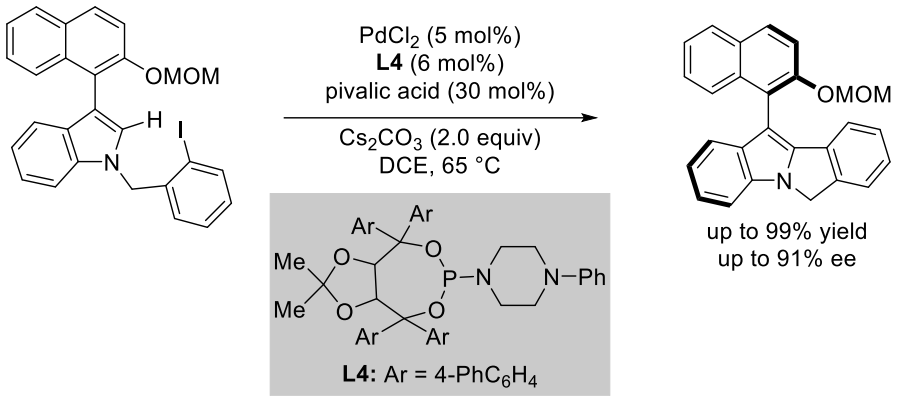


图 1.11 钯(0)催化分子内不对称碳氢键环化反应

自从 2000 年 Murai 课题组以中等的对映体选择性报道了 Rh(I)催化不对称碳氢键烷基化反应构建轴手性联芳化合物后，直到 2019 年，游书力课题组[22]才成功实现高对映体选择性的 Rh(I)催化碳氢键芳基化反应来构筑芳基吡啶和芳基异喹啉类轴手性化合物(**图 1.12**)。该反应使用膦配体(**L5**)作为手性配体，最高以 99%的产率和 97%的 ee 值得到轴手性产物，并且反应拥有良好的官能团容忍性。值得一提的是，得到的 2-异喹啉联芳骨架((***S***a)**1-2**)可以通过简单的氧化反应变成手性氮氧化合物((***S***a)**1-3**)。该化合物可以作为手性路易斯碱催化剂催化苯甲醛的不对称烯丙基化反应。

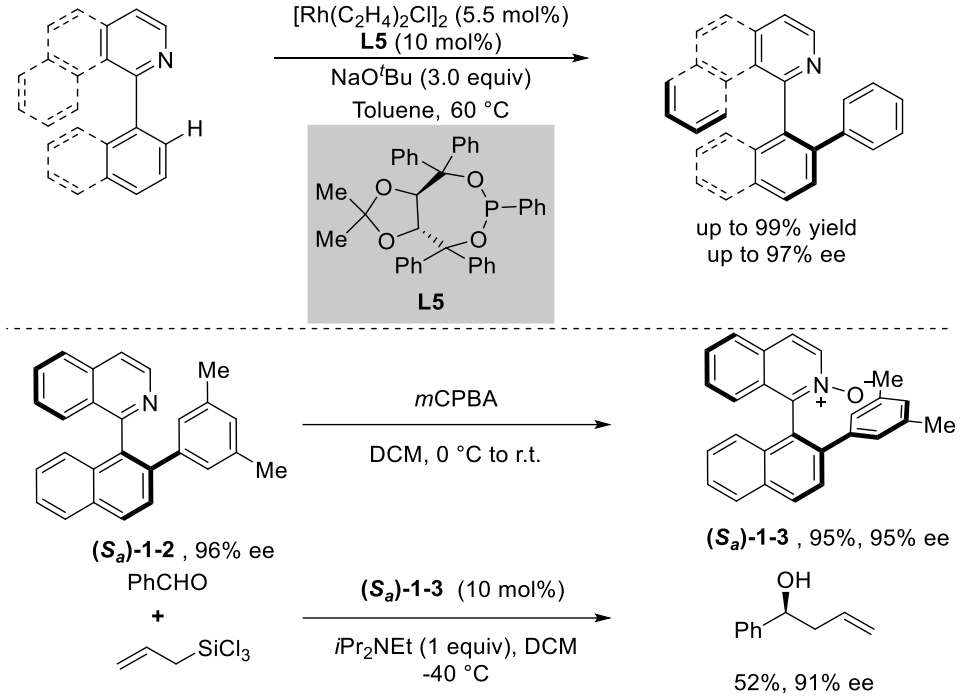


图 1.12 铑(I)催化不对称碳氢键芳基化反应构建轴手性联芳杂环

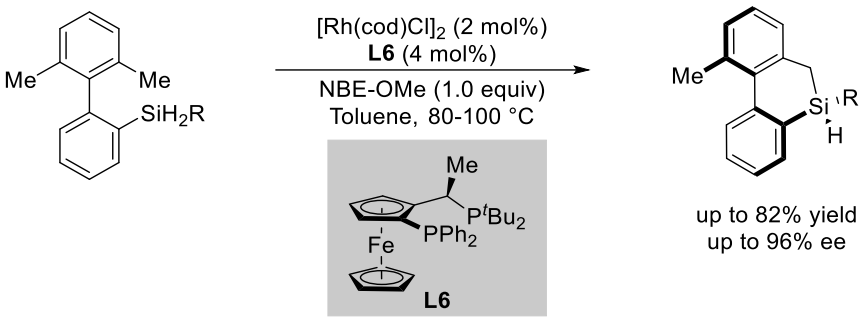


图 1.13 铑(I)催化不对称碳氢键硅基化反应构建轴手性联芳

2021 年，何川课题组[23]通过 Rh(I)催化不对称碳硅键的构建得到了一系列含硅手性中心的联芳轴手性化合物(**图 1.13**)。反应使用二茂铁膦配体(**L6**)为手性配体，通过不对称 C(sp^3)–H 脱氢硅基化，以最高 82%的产率和 96%的 ee 值合成了含有轴手性和硅中心手性的手性化合物。

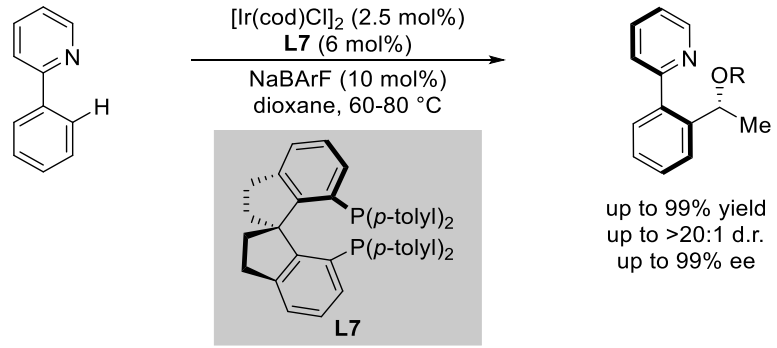


图 1.14 铱(I)催化不对称碳氢键烷基化反应构建轴手性联芳氮杂环

2020 年，Lassaletta 课题组[24]则报道了一例 Ir(I)催化的不对称烷基化反应(**图 1.14**)。反应以基于螺环骨架的膦配体(**L7**)为手性配体，通过原位生成[Ir^I/Tol-SDP]物种，最高以 99%的产率，大于 20:1 的 dr 值和 99%的 ee 值得到拥有双手性属性的化合物。

1.2.2.1.2 手性金属催化不对称碳氢键活化构建联芳轴手性

相比金属和手性配体协同催化的不对称碳氢键活化模式，直接使用手性的金属催化剂进行不对称碳氢键活化反应可以有效的抑制背景反应，从而提高对反应手性的控制。该方面研究主要集中于使用 C_2 对称的手性[Cp^xRh^{III}]催化剂催化的不对称碳氢键官能团化反应[25]。在 2014 年，游书力课题组首次报道了手性铑催化剂(**Rh-1**)催化的不对称烯基化反应[25a]，最高以 99%的产率和 86%的 ee 值得到轴手性化合物(**图 1.15**)。随后，该课题组使用

基于螺环骨架的手性环戊二烯配体(SCp)替代之前手性骨架，实现了在更温和的反应条件下以更高的对映体选择性合成轴手性联芳化合物(**图 1.15**，**Rh-2** vs **Rh-1**)[25b]。

得益于手性 SCp 骨架对反应对映体选择性控制的提升，游书力课题组[25c]在 2020 年报道了手性 SCpRh(III)(**Rh-2**)和手性羧酸(**A-1**)组合催化的 C-H/C-H 氧化偶联反应(**图 1.16**)。许多芳基异喹啉化合物可以与富电子杂环底物进行直接氧化偶联反应，最高以 99%的产率和 99%的 ee 值得到相应的轴手性产物。

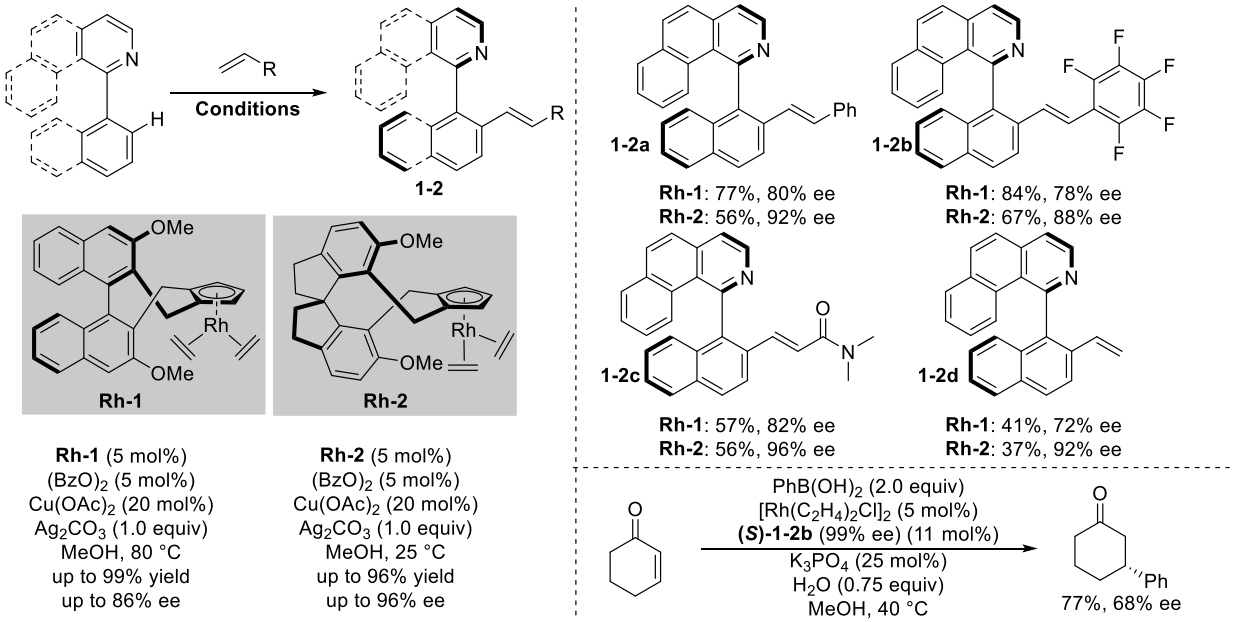


图 1.15 铑(III)催化不对称碳氢键烯基化反应构建轴手性联芳

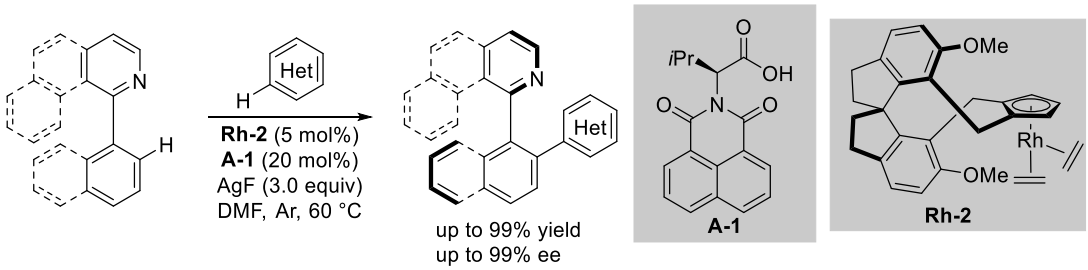


图 1.16 铑(III)催化不对称碳氢键芳基化反应构建轴手性联芳

1.2.2.1.3 手性辅基参与不对称碳氢键活化构建联芳轴手性

在底物中安装一个手性辅基作为反应的导向基，进行非对映体选择性的碳氢键官能团转化被证实是一种有效合成轴手性联芳化合物的方法[26]。2013 年，Colobert 课题组首次报道了手性亚砜导向钯催化非对映体选择性碳氢键烯基化反应[26a]。在手性亚砜辅基作用下，反应得到了一系列高非对映体选择性的轴手性联芳化合物(**图 1.17a**)。同时，通过对机理的

研究，该课题组发现六氟异丙醇可以显著地提高反应的活性和非对映体选择性**(图 1.17b, c)**[26c]。2018 年，该课题组将策略应用于非对映体选择性碳氢键芳基化反应中，实现了同时构建两个手性轴的挑战**(图 1.17d)**[26d]。此外，产物中的手性亚砜结构可以进行一系列的后续转化，生成相应的手性膦配体。

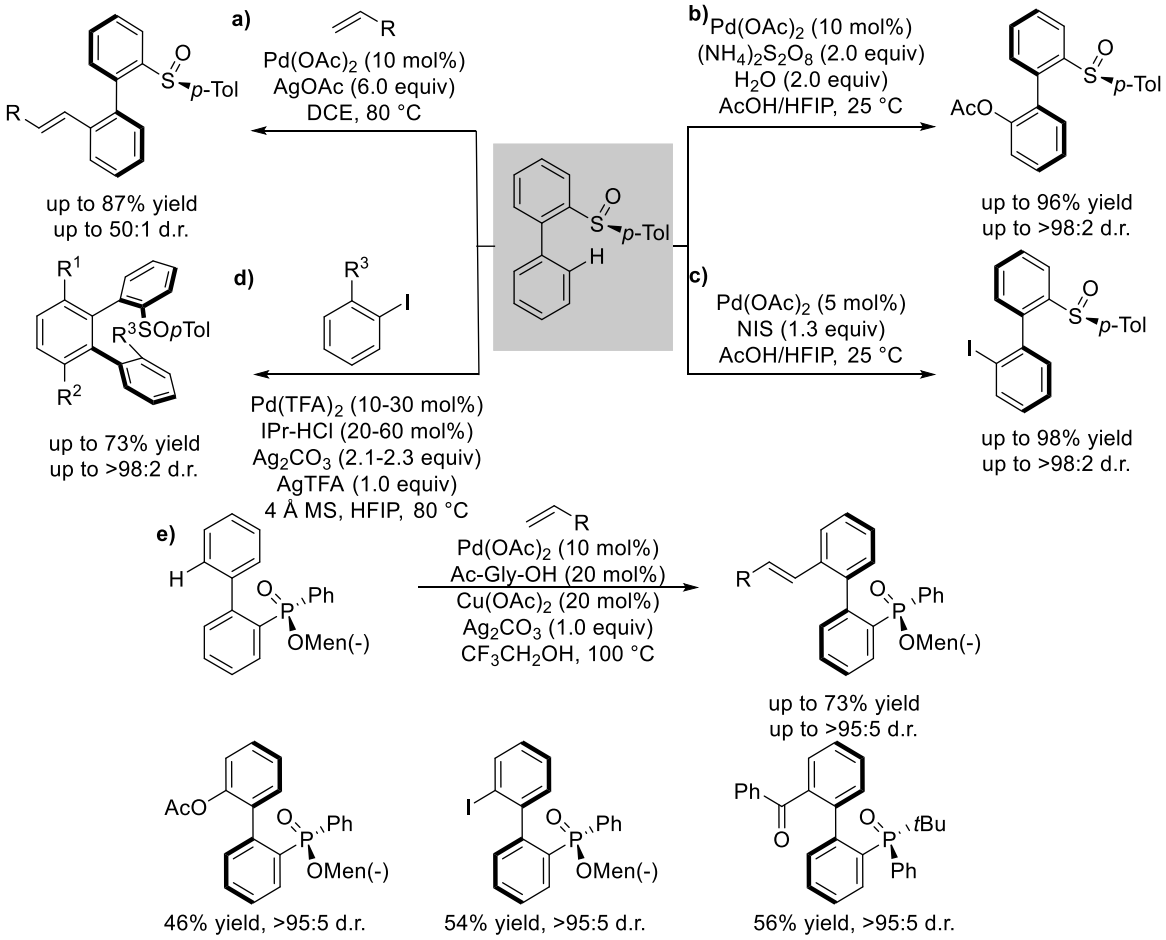


图 1.17 钯催化非对映选择性碳氢键官能团化反应

2015 年，杨尚东课题组[26e]则利用手性磷酸酯作为反应的导向基，实现了钯催化非对映体选择性碳氢键烯基化反应，成功合成了一系列含有膦氧结构的轴手性联芳化合物**(图 1.17e)**。另外，该手性磷酸酯导向基也可以被使用于不对称碳氢键乙酰氧化、碘代和酰基化反应中。

虽然手性辅基的使用可以很好地实现轴手性联芳化合物的非对映体选择性合成，但是底物往往需要预先引入化学当量的手性辅基，同时导向基团的残留问题都会阻碍该策略的后续应用。余金权课题组[27]开创性地报道了使用瞬态导向策略来解决这一问题。之后，受此影响，史炳锋课题组利用该策略，做出了一系列工作来解决联芳轴手性的不对称构建问

题[28]。比如在 2017 年，该课题组利用手性叔亮氨酸作为瞬态手性辅基，联芳基醛化合物**(1-5)**为反应底物，通过钯催化不对称碳氢键烯基化反应构筑了一系列高产率和高对映体比率的轴手性联芳基醛-烯烃化合物**(图 1.18a)**[28a]。随后，同一课题组使用同样的醛底物和手性催化策略，实现了对映体选择性的碳氢键炔基化**(图 1.18b)**[28b]、烯丙基化**(图 1.18c)**[28c]、萘基化**(图 1.18d)**[28d]和烷基化反应**(图 1.18e)**[28e]。

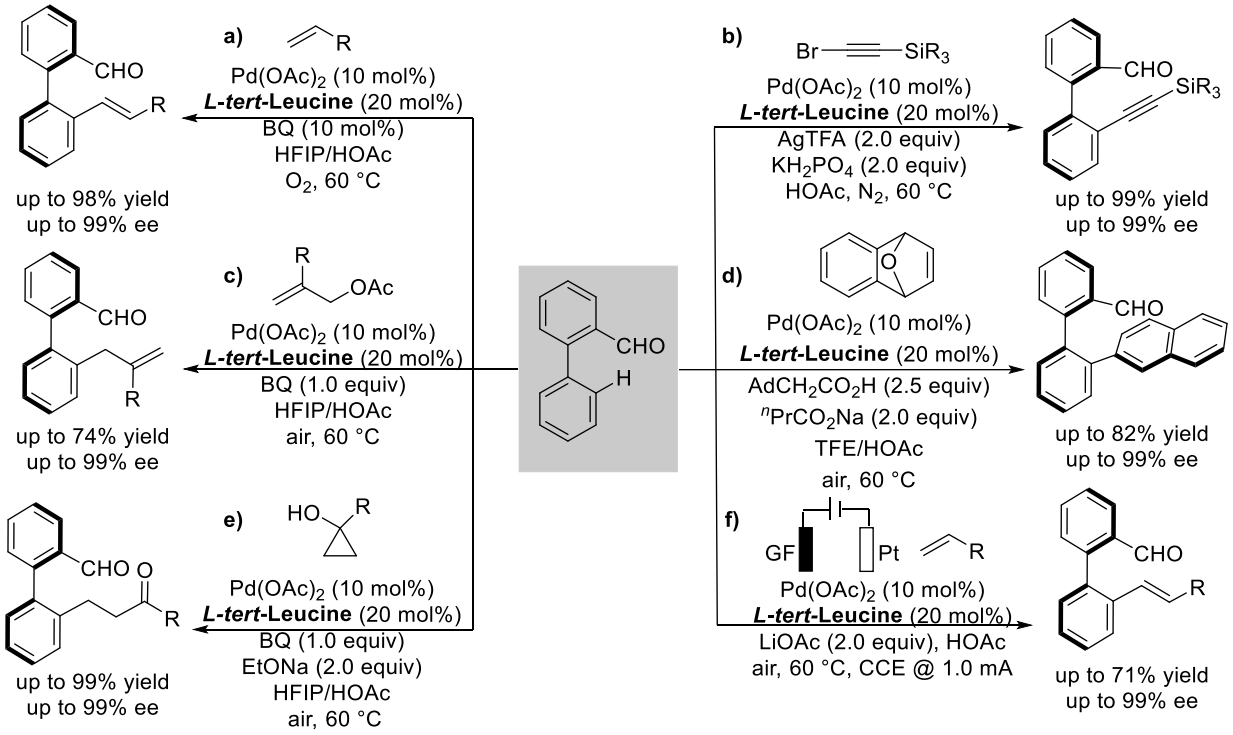


图 1.18 钯(II)催化瞬态导向不对称碳氢键官能团化反应

在 2020 年，Ackermann 课题组对钯催化瞬态导向的不对称碳氢键烯基化反应进行了一个有趣的改进[29]。作者利用电化学的方式来避免氧化剂的使用，成功以高对映体选择性合成了联芳轴手性化合物**(图 1.18f)**。

1.2.2.2 芳基-芳基偶联构建联芳轴手性

动力学拆分或去对称化已经被证明是一种高效构建联芳轴手性的方法，但是这些反应往往需要预先合成含有前手性轴的底物。因此，芳基-芳基偶联反应可以从较为简单的芳香底物出发，更加直接地构筑联芳轴手性化合物。但是要实现这一策略也充满着不少挑战，比如活化芳环上处于位阻不利位置的碳氢键往往需要比较高的反应温度，这为轴手性的诱导和控制增加了很大的难度。

Itami 课题组在 2012 年报道了钯催化噻吩类化合物的不对称碳氢键芳基化反应来直接构筑联芳轴手性(**图 1.19**)[30]。反应以 TEMPO 为氧化剂，手性双噁唑啉配体为手性配体，最高可以以 72%的 ee 值得到目标轴手性化合物。之后的研究表明[30b]，在钯和卟啉铁协同催化下，手性亚砜-噁唑啉配体可以以 61%的产率和 61%的 ee 值诱导出对应的轴手性产物，并且可以省略反应中过量 TEMPO 氧化剂的使用。

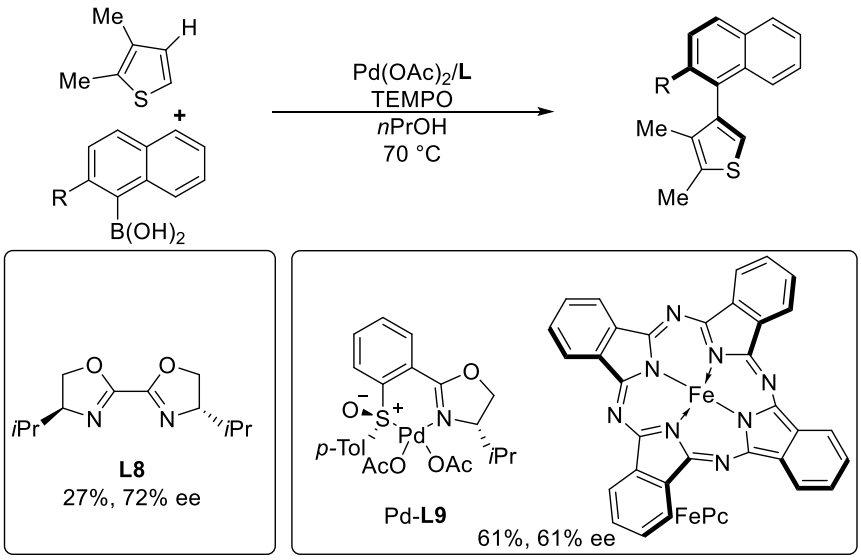


图 1.19 钯(II)催化噻吩和位阻取代苯硼酸不对称分子间碳氢键偶联

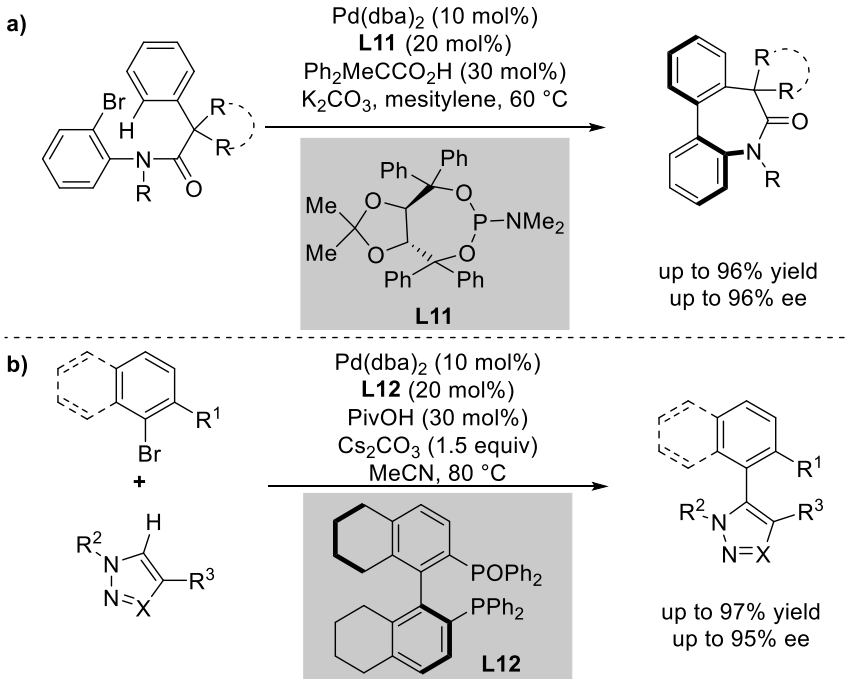


图 1.20 钯(0)催化不对称碳氢键芳基化反应

之后，Cramer 课题组[31]使用手性膦配体，相继报道了钯催化不对称碳氢键分子内和分子间的芳基化反应来高效地构建轴手性联芳化合物(**图 1.20**)。在分子内的反应中，Cramer 发现芳环邻位的取代基是至关重要的，可以阻止轴手性产物发生消旋化反应[31a]。而在分子间的反应中，作者发现手性膦配体的二面角是反应手性控制的关键[31b]。

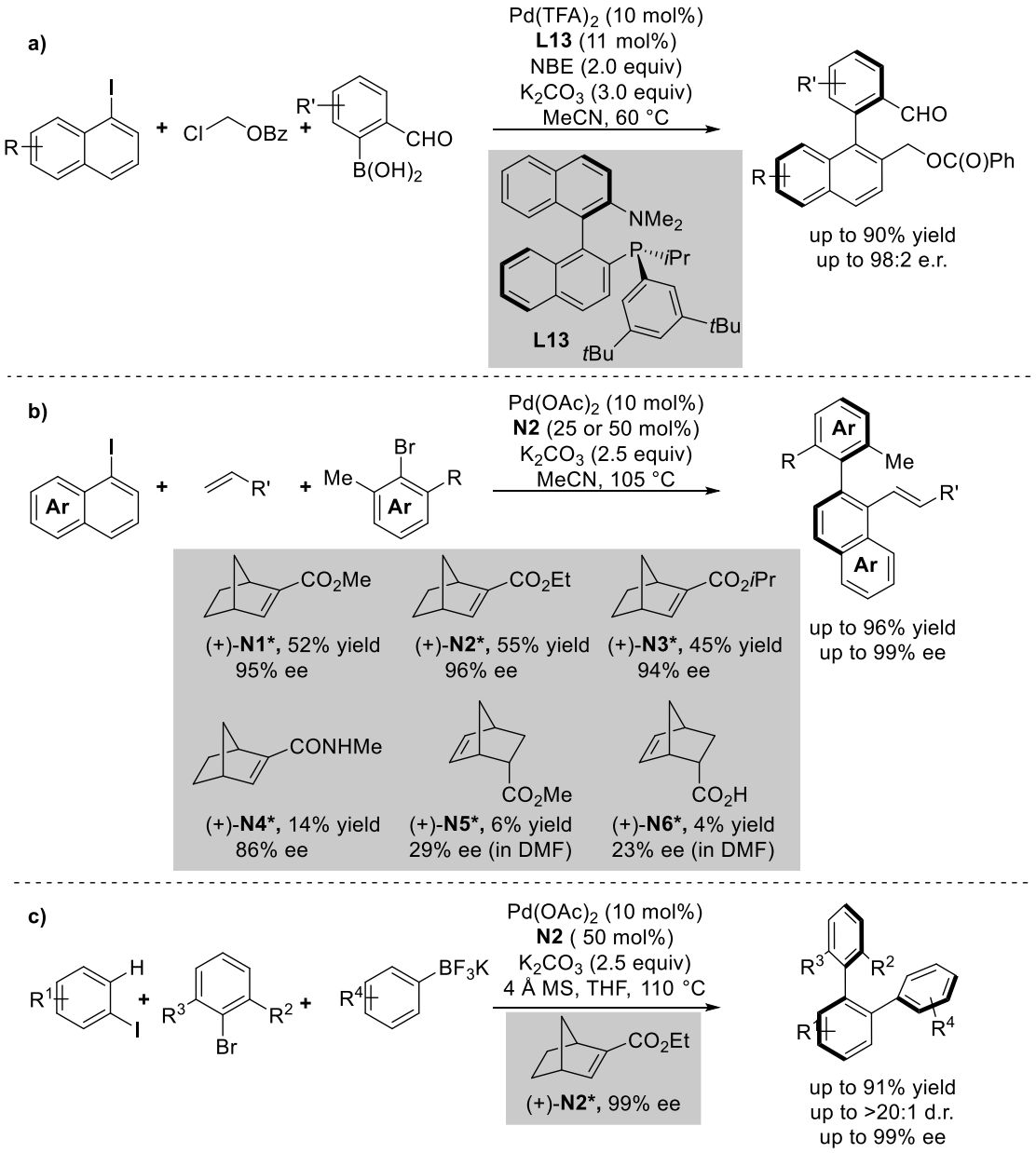


图 1.21 钯/降冰片烯协同催化不对称碳氢键芳基化反应

钯/降冰片烯协同催化的 Catellani 反应可以连续实现芳基卤代物邻位和间位的官能团转化[32]。与此同时，反应无需额外引入导向基团就可以直接实现选择性的碳氢键活化，是一种高效直接地实现碳氢键官能团转化的策略。因此顾振华和周强辉等人先后报道了利用

不对称 Catellani 反应进行构筑轴手性联芳的工作(**图 1.21**)[33]。2018 年，顾振华课题组首先报道了通过 Catellani 反应对联芳轴手性进行不对称构建(**图 1.21a**)[33a]。作者使用手性膦配体(**L13**)，通过一个不对称 Suzuki 偶联反应作为 Catellani 反应的终止步骤，合成了一系列轴手性联芳基醛化合物。虽然反应的底物比较受限制，产物的对映体选择性控制也不是非常理想，但是这一先导性工作为后续利用不对称 Catellani 反应构建轴手性奠定了基础。

之后，在 2020 年，周强辉课题组[33b]则利用钯/手性降冰片烯协同催化策略来实现不对称的 Catellani 反应构筑联芳轴手性化合物(**图 1.21b**)。在手性降冰片烯(**N2***)的作用下，反应从一开始的邻位碳氢键活化步骤就产生了轴手性，之后与各种偶联试剂进行官能团化，产生多样化的联芳轴手性化合物。手性降冰片烯的使用大大拓展了反应的底物使用范围。在 2021 年，该课题组[33c]将反应的终止试剂烯烃换成一个邻位取代的芳基硼酸，通过同样的反应策略，非对映体选择性地合成了一系列 1,2-双轴轴手性化合物(**图 1.21c**)。

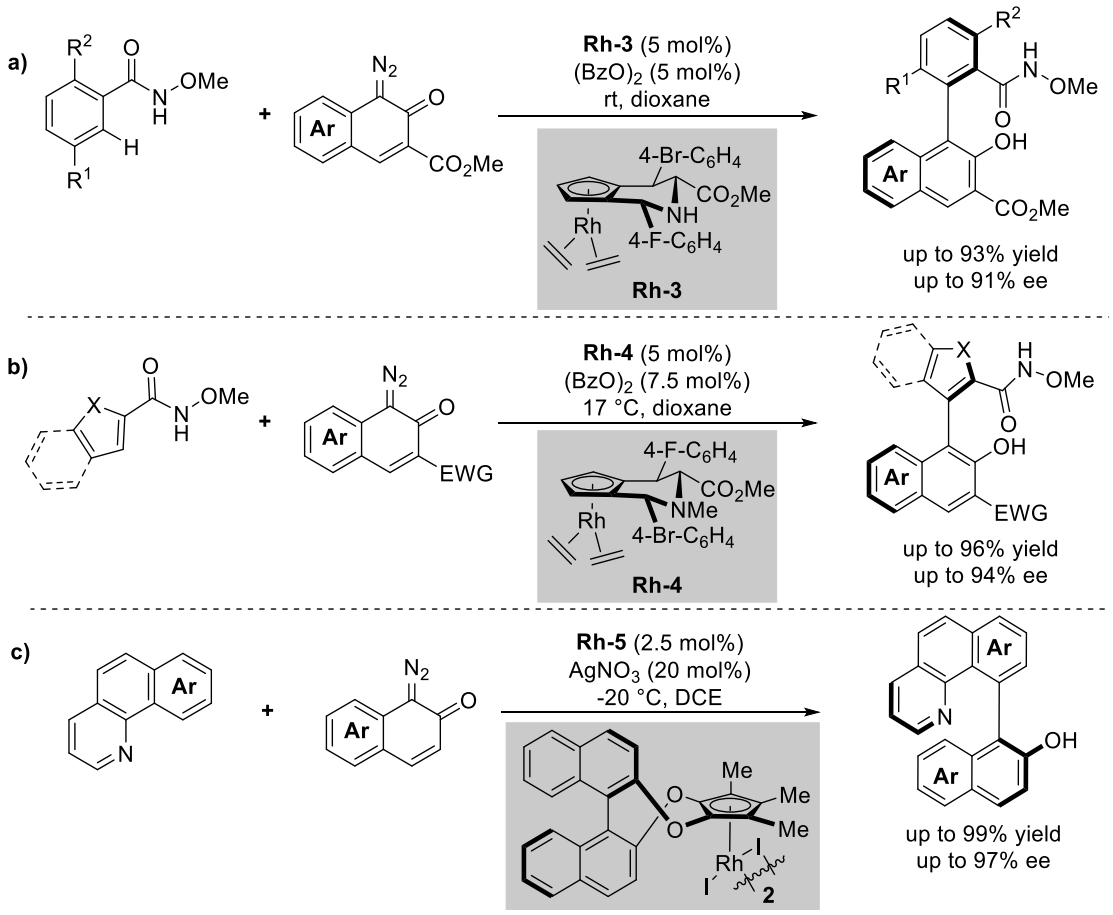


图 1.22 铑(III)催化不对称碳氢键芳基化反应

2017 年，Waldmann 课题组[34]开发了新型的手性[*Jas*CpRh^{III}]催化剂(**Rh-3**)用于苯甲酰

胺底物的邻位不对称碳氢键活化反应(**图 1.22a**)。在手性铑催化剂作用下，苯甲酰胺底物可以与重氮萘醌类化合物反应，通过直接构建芳基-芳基键，最高以 93%的产率和 91%的 ee 值合成轴手性联芳化合物。同样的手性催化剂(**Rh-4**)也可以构建含五元杂环的轴手性联芳(**图 1.22b**)[34b]。

2021 年，游书力课题组[35]利用氧原子连接的手性环戊二烯基铑复合物(**Rh-5**)为催化剂，实现了苯并喹啉类化合物的直接碳氢键芳基化反应来构建轴手性联芳化合物(**图 1.22c**)。反应机理研究表明反应经历了手性铑卡宾物种对碳氢键的迁移插入过程，实现手性轴的构建。

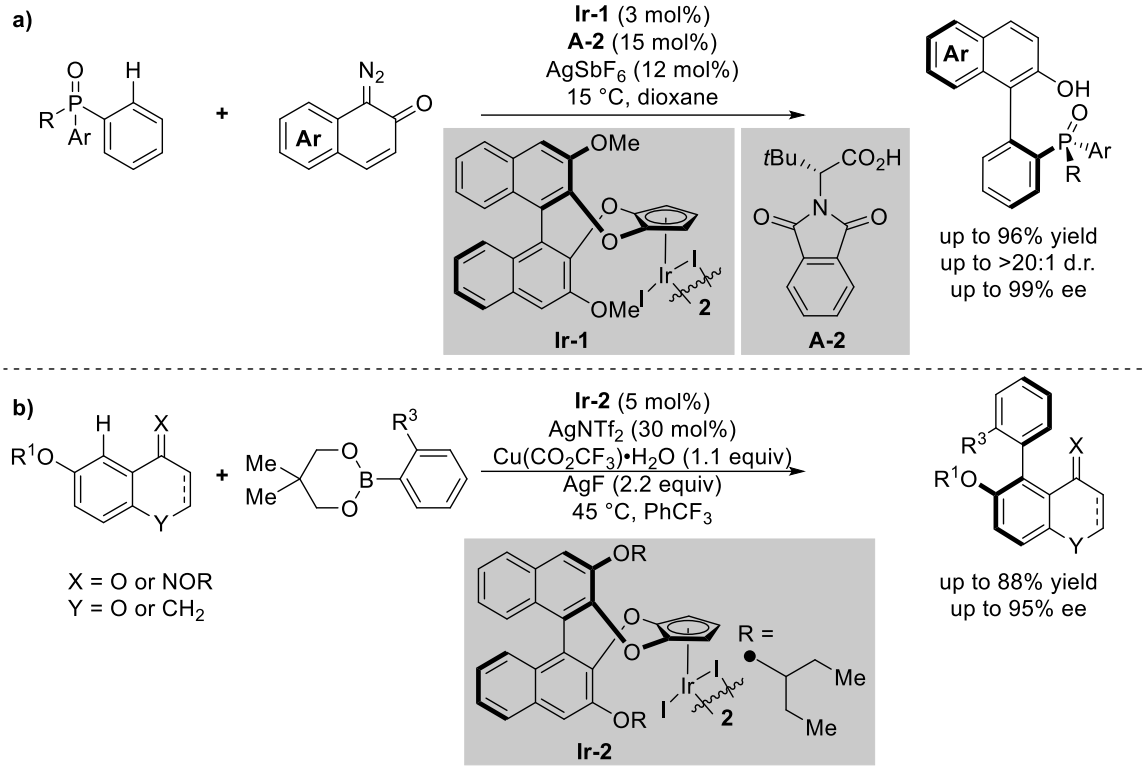


图 1.23 铱(III)催化不对称碳氢键芳基化反应

2018 年，Cramer 课题组[36]通过手性铱(**Ir-1**)催化，实现了膦氧导向的不对称碳氢键芳基化反应来构筑轴手性联芳化合物。在手性酸(**A-2**)的协同作用下，反应可以以最高 96%的产率，大于 20:1 的 dr 值和 99%的 ee 值同时构建轴手性和膦中心手性骨架(**图 1.23a**)。

2021 年，Cramer 课题组[37]使用硼酸酯替代重氮衍生物作为偶联试剂，在手性 CpIr(III)(**Ir-2**)催化下，实现了 α-四氢萘酮衍生物的不对称碳氢键芳基化反应(**图 1.23b**)。反应可以以最高 88%的产率和 95%的 ee 值得到一系列轴手性联芳化合物。

1.2.2.3 通过新芳香环的构筑构建联芳轴手性

通过不对称环化反应重新构建芳香环的策略是另一种被成功应用的直接构筑联芳手性轴的方法。这方面工作主要是手性 Rh(III)催化的不对称碳氢键环化反应。同时通过对其机理的研究，我们发现轴手性的产生源于芳香环的形成过程，而不是轴的建立过程。

2019 年，李兴伟课题组[38a]使用手性铑催化剂**(Rh-6)**实现了不对称碳氢键活化环化反应**(图 1.24a)**。反应通过一个炔烃的插入环化过程构建新的芳香环，合成了一系列较低翻转能垒的轴手性 2,3'-联吲哚化合物。

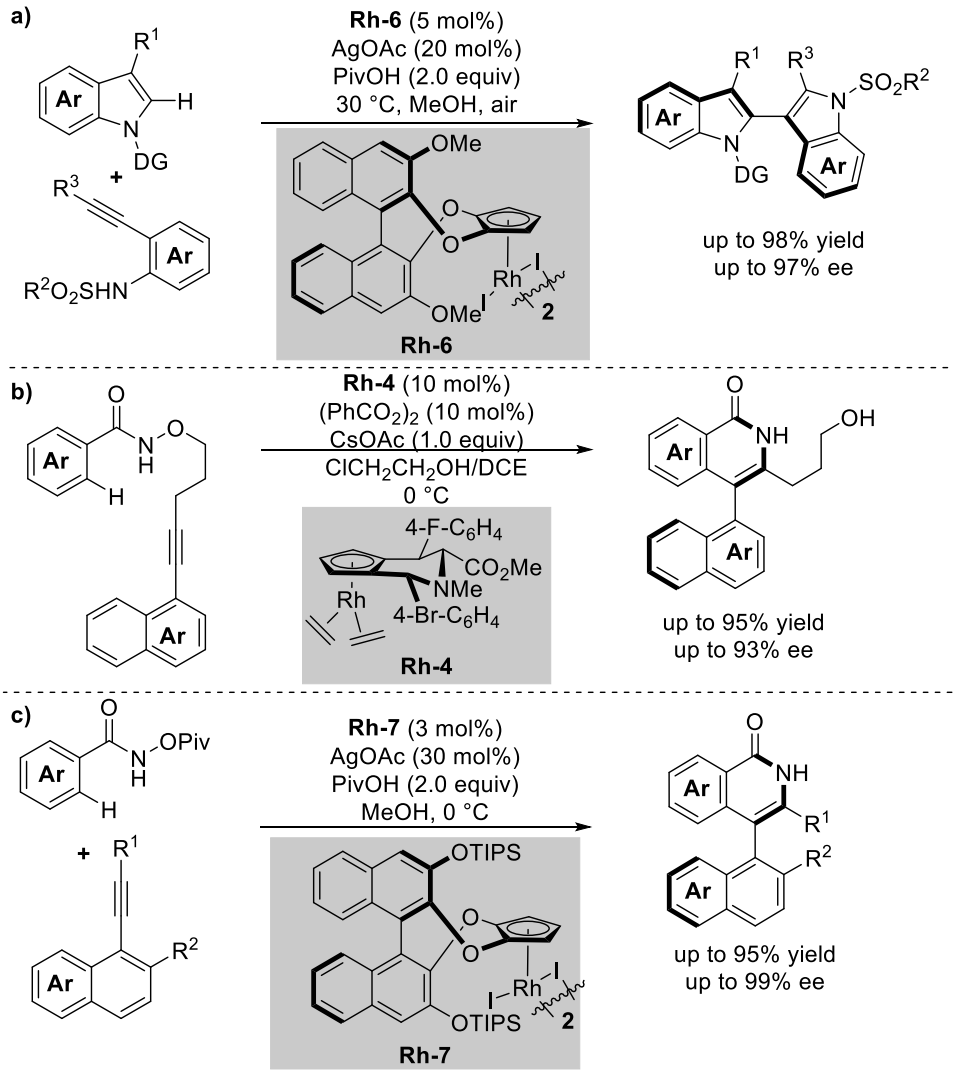


图 1.24 铑(III)催化不对称碳氢键活化与炔烃的环加成反应

4-芳基异喹啉酮轴手性化合物是一类具有良好生物活性的抑制剂，因此 Waldmann[38b]使用手性铑**(Rh-4)**催化不对称分子内碳氢键活化环化反应构筑了一系列 4-芳基异喹啉酮化

合物(**图 1.24b**)。此后，在 2020 年，李兴伟课题组[38c]利用同样的不对称碳氢键环化策略实现了手性铑(**Rh-7**)催化的分子间偶联反应构建 4-芳基异喹啉酮轴手性化合物(**图 1.24c**)。值得一提的是，反应可以很好地容忍带有各种电子效应取代基的苯甲酰胺底物。

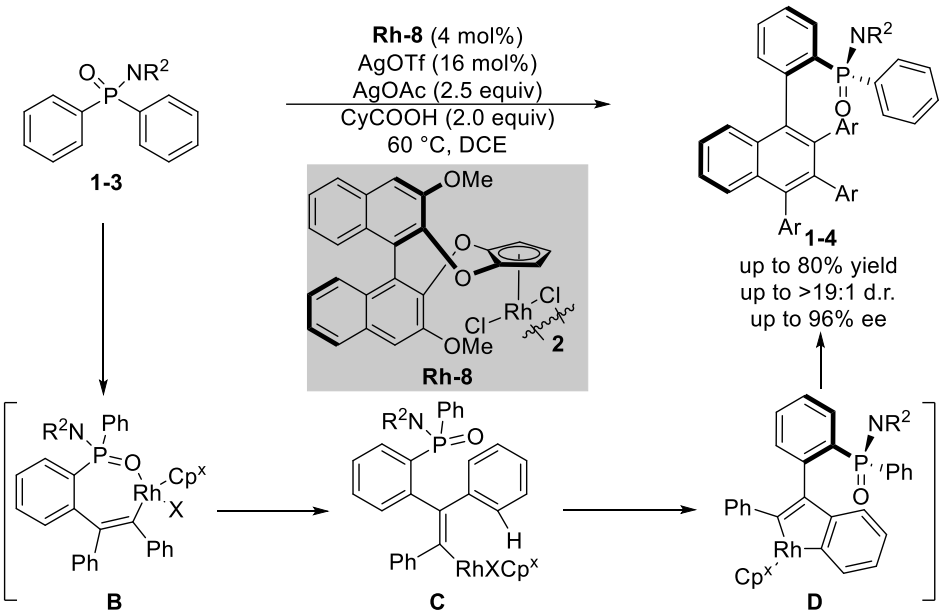


图 1.25 铑(III)催化磷酰胺与双分子二芳基乙炔的不对称碳氢键芳基化反应

2021 年，李兴伟课题组[39]对反应进行了进一步的衍生，通过使用双芳基取代的内炔烃作为偶联试剂，经过连续两次不对称碳氢键活化反应，在构建苯环的同时产生膦中心手性和联芳轴手性(**图 1.25**)。反应可能在手性铑催化剂(**Rh-8**)作用下首先历经了 CMD 机理的碳氢键活化过程紧接着插入一分子炔烃生成手性中间体物种 **B**，之后物种 **B** 经过异构化生成活性物种 **C**，物种 **C** 再通过第二次碳氢键活化生成中间体 **D**，这时已经产生了膦中心手性。之后中间体 **D** 再插入一分子内炔烃，经还原消除过程生成轴手性的产物 **1-4**。

1.3 轴手性烯基芳烃的发展

1.3.1 轴手性烯基芳烃简介

在庞大的阻转异构体家族中，存在一类被称为轴手性烯基芳烃[40]的化合物，其旋转轴存在于芳环和取代烯烃之间。与联芳轴手性相比，较低的翻转能垒和灵活的烯烃骨架都限制了烯基芳烃轴手性化合物的发展(**图 1.26**)。但作为轴手性化合物研究的重要组成部分，

轴手性烯基芳烃的合成研究也引起了科学家们的强烈兴趣[7, 12i, 41]。

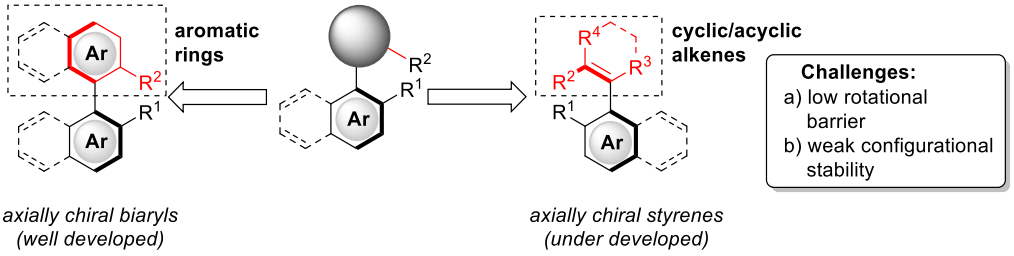


图 1.26 轴手性烯基芳烃的合成挑战

1.3.2 轴手性烯基芳烃的早期研究

1930 年，Maxwell 和 Adams[42a]尝试对一些苯乙烯酸化合物(**1-5** – **1-7**)进行对映体的拆分，遗憾的是这些 α-位置上是氢原子的苯乙烯结构的位阻还不足以产生稳定的手性轴(**图 1.27a**)。之后，Mills 和 Dazaley[42b]合成了一类芳基三甲基碘化铵分子(**1-8**)，并成功地拆分出了一对对映异构体。此外，如果将化合物 **1-8** 中处于 *Z* 构型的一个甲基替换成氢原子，化合物(**1-9**)将不再有被分离的对映异构体。

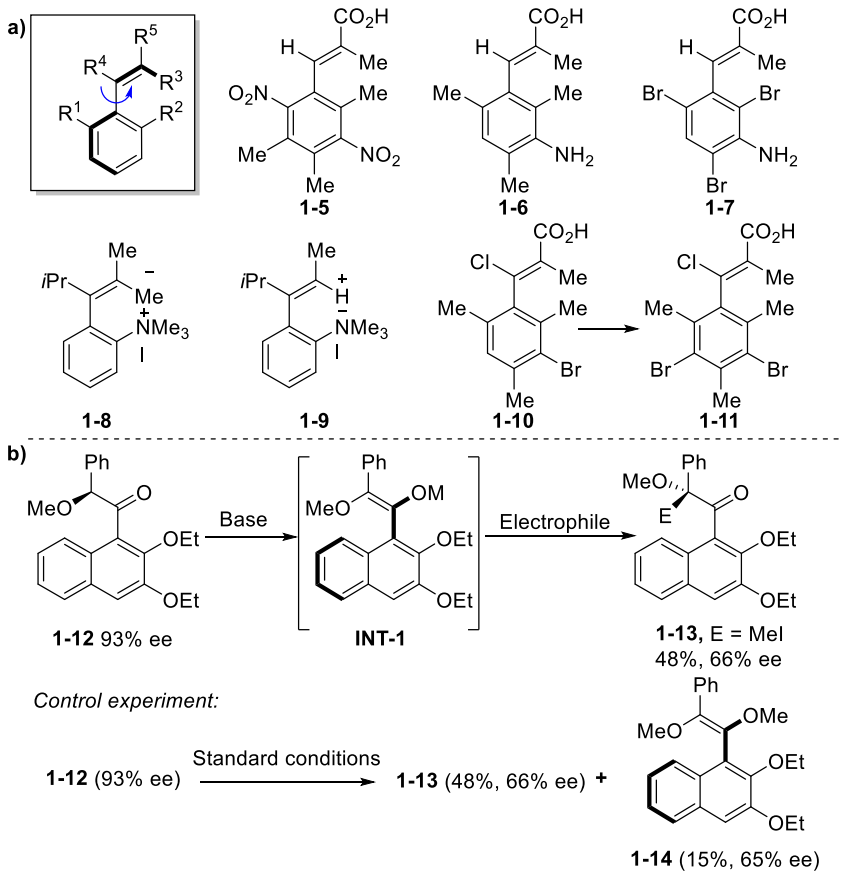


图 1.27 阻转手性苯乙烯的早期研究

紧接着，Miller 和 Adams 合成了一类位阻更加拥挤的苯乙烯酸化合物**(1-10)**，并成功对其进行对映异构体的拆分。化合物中甲基和氯原子的存在阻碍了转动轴的转动，使得该类化合物拥有非常稳定的手性轴[42c]。化合物 **1-10** 可以顺利的进行后续的溴代反应得到化合物 **1-11**。

1991 年，Fuji 课题组[42d]发现对手性的萘基酮**(1-12)**进行 α 位的亲电取代反应时，反应可以得到相应的烷基化产物**(1-13)**和少量的轴手性烯基芳烃**(1-14)**。反应历经了一个轴手性的烯醇中间体**(INT-1)**，在得到烷基化产物的同时，产生了轴手性烯基芳烃(**图 1.27b**)。

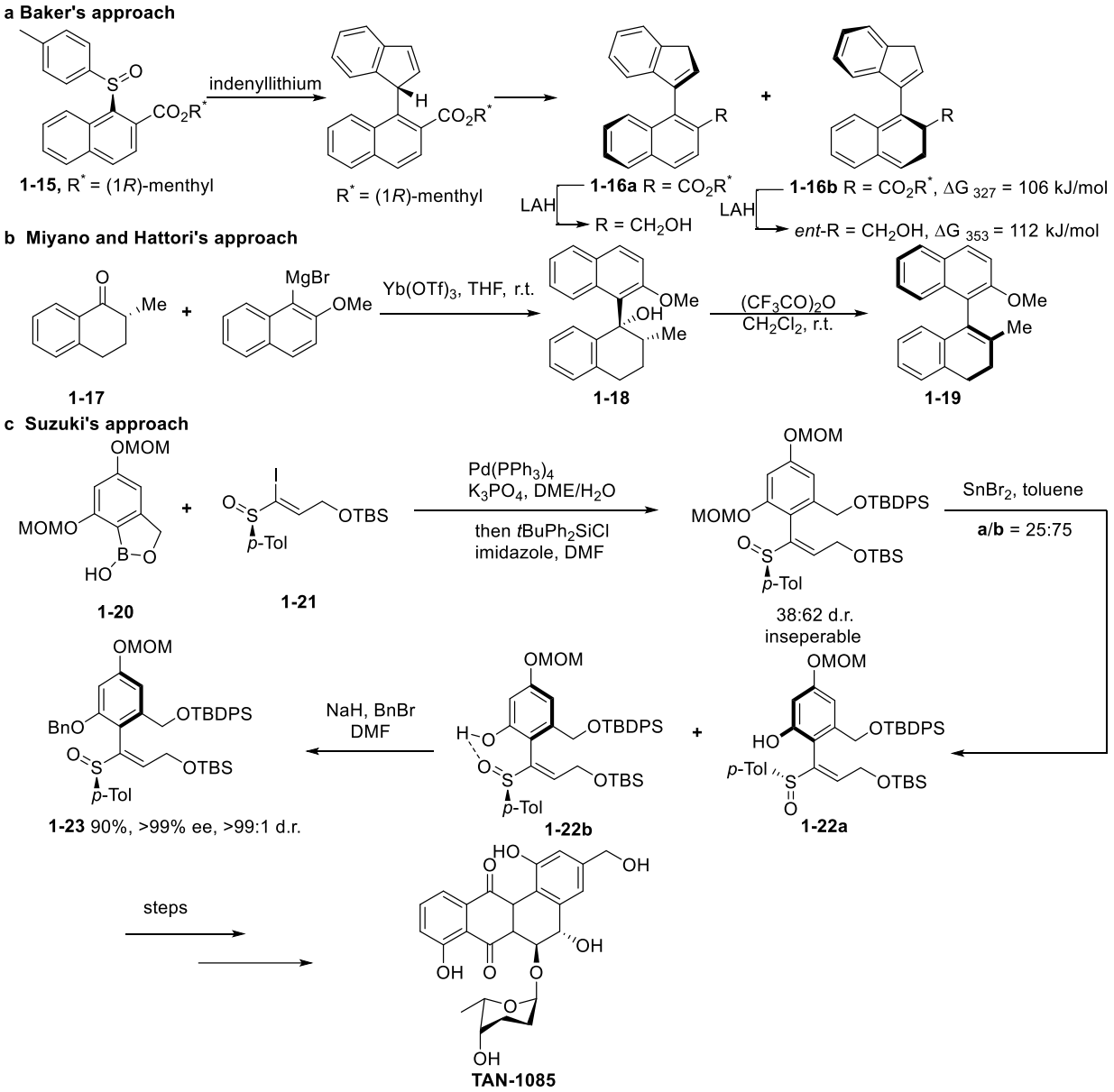


图 1.28 轴手性烯基芳烃的早期合成研究

不对称合成轴手性烯基芳烃的例子直到 1996 年才被 Baker 报道。Baker 课题组[43a]利用手性亚砜作为手性辅基，通过中心到轴的手性转移策略来合成轴手性烯基芳烃(**图 1.28a**)。手性芳基亚砜化合物(**1-15**)先与锂试剂发生反应，之后经过 1,3-氢迁移生成一对轴手性对映异构体(**1-16a, 1-16b**)。该对映异构体可以通过手性 HPLC 进行分离。

在 2001 年，Miyano 和 Hattori[43b]报道了通过 α-甲基取代的手性环酮化合物(**1-17**)和格式试剂通过 1,2-加成反应来合成手性四级醇(**1-18**)。之后产物可以立体专一性地脱除水生成轴手性化合物 **1-19**(**图 1.28b**)。

2009 年，Suzuki 课题组[43c]将非对映体选择性合成轴手性烯基芳烃的策略成功应用于抗生素 TAN-1085 的全合成中(**图 1.28c**)。反应以含有手性亚砜辅基的烯基碘 **1-21** 和硼酸酯 **1-20** 为原料，首先发生 Suzuki-Miyaura 偶联反应，再经过上保护基和选择性去保护基生成一对非对映异构体 **1-22a** 和 **1-22b**。**1-22b** 可以经硅胶柱层析方式分离，接着进行一步苄基化生成单一的轴手性产物 **1-23**。最后经过一系列转化就可以对映体选择性地合成 **TAN-1085**。

1.3.3 轴手性烯基芳烃的催化不对称合成

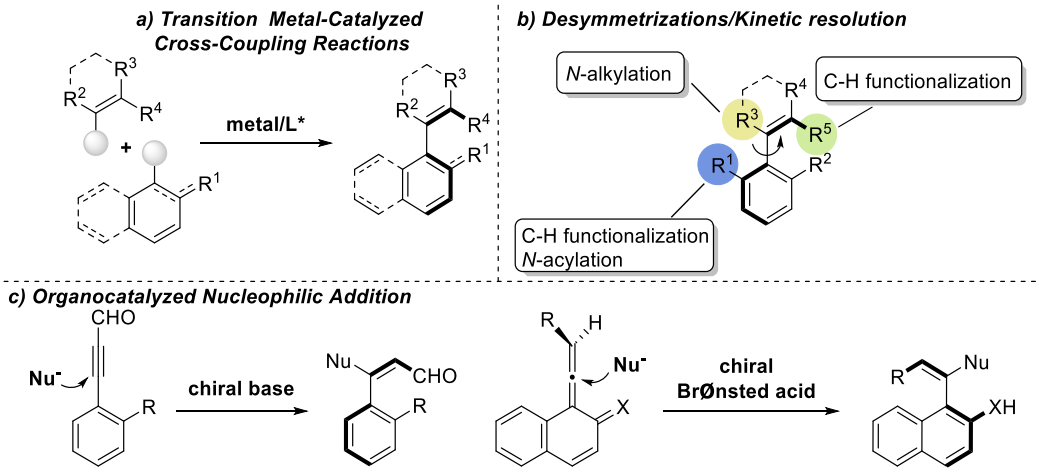


图 1.29 轴手性烯基芳烃的催化不对称合成策略

轴手性烯基芳烃的早期研究主要是使用化学当量的手性分子作为反应前体，通过中心手性传递到轴手性的方法来实现轴手性骨架的不对称合成(**图 1.28**)。而催化不对称地合成轴手性烯基芳烃骨架是更加有实用价值的。因此近年来，科学家们极力开展了烯基芳烃轴手性骨架的催化不对称合成研究。催化不对称合成轴手性烯基芳烃的方法可以总结为以下几类(**图 1.29**)：1）过渡金属催化的不对称交叉偶联反应直接构建芳基-烯烃手性轴；2）对

已存在前手性轴的苯乙烯底物进行去对称化或动力学拆分反应来构建轴手性；3）通过有机小分子催化不对称加成反应合成多取代烯烃并产生手性轴。

1.3.3.1 不对称交叉偶联反应构建轴手性烯基芳烃

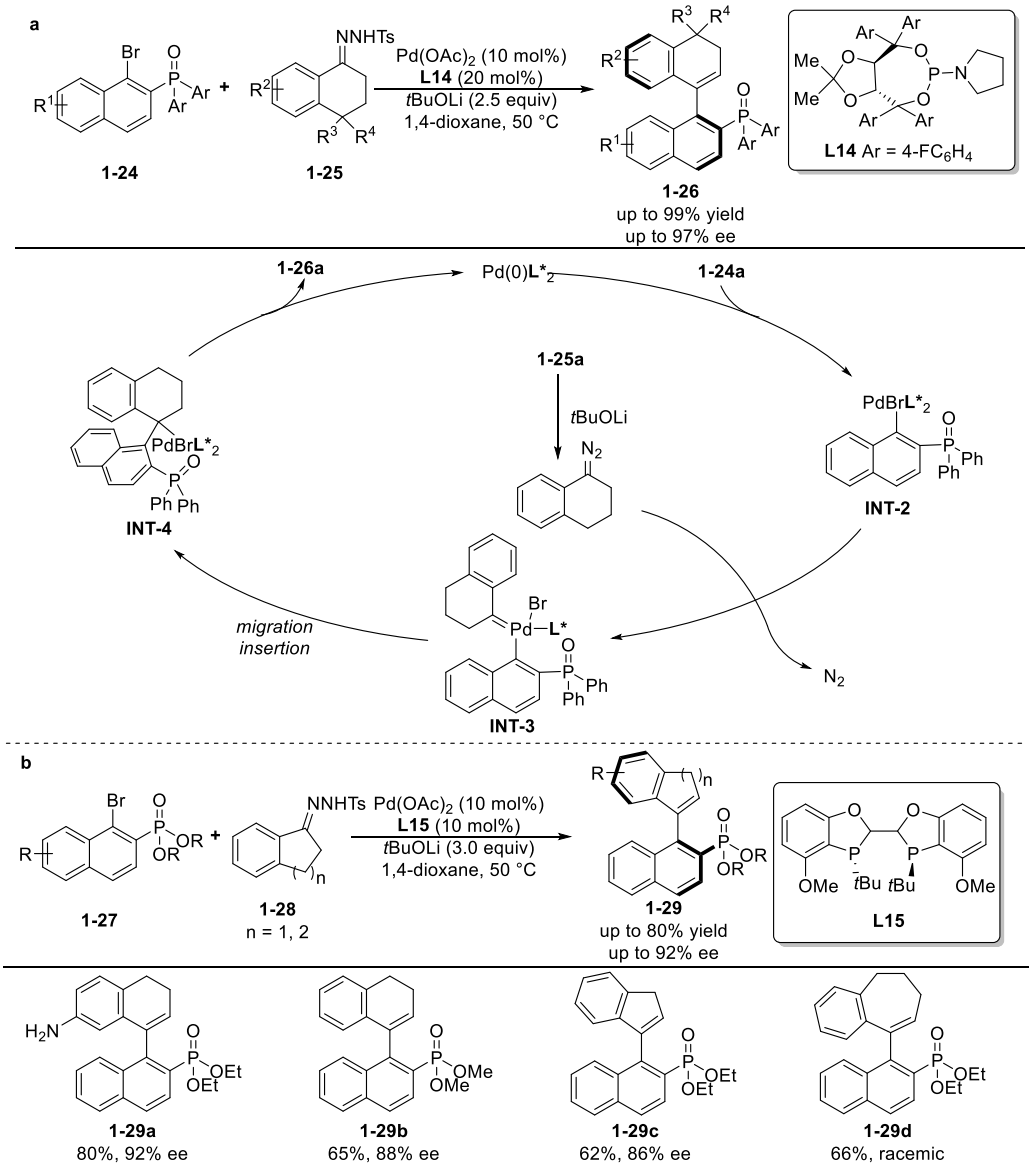


图 1.30 钯催化芳基卤代物与卡宾前体反应不对称合成阻转手性苯乙烯

金属催化的不对称交叉偶联反应是直接高效构建烯基芳烃手性轴的方法。2016 年，顾振华课题组[44a]报道了首例催化不对称手段合成轴手性烯基芳烃的研究(**图 1.30a**)。反应以芳基溴代物 **1-24** 和卡宾前体 **1-25** 为起始底物，在醋酸钯和 Taddol 衍生的手性亚膦酰胺配体 **L14** 的作用下，可以以最高 99%的产率和 97%的 ee 值得到一系列芳基环烯烃轴手性化

合物 **1-26**。该反应展现出良好的官能团容忍性。机理研究表明反应可能经历了以下过程：首先催化剂与卤代芳烃底物发生氧化加成反应生成 **INT-2**，然后卡宾前体在碱作用下脱除一分子氮气，再与活性物种 **INT-2** 反应生成一个钯卡宾物种 **INT-3**，接着发生卡宾对碳钯键的迁移插入生成中心手性的中间物种 **INT-4**，最后 **INT-4** 通过 β-H 消除反应得到对应的轴手性化合物并实现催化剂循环。

2016 年，Senanayake 课题组[44b]报道了利用同样的策略构建烯基芳烃轴手性骨架的研究(**图 1.30b**)。作者使用二烷基磷酸酯 **1-27** 为底物，腙类化合物 **1-28** 为卡宾前体，醋酸钯为催化剂，在手性双膦配体 **L15** 作用下以良好的产率和手性控制合成了一系列芳基-环烯烃轴手性化合物。六元环和五元环的环烯烃轴手性产物(**1-29a, 1-29b, 1-29c**)均可以以很好的结果得到，但是当环烯烃扩大到七元环时，其产物是消旋的(**1-29d**)。

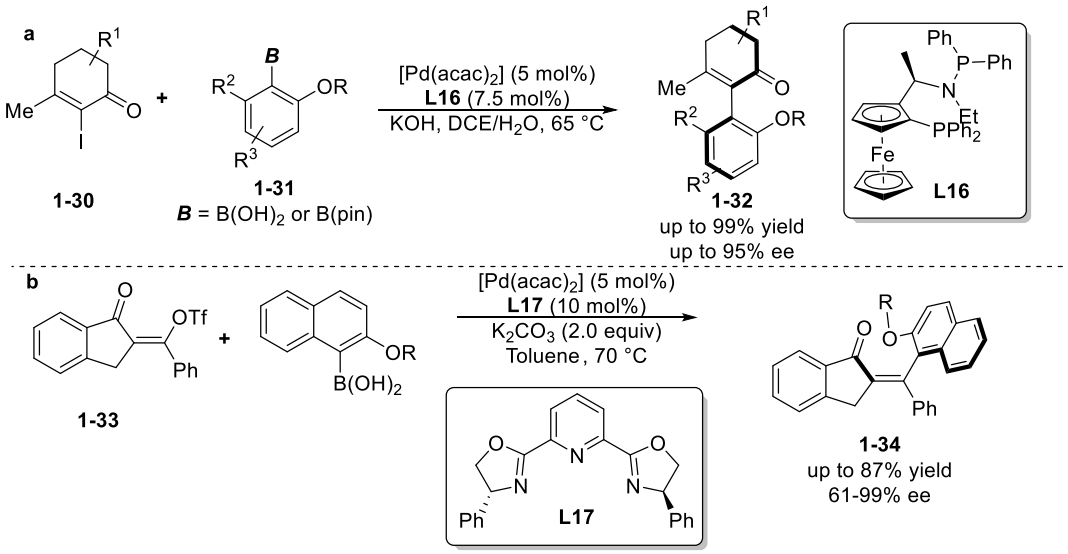


图 1.31 Suzuki–Miyaura 交叉偶联反应构建轴手性烯基芳烃

2017 年，顾振华课题组[45a]报道了环已烯碘化合物 **1-30** 和芳基硼酸化合物 **1-31** 经不对称 Suzuki 偶联生成轴手性烯基芳烃的研究工作(**图 1.31a**)。反应在手性二茂铁膦配体 **L16** 的作用下可以以最高 99%的产率和 95%的 ee 值得到轴手性化合物 **1-32**。近期，Ramasastry 等人报道了三氟甲磺酸酯取代的烯烃底物 **1-33** 和芳基硼酸之间的不对称 Suzuki 偶联反应(**图 1.31b**)[45b]。反应在手性 PyBox 配体 **L17** 的作用下，可以以最高 87%的产率和 61%到 99%的 ee 值得到一系列含有开链烯烃结构的烯基芳烃轴手性产物(**1-34**)。与之前 Gu 课题组报道的环状烯烃-芳烃轴手性骨架相比，存在开链式烯烃结构的骨架稳定性更差，拥有相对更低的翻转能垒，因此该不对称偶联反应的手性控制结果也相应较差。

2021 年，杨尚东课题组[46]成功实现了吡啶噁唑啉配体和金属钴催化体系下的溴代芳烃 **1-35** 和三氟甲磺酸酯取代的环烯烃 **1-36** 之间的不对称还原交叉偶联反应(**图 1.32**)。反应可以以最高 92%的产率和 95%的 ee 值合成一系列含二苯基膦氧结构的轴手性烯基芳烃。产物 **1-37** 可以经过简单的一步还原反应得到相应的手性膦烯配体。

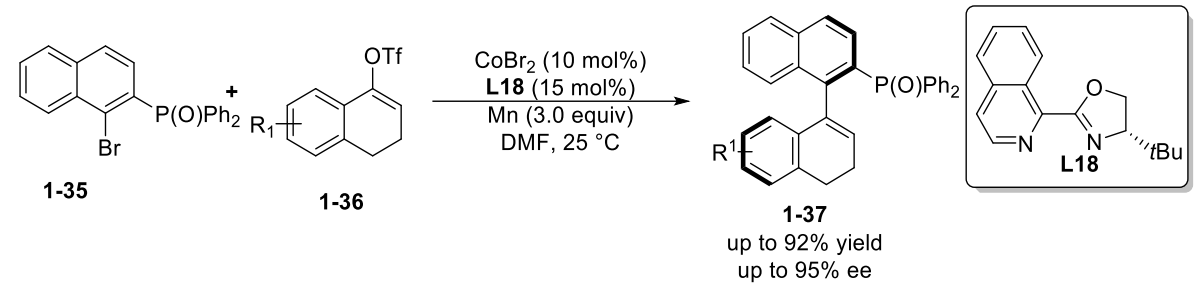


图 1.32 钴催化还原交叉偶联反应合成轴手性烯基芳烃

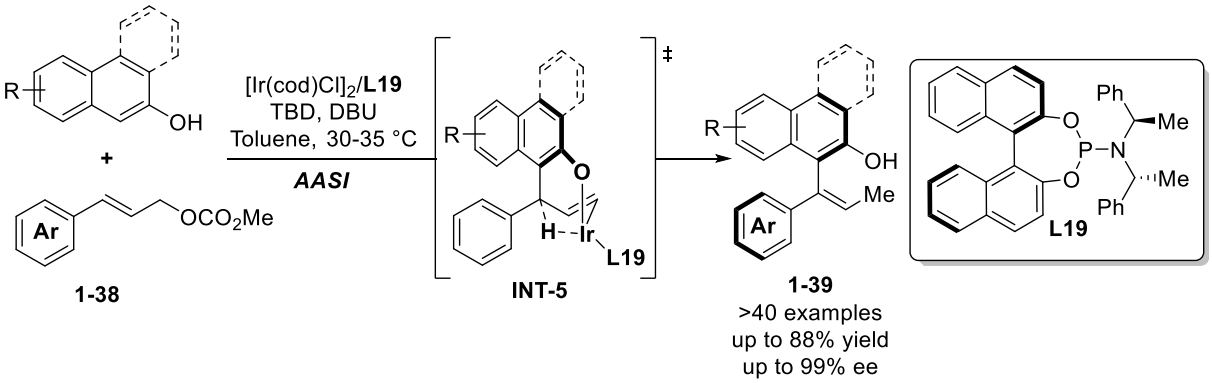


图 1.33 串联铱不对称催化策略构建轴手性烯基芳烃

最近，一个铱和手性膦配体催化的串联不对称烯丙基取代异构化反应被应用于开链式烯烃-芳烃手性轴的直接构建中[47]。何英课题组使用烯丙基碳酸酯 **1-38** 为起始原料，在铱催化剂和手性配体 **L19** 的作用下，通过发生不对称烯丙基萘基化反应，完成烯烃-芳烃的脱氢交叉偶联，生成手性的中间物种 **INT-5**，再经过金属参与的烯烃异构化反应将手性传递到芳烃-烯烃轴上，生成最终的开链式烯基芳烃轴手性化合物 **1-39**(**图 1.33**)。

1.3.3.2 去对称化和动力学拆分构建轴手性烯基芳烃

对于已存在前手性轴的苯乙烯类化合物而言，利用去对称化或动力学拆分的方式是一种原子经济性地合成轴手性烯基芳烃的方法。该策略主要包含过渡金属催化的不对称碳氢键官能团化反应和有机小分子催化的动力学拆分反应。

1.3.3.2.1 过渡金属催化不对称碳氢键官能团化反应构建轴手性烯基芳烃

近年来，过渡金属催化的不对称碳氢键活化反应作为一种步骤和原子经济性的合成手段而被广泛应用于复杂手性分子构建中[2]。与过渡金属催化不对称碳氢键活化构建联芳轴手性[13]相类似，轴手性烯基芳烃的不对称构建也是利用导向策略，通过直接碳氢键官能团化反应在转轴的附近引入一个位阻基团，从而阻碍芳基-烯烃轴的自由转动来产生轴手性。

基于芳基-环己烯骨架结构，2018 年，徐利文课题组[48]报道了一例钯催化肟醚导向的不对称碳氢键烯基化反应(**图 1.34**)。反应使用醋酸钯为催化剂，单保护氨基酸 **L20** 为手性配体，2-芳基环己烯基-2-酮肟醚 **1-40** 为反应底物，可以以优异的对映体选择性得到轴手性芳基烯烃化合物 **1-41**。作为临时导向作用的肟醚可以在盐酸作用下被顺利脱除。化合物 **1-41a** 可以通过与二苯基氯化膦反应生成手性膦配体 **1-42**，在钯催化的不对称烯丙基取代反应中以 60%的产率和 37%的 ee 值得到烯丙基取代产物 **1-43**。

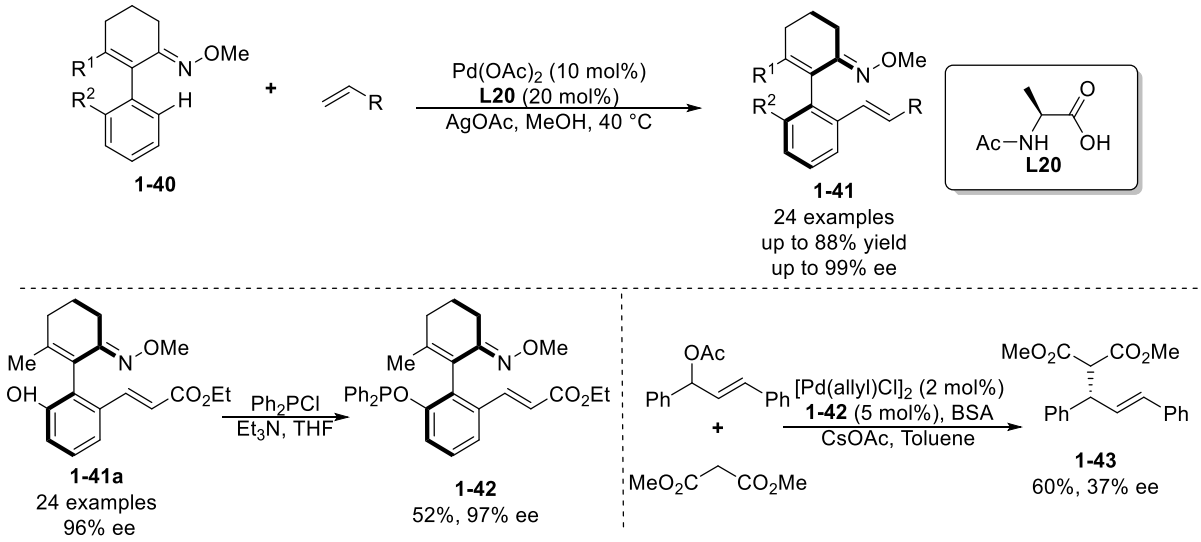


图 1.34 钯催化肟醚导向不对称碳氢键烯基化反应构建轴手性烯基芳烃

相比于结构刚性的轴手性环己烯基芳烃骨架，拥有一个开链式烯烃结构单元的轴手性烯基芳烃因为灵活的烯烃结构而具有较低的翻转能垒。因此催化不对称地合成这类轴手性烯烃骨架是更加具有挑战性的。2020 年，史炳锋课题组[49]利用手性瞬态辅基策略，实现了钯催化芳烃碳氢键不对称烯基化反应，成功合成了一类轴手性苯乙烯醛化合物 **1-45(图 1.35)**。该反应拥有良好的官能团容忍性，最高能以 95%的产率和 99%的 ee 值得到轴手性产物。产物可以经过一步氧化得到相对应的轴手性羧酸配体，并应用于钴催化的不对称 C(sp^3)–H 酰胺化反应中。

同时我们课题组[50]基于导向不对称碳氢键活化的策略，分别实现了钯催化不对称芳烃和烯烃碳氢键活化官能团化反应来构建含开链式烯烃结构单元的轴手性烯基芳烃骨架。此后，其他课题组也纷纷效仿，利用过渡金属催化的不对称碳氢键活化手段对含开链式烯烃结构单元的轴手性烯基芳烃化合物进行不对称合成。

2021 年，王细胜课题组[51]直接使用羧基作为导向基团，叔丁氧羰基保护的叔亮氨酸为手性配体，成功实现了钯催化芳烃不对称碳氢键烯基化和芳基化反应(**图 1.36**)，直接合成了一系列基于烯基芳烃轴手性骨架的羧酸配体 **1-45**。该类配体在钴催化吲哚 2-位的不对称碳氢键烷基化反应中展现出不错的效果。

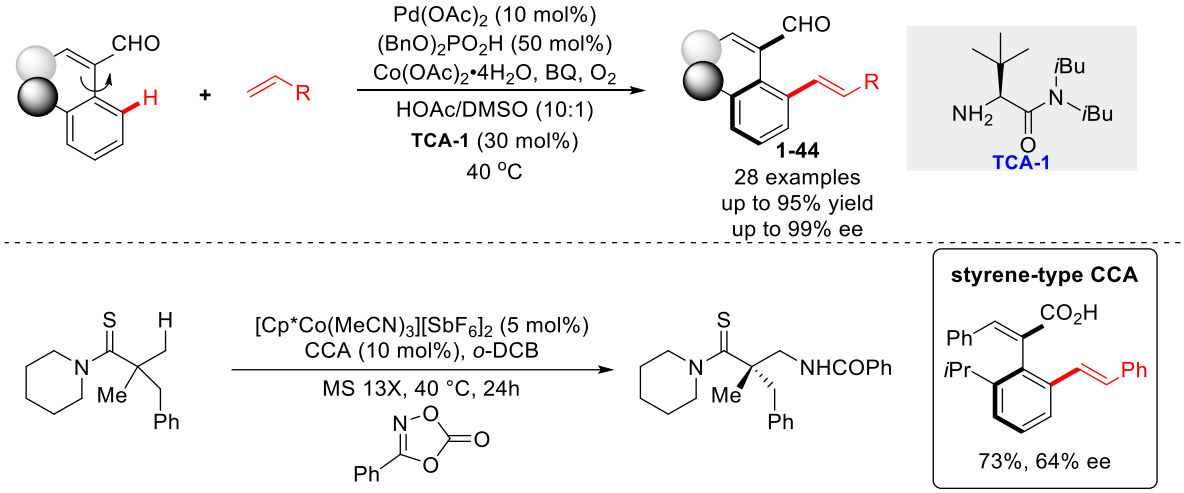


图 1.35 手性瞬态导向策略的钯催化不对称碳氢键烯基化反应构建轴手性烯基芳烃

受到我们课题组工作[49,50]的启发，张坚和钟国富等人[52a]在前不久报道了以 **TCA-1** 为瞬态导向基，钯催化不对称烯烃碳氢键烯基化反应来合成含 1,3-共轭二烯结构单元的轴手性烯基芳烃化合物(**图 1.37**)。反应最高可以以 89%的产率和 99%的 ee 值得到轴手性产物 **1-46**。醛基的使用为产物的后续应用提供了极大的可能性。比如化合物 **1-46** 可以经过简单的氧化生成一系列手性酸 **1-47**，该手性酸可以作为手性酸配体应用于吲哚 2-位的不对称碳氢键烷基化反应中，并最高诱导出 36%的产率和 9:91 的 er 值。

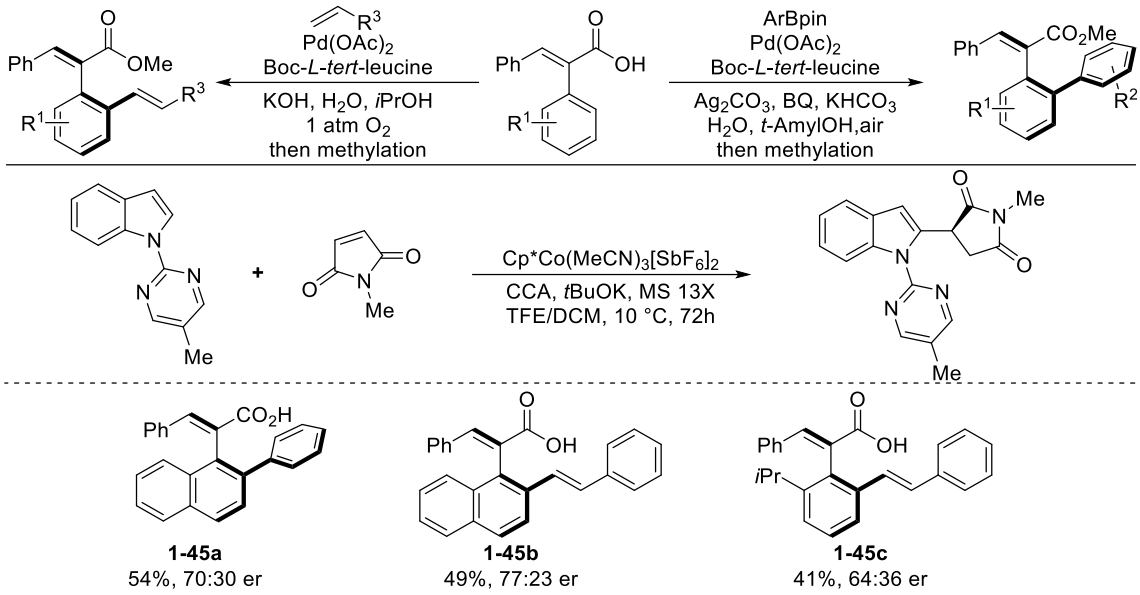


图 1.36 羧酸导向不对称碳氢键官能团化反应构建轴手性烯基芳烃

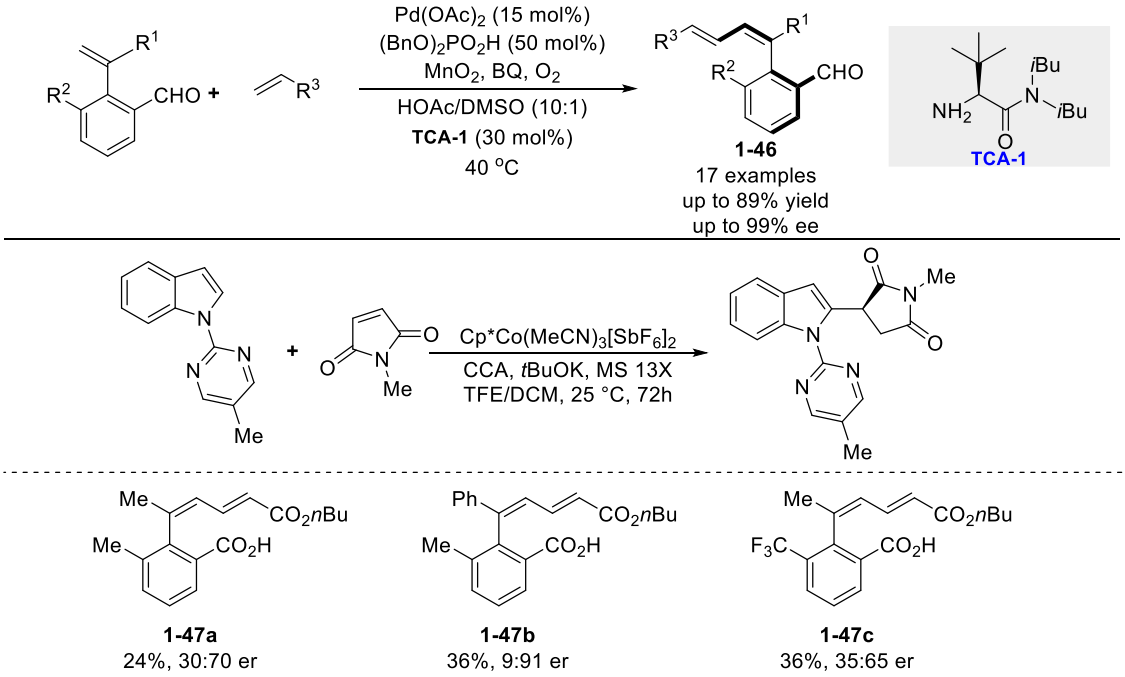


图 1.37 瞬态导向策略不对称碳氢键烯基化反应构建轴手性芳基 1,3-二烯

徐允河课题组[52b]也几乎在同时发表了通过钯催化不对称烯烃碳氢键烯基化反应来合成含 1,3-共轭二烯结构单元的轴手性烯基芳烃化合物(**图 1.38**)。反应中，作者使用了一个 Pincer 类型的吡啶噁唑啉配体 **L17**，通过一个螯合作用的新的手性控制模式实现了不对称烯烃碳氢键的烯基化反应，以最高 86%的产率和 93%的 ee 值得到轴手性化合物 **1-48**。

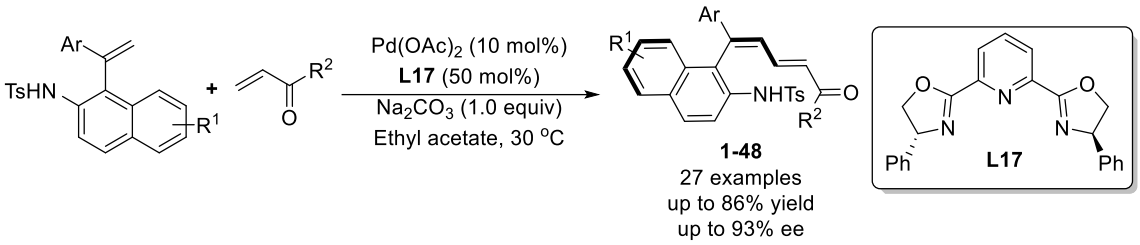


图 1.38 不对称合成含共轭二烯结构的轴手性烯基芳烃

1.3.3.2.2 有机小分子催化的动力学拆分反应构建轴手性烯基芳烃

有机小分子催化的不对称取代反应是对已存在前手性轴的烯基芳烃化合物进行动力学拆分的有效手段之一。这一部分工作首先由谭斌和石枫课题组[53]报道。

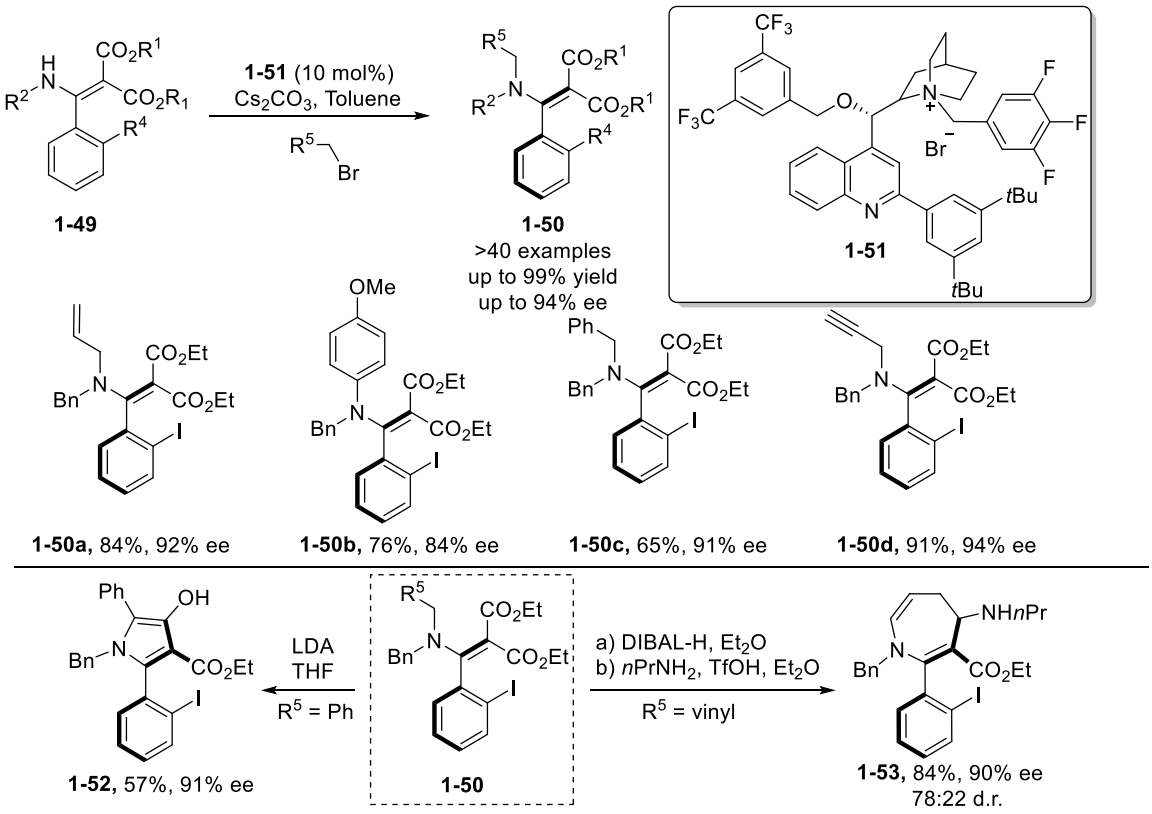


图 1.39 不对称 *N*-烷基化反应构建轴手性烯基芳烃

2019 年，谭斌课题组[53a]报道了一例有机小分子催化的不对称 *N*-烷基化反应来快速构筑轴手性烯基芳烃。在催化剂 **1-51** 的作用下，芳基烯胺底物 **1-49** 可以跟烷基溴代物发生亲核取代反应，以令人满意的立体选择性控制和官能团容忍得到轴手性烯基芳烃化合物 **1-50(图 1.39)**。该方法适用多种溴代底物，比如烯丙基溴、芳基溴代物、苄基溴化物和炔丙基溴，都可以产生不错的结果**(1-50a–1-50d)**。此外，反应生成的轴手性产物可以通过一步

或两步关环反应生成含五元或七元杂环结构的联芳轴手性化合物(**1-52, 1-53**)。

2020 年，石枫课题组[53b]利用手性磷酸 **1-57** 作为手性催化剂，通过不对称取代反应对含有吲哚骨架的轴手性乙烯基苯胺 **1-54** 进行动力学拆分反应(**图 1.40**)。该反应成功以高非对映体选择性和优秀的对映体选择性以及拆分因子得到两种不同的含吲哚骨架的轴手性烯基芳烃化合物(**1-55, 1-56**)。之后将得到的轴手性乙烯基苯胺 **1-55** 进行简单转化，可以得到一系列轴手性烯基芳烃骨架的手性硫脲、硫脲-三苯基膦、硫脲-二苯基膦和硫脲-三苯基硫化膦化合物。这些手性化合物可以在不对称催化中表现出不错的效果。

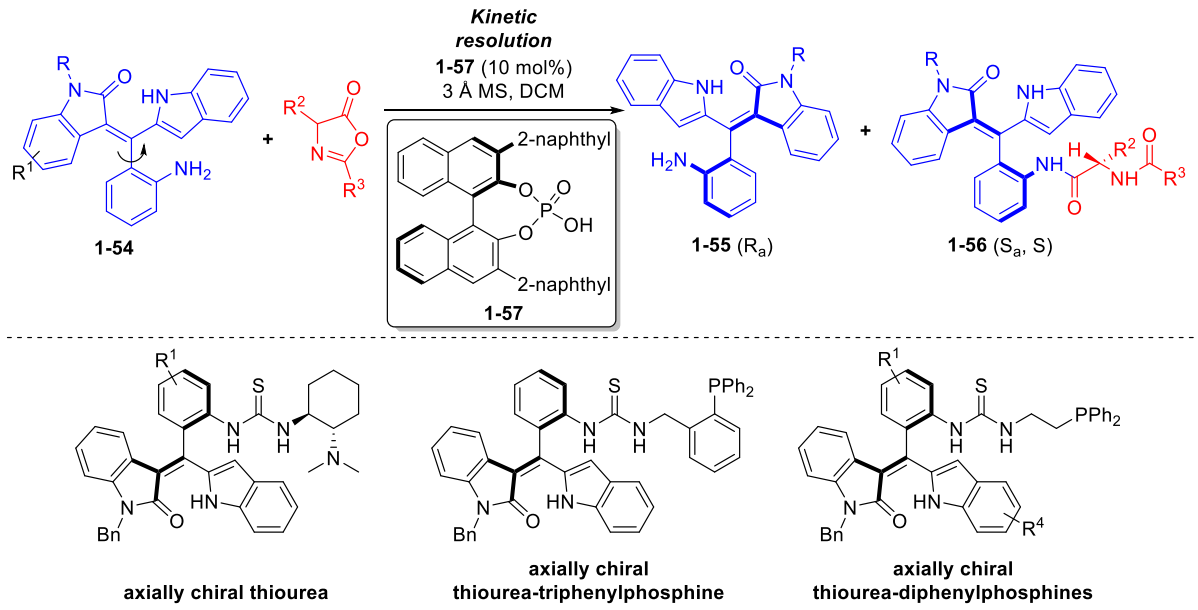


图 1.40 不对称 *N*-酰基化反应构建轴手性烯基芳烃

近期，程道娟等人[54]报道了一例手性磷酸催化的还原胺化反应，通过一个动态动力学拆分的方式来对映体选择性地构建烯基芳烃轴手性(**图 1.41**)。反应通过手性磷酸 **1-60** 催化的不对称转移氢化对烯基芳烃底物 **1-58** 进行动态动力学拆分，最终可以以最高 91%的产率和 66-90%的 ee 值得到一系列烯基芳烃轴手性骨架的烯丙基胺化合物 **1-59**。

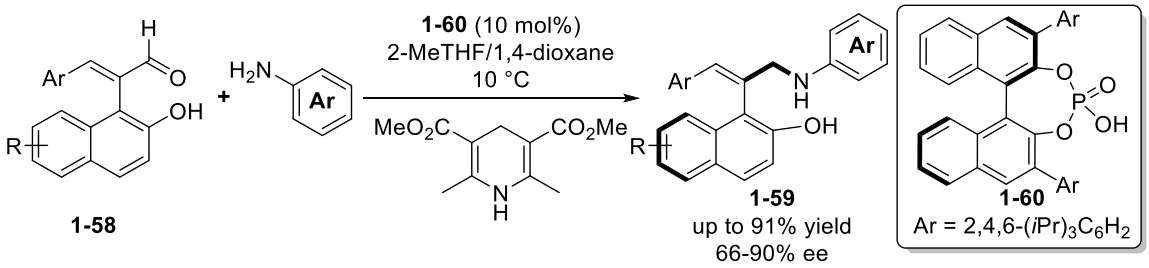


图 1.41 不对称还原胺化反应构建轴手性烯基芳烃

1.3.3.3 有机小分子催化不对称加成反应构建轴手性烯基芳烃

有机小分子催化不对称加成反应是一类非常重要且被科学家广泛用于构建含开链式烯烃结构单元的烯基芳烃轴手性骨架的方法。该策略通过亲核试剂和炔烃发生不对称加成反应，在生成多取代烯烃的同时诱导出烯烃-芳烃轴手性。我们根据使用的催化剂类型可以将其分为有机碱催化不对称加成反应构建轴手性烯基芳烃和布朗斯特酸催化不对称加成反应构建轴手性烯基芳烃两大类。

1.3.3.3.1 有机碱催化不对称加成反应构建轴手性烯基芳烃

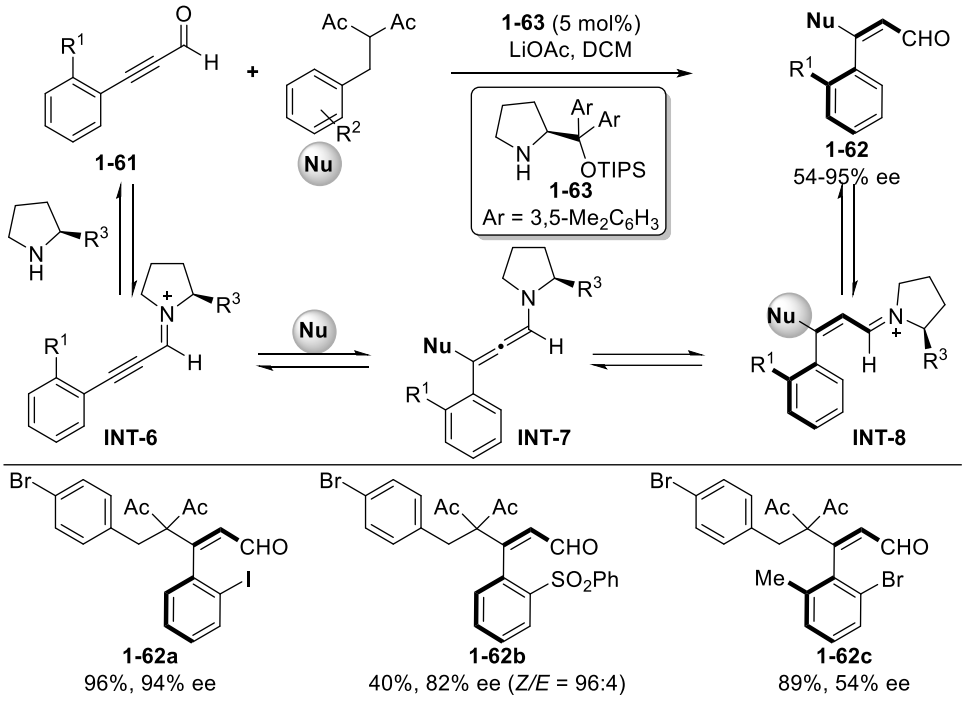


图 1.42 手性吡咯催化不对称合成轴手性苯乙烯

2017 年，谭斌课题组[55]报道了首例有机小分子碱催化不对称合成轴手性烯基芳烃的研究。底物内炔烃 **1-61** 与手性吡咯催化剂 **1-63** 结合生成中间物种 **INT-6**，紧接着中间体 **INT-6** 受到亲核试剂进攻产生手性的联烯基化合物 **INT-7**，之后联烯异构化得到盐 **INT-8**，最后催化剂解离，得到最终的烯基芳烃轴手性产物 **1-62**(**图 1.42**)。在底物扩展中作者发现，苯乙烯底物的邻位是碘原子和磺酸基团时，产物将表现出一个比较好的结果(**1-62a**, **1-62b**)。如果将取代基换成甲基和溴原子，产物的对映体比率就会下降到 54% ee(**1-62c**)。

2020 年，赵晓丹课题组[56]使用一个手性硫醚分子作为催化剂，催化内炔烃底物 **1-64** 发生不对称亲电碳硫化和分子内环化反应，生成轴手性环己烯基芳烃骨架 **1-65(图 1.43)**。亲电试剂在路易斯酸的作用下先与催化剂结合生成活性中间体 **INT-9**，接着与底物内炔烃结合成 **INT-10**，之后催化剂解离生成手性的氮杂联烯基醌中间物种 **INT-11**，最后该物种脱除一分子酸后得到目标轴手性产物 **1-65**。

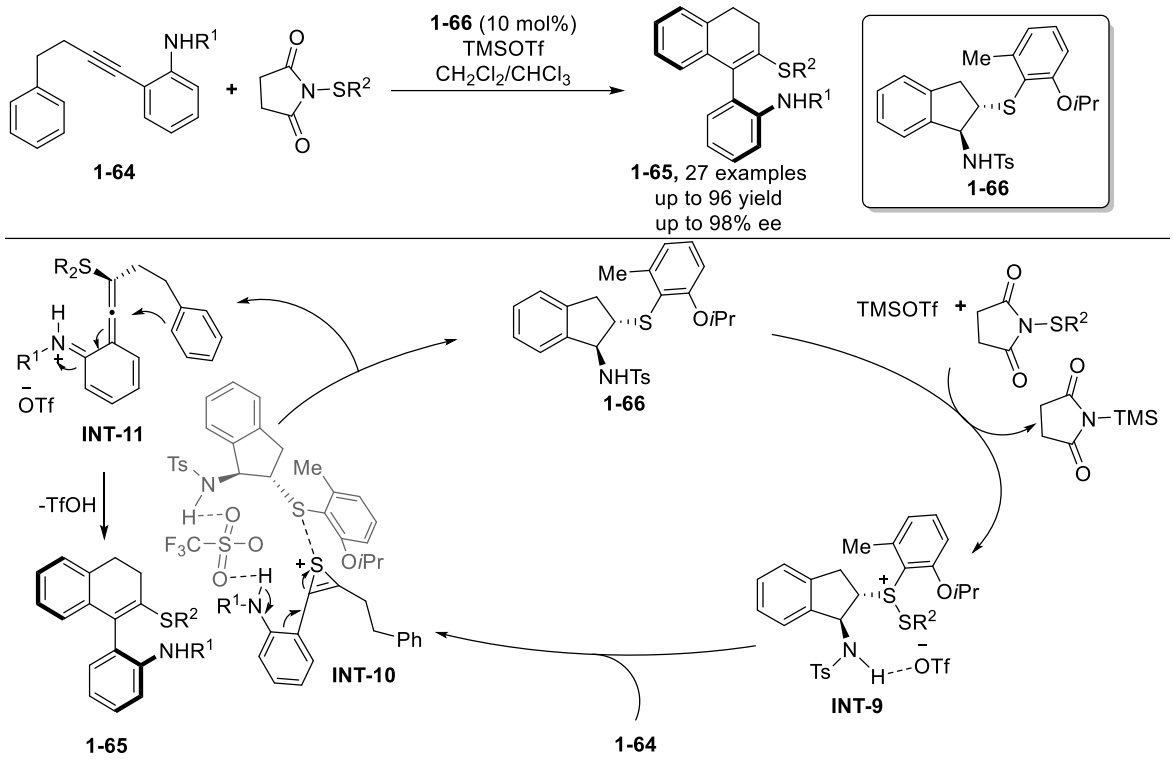


图 1.43 一个含杂原子 VQM 中间体策略合成轴手性苯乙烯

近期，池永贵等人报道了卡宾催化的炔烃不对称加成反应[57]。手性卡宾催化剂作为有机碱物种首先与炔基醛物种 **1-67** 发生反应生成中间物种 **INT-12**，**INT-12** 经过氧化异构化得到 **INT-13**，之后 **INT-13** 先受到一个软亲核试剂磺酸化合物的进攻，历经手性的联烯物种 **INT-14** 后转化成中间体 **INT-15**，再受到硬亲核试剂苯酚化合物的进攻，催化剂离去后得到最终的轴手性烯基芳烃砜类化合物 **1-68(图 1.44)**。反应的底物适用性非常广阔，不管是萘环底物还是杂环底物，比如喹啉、吲哚和苯并噻吩结构都可以得到很好的对映体选择性控制。

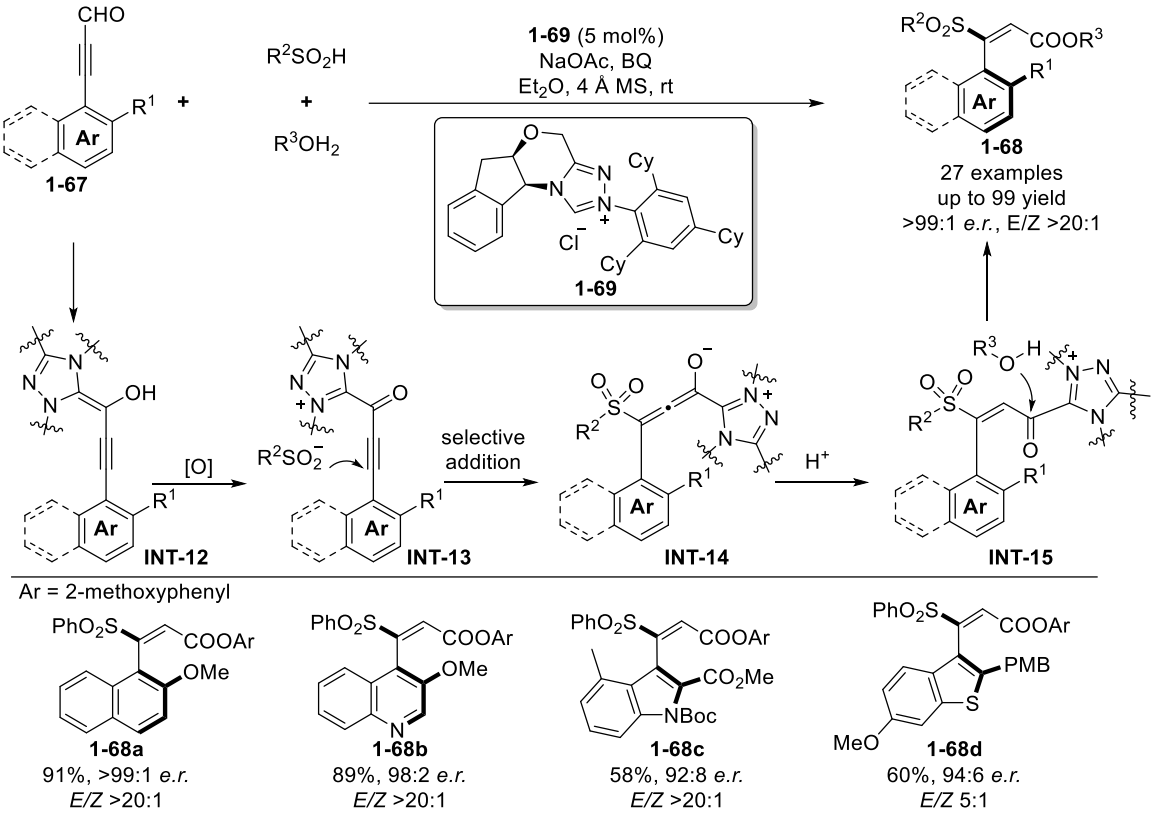


图 1.44 卡宾催化不对称合成轴手性烯基芳烃

1.3.3.3.2 布朗斯特酸催化不对称加成反应构建轴手性烯基芳烃

布朗斯特酸作为一类良好的氢键给体被广泛应用于有机小分子催化反应中。2018 年，闫海龙课题组[58]使用奎宁衍生的手性硫脲 **1-72** 作为氢键给体，在 *L*-脯氨酸的协同催化下，不对称合成了轴手性烯基芳烃砜类化合物(**图 1.45**)。作者首次提出该反应历经了一个手性的联烯基醌活性中间体(VQM)。反应从 2-炔基萘酚化合物 **1-70** 开始，在手性硫脲分子的作用下生成立体选择性控制的关键中间体 **INT-16**，之后该联烯基醌中间体受到亲核试剂的进攻，手性从联烯转移到轴手性烯基芳烃产物 **1-71** 中。

基于历经联烯基萘醌活性中间体的有机小分子催化策略，闫海龙课题组又开展了一系列延续性的工作(**图 1.46**)[59]。2018 年，闫海龙等人[59a]利用手性硫脲 **1-75** 为催化剂，通过对炔烃底物 **1-73** 进行不对称亲核加成反应，一次性构筑了含多个手性轴的烯基芳烃轴手性骨架化合物(**图 1.46a**)。反应历经了一个四取代的联烯基醌中间体 **INT-17**，以优秀的产率和优异的对映体选择性以及大于 20:1 的非对映体选择性得到双轴手性烯基芳烃化合物。同时，该策略也能对已有手性轴的底物进行动力学拆分，其拆分因子 *S* 高达 117(**1-74c**)。之后同一课题组[59b]将策略应用于不对称合成拥有 C_2 对称的双轴手性的萘乙烯基二酚化合物中(**图 1.46b**)。

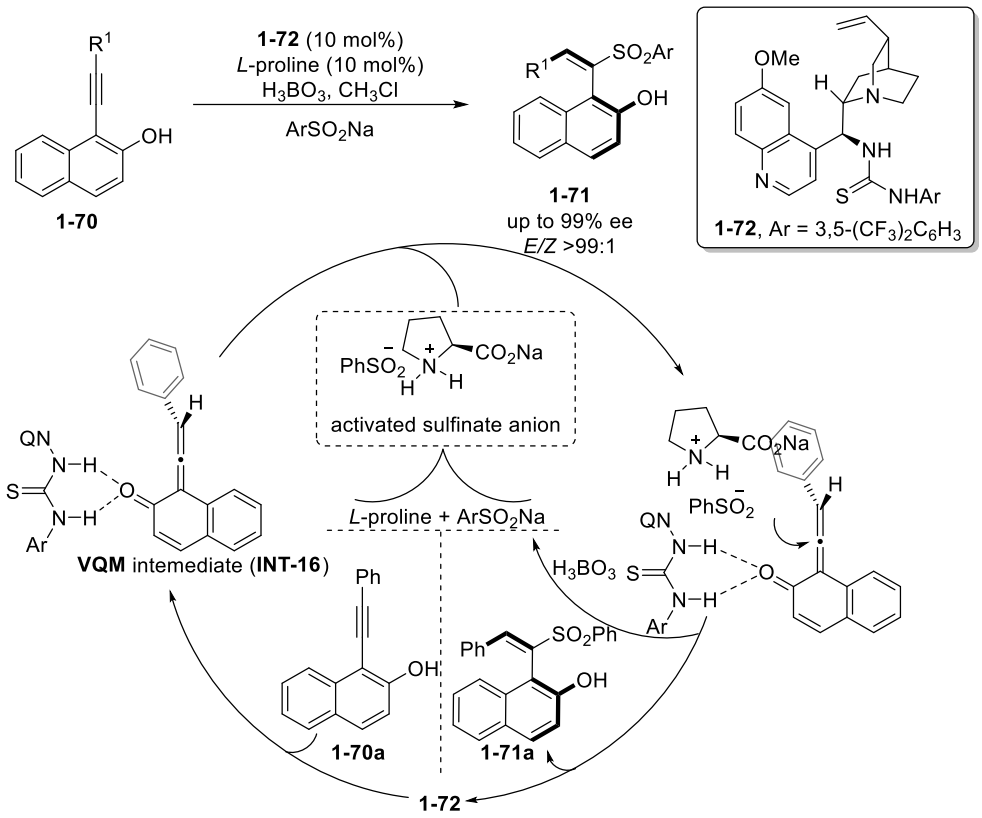


图 1.45 有机小分子催化不对称合成轴手性苯乙烯砜类化合物

2019 年，李文军、闫海龙和刘易东等人[59c]报道了有机硫脲分子催化不对称加成反应来构建拥有多个手性元素的轴手性烯基芳烃化合物(**图 1.46c**)。反应以 2-炔基萘酚 **1-79** 为底物，噁唑酮 **1-80** 为亲核试剂，在催化剂 **1-78** 的作用下，经过一个四取代联烯基醌中间体，以最高 96%的 ee 值，大于 20:1 的 dr 值和大于 99:1 的 *E/Z* 选择性得到一系列同时拥有中心和轴手性属性的轴手性烯基芳烃化合物 **1-81**。

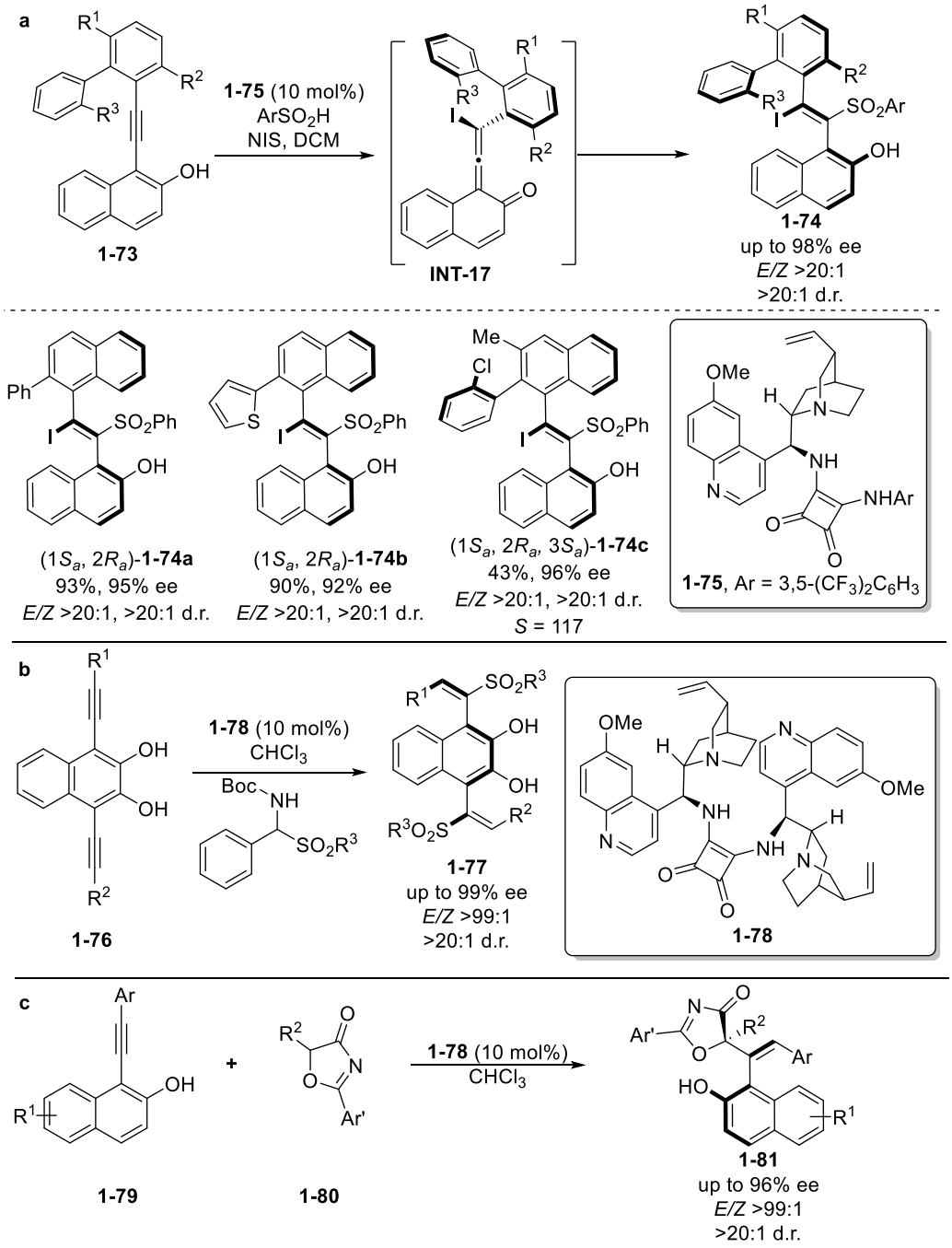


图 1.46 经四取代 VQMs 中间体构建含多个手性元素的轴手性苯乙烯

随后不久，闫海龙课题组[60]将反应体系扩展到催化不对称 Michael 加成反应中(**图 1.47a**)。反应在 **1-84** 催化下，使用 *α*-氨基砜化合物作为亲核试剂，对 *α*-*β*-不饱和炔基酮进行不对称 Michael 加成，生成高立体选择性和高 *E/Z* 比率的轴手性烯基芳烃产物 **1-83**。

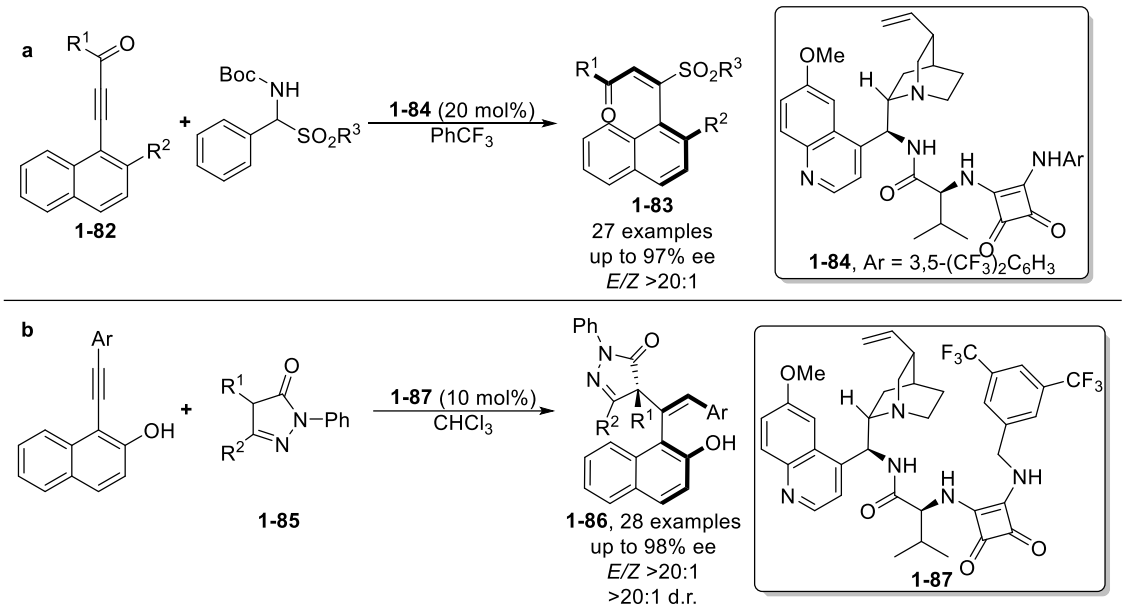


图 1.47 经 VQMs 中间体合成轴手性烯基芳烃

2021 年，王保民课题组[61]将亲核试剂替换成吡唑啉酮类化合物 **1-85**，在催化剂 **1-87** 的作用下，对炔基萘酚类底物进行不对称亲核加成(**图 1.47b**)，以高产率、高对映体选择性和高非对映体选择性以及大于 20:1 的 *E/Z* 比率得到含有手性吡唑啉酮结构单元的轴手性烯基芳烃化合物 **1-86**。

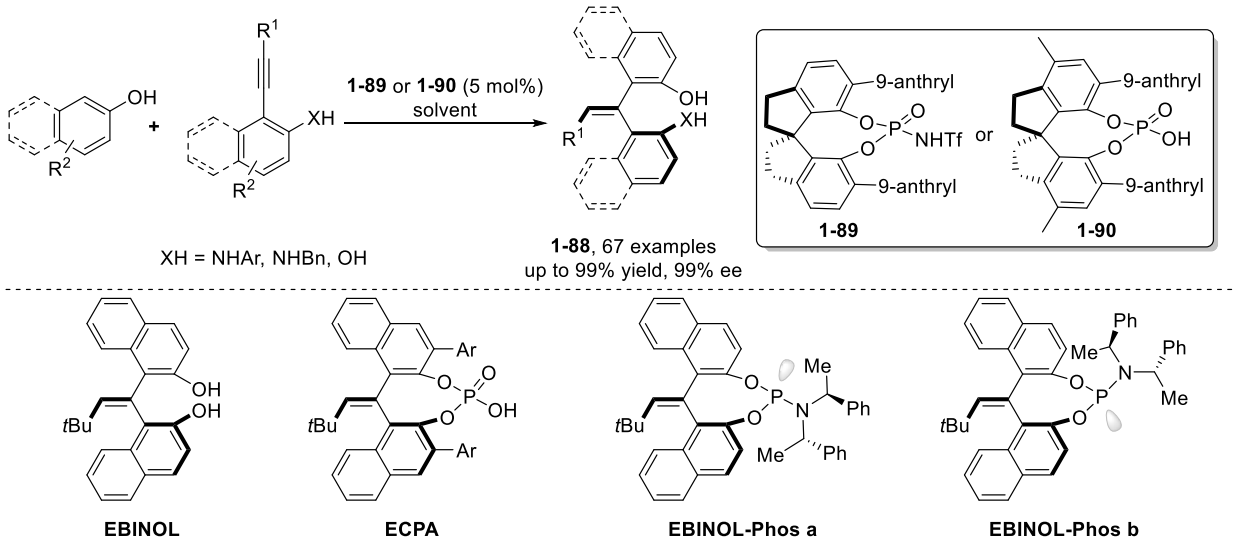


图 1.48 不对称合成阻转手性的 EBINOL

除了手性硫脲分子可以作为一种良好的布朗斯特酸作用于有机不对称反应中，手性磷酸也是一类非常重要的质子给体，可以起到手性质子梭的作用，在催化不对称地合成轴手

性烯基芳烃化合物中起到至关重要的作用。

在 2019 年，谭斌[62a]课题组使用手性磷酸(**1-89** 或 **1-90**)为催化剂，2-萘酚为亲核试剂，对内炔烃进行不对称亲核加成，成功合成了具有轴手性烯基芳烃骨架的 EBINOL 化合物(**图 1.48**)。该反应经过一个活性的联烯基邻萘醌(VQM)中间体，在温和的条件下以高产率，高对映体选择性以及完全的 *E/Z* 选择性得到相对应的轴手性烯基芳烃化合物(**1-88**)。之后，该课题组将得到的 EBINOL 骨架衍生成更具有实用价值的 ECPA 和亚磷酰胺手性化合物，并在不对称催化中进行了应用。

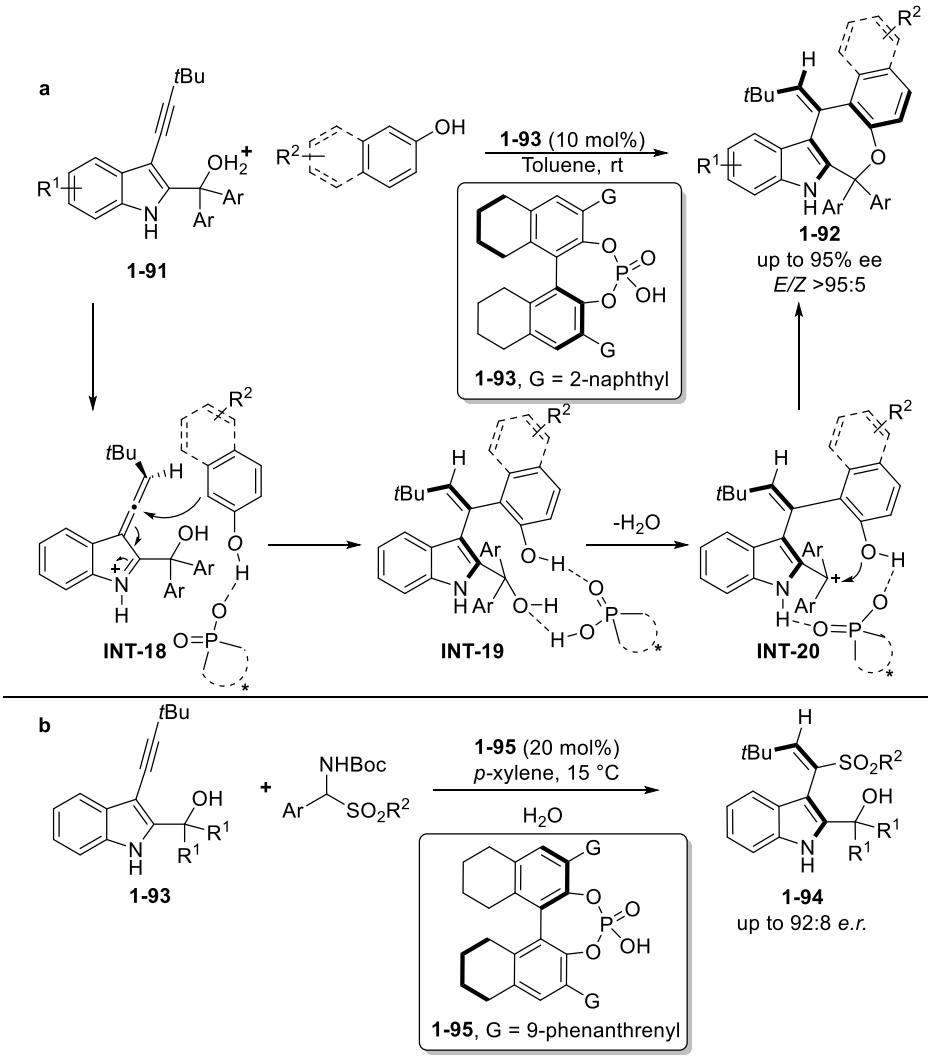


图 1.49 从 3-炔基-2-吲哚甲基醇合成轴手性烯基芳烃

与含五元杂芳环的轴手性联芳化合物一样，含有五元杂环结构的烯基芳烃化合物相比于六元环结构的烯基芳烃骨架拥有更加灵活的转动轴，其翻转能垒将会变的更低，因此对其进行催化不对称合成是更加有挑战性的。

石枫课题组[62b]则利用手性磷酸催化的不对称亲核加成反应，对烯基吲哚类轴手性化

合物进行不对称合成研究(**图 1.49**)。反应以 3-炔基吲哚 **1-91** 为底物，通过手性磷酸 **1-93** 的作用生成手性联烯物种 **INT-18**，之后亲核试剂萘酚在手性磷酸的辅助下，对 **INT-18** 进行亲核进攻，生成轴手性烯基吲哚 **INT-19**，再通过脱除一分子水后生成 **INT-20**，该物种再被分子内的酚羟基进行第二次亲核加成，最终生成一个带有七元环结构的轴手性烯基吲哚化合物 **1-92**。由于反应历经了一个分子内的亲核环化过程，其对映体比率最高可达 95% (**图 1.49a**)。

之后，石枫课题组[62c]将亲核试剂换成 *α*-氨基砜化合物，在手性磷酸 **1-95** 的催化下，对炔基吲哚底物 **1-93** 进行不对称亲核加成，生成了一系列轴手性烯基吲哚产物 **1-94**。产物结构中由于少了刚性的七元环结构，使得烯烃和吲哚之间的转动轴变的比较灵活，因此手性磷酸对产物的立体选择性控制最高只能达到 92:8 的 er 值(**图 1.49b**)。

张书宇和吕健等人直接将吲哚作为亲核试剂，通过手性磷酸的催化，对内炔烃底物进行不对称亲核加成，合成了具有吲哚结构单元的轴手性烯基芳烃化合物(**图 1.50**)[62d–e]。

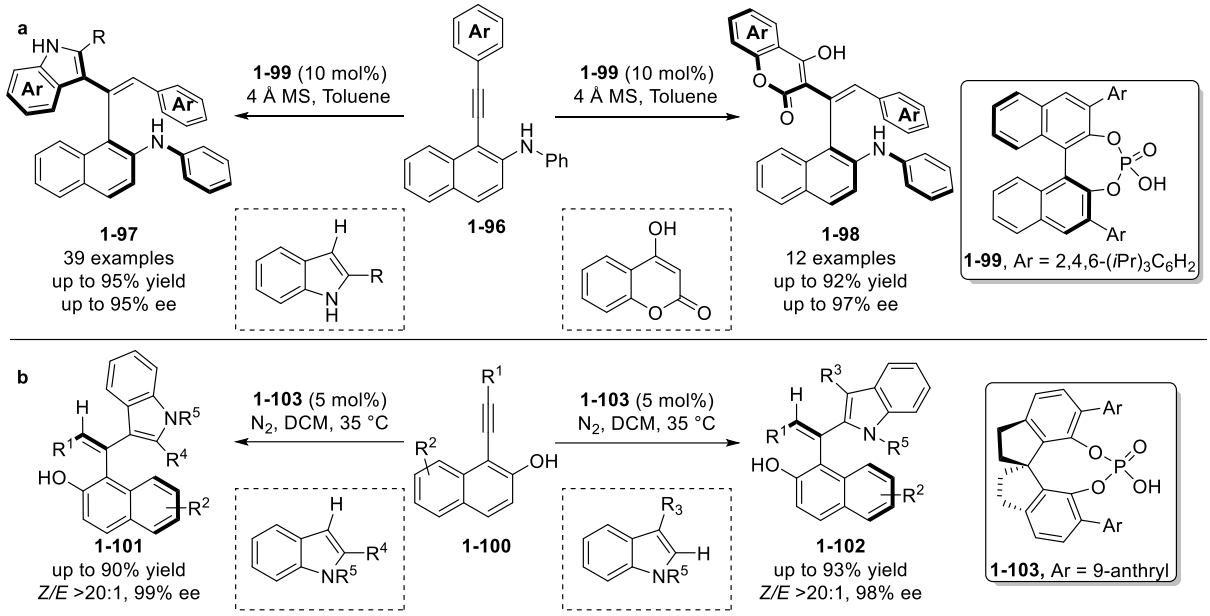


图 1.50 手性磷酸催化不对称合成含吲哚结构的轴手性烯基芳烃

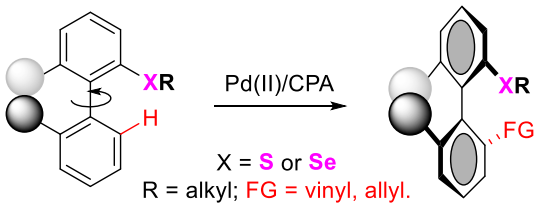
2020 年，张书宇课题组[62d]以手性磷酸 **1-99** 作为催化剂，使用 2-炔基萘胺 **1-96** 为反应底物，吲哚和 4-羟基香豆素类化合物为亲核试剂，通过不对称亲核加成反应，分别生成了一系列含有吲哚和 4-羟基香豆素结构单元的轴手性烯基芳烃化合物(**图 1.50a, 1-97** 和 **1-98**)。因为手性轴在萘芳环和烯烃之间，相比于石枫课题组的烯基吲哚结构，该轴手性化合物的稳定性更高，反应也拥有更好的立体选择性控制。

2022 年，吕健课题组[62e]将炔烃底物换成 2-炔基萘酚类化合物 **1-100**，在手性螺环磷酸 **1-103** 的催化下，分别使用 2-位和 3-位取代的吲哚作为反应的亲核试剂，通过不对称亲核加成反应合成了含吲哚结构的轴手性烯基芳烃化合物(**图 1.50b, 1-101** 和 **1-102**)。

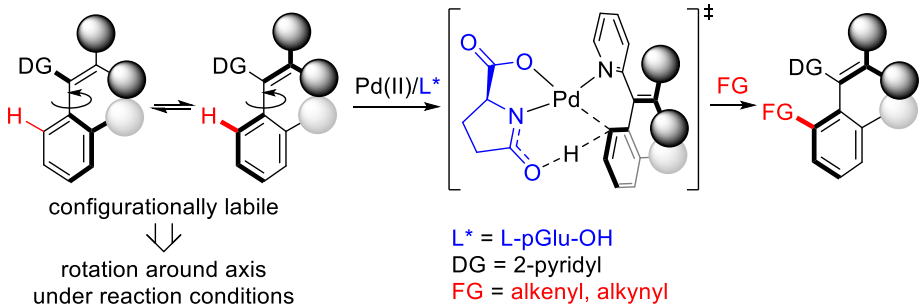
1.4 博士论文的主要工作

轴手性化合物在天然产物、药物分子以及催化不对称反应中展现出独特的优越性。因此，催化不对称地合成轴手性化合物成为研究轴手性的重点。虽然经过几十年的发展，已经涌现出许多方法和手段用于不对称构建联芳轴手性化合物，但是这些方法或多或少都存在着不足和限制。所以发展一种更加高效快速地构建联芳轴手性化合物的方法是非常有必要的。同时，轴手性联芳化合物只是庞大的轴手性家族中的一员。除此之外还有许多结构独特，具有实用前景的轴手性骨架，但是科学家们对这些轴手性骨架的研究还存在着许多空白。我们仍然需要对轴手性化合物的研究进行更加深入的探索。本论文主要围绕钯催化不对称碳氢键活化构建轴手性联芳化合物和轴手性烯基芳烃两个方面进行展开。具体将包含以下三个工作：

1. 使用手性磷酸作为手性配体，通过硫醚导向实现钯催化不对称碳氢键烯基化和烯丙基化反应来构建轴手性联芳化合物。并且利用 DFT 理论计算，研究了氧族元素作为导向基团的不同导向能力。

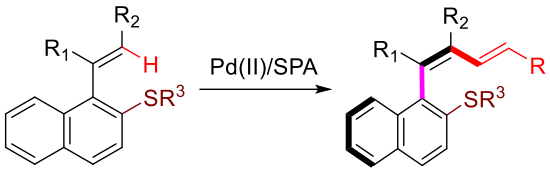


2. 以 *L*-焦谷氨酸为手性配体，通过吡啶导向实现钯催化不对称芳烃碳氢键烯基化和炔基化反应来构建含开链烯烃结构的轴手性烯基芳烃。并且通过 DFT 理论计算对烯基化反应的机理和手性控制进行了详细研究。



3. 以手性螺环磷酸为手性配体，通过硫醚导向实现钯催化不对称烯烃碳氢键烯基化反应来构建轴手性烯基芳烃。反应合成了一系列含多取代 1,3-二烯结构单元的轴手性烯基芳烃化合物，也可以一步直接构建双轴手性的烯基芳烃化合物。产物经氧化可以得到基于烯基芳烃轴手性骨架的硫烯配体，在铑催化不对称加成反应中

有很好的应用。



Asymmetric alkenyl C–H functionalization

相关内容将依次在第二、三和四章进行详细阐述。

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第二章 钯催化硫醚导向不对称碳氢键烯基化和烯丙基化反应构建轴手性联芳化合物

2.1 研究背景

联芳轴手性化合物广泛存在于天然产物、药物分子和功能性材料分子中，同时也是各种手性配体和催化剂的优势骨架[1](**图 2.1**)。比如 vancomycin 是用于治疗败血症以及各种组织器官感染安全可靠的抗生素，其核心骨架中就具有多个轴手性联芳结构单元。因此联芳轴手性化合物的催化不对称构筑一直以来备受科学家们的关注[2]。

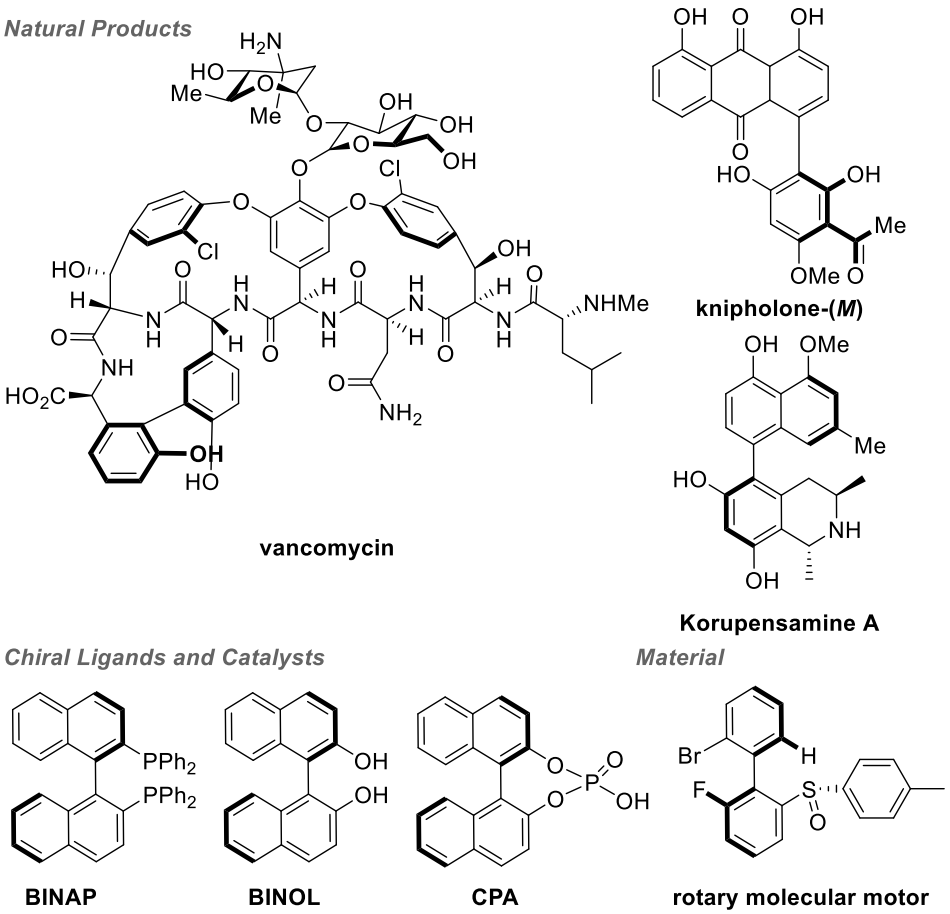


图 2.1 天然产物、手性配体和催化剂当中的阻转异构体

近年来，过渡金属催化的不对称碳氢键活化策略为手性复杂分子的快速合成提供了一条有效途径[3]。通过阻转选择性地邻位碳氢键官能团化对联芳轴手性化合物进行不对称合成也得到了迅猛发展[2d,3d]。基于导向策略，科学家们开发了许多催化体系来不对称合成轴

手性联芳化合物(该部分研究背景详情见绪论)(**图 2.2**)。比如 Murai、游书力和 Lassaletta 等课题组[4]发展了吡啶导向铑或铱催化不对称碳氢键活化策略来构建轴手性联芳。同时期游书力课题组[5]报道了吡啶氮氧导向的钯催化不对称碳氢键碘代反应。此外，手性亚砜和手性磷酸酯作为一类很好的手性辅基也可以适用于非对映体选择性的碳氢键活化反应。Colobert 和杨尚东课题组[6]在手性辅基导向钯催化不对称碳氢键官能团化构建轴手性联芳化合物方面进行了详细的研究。值得注意的是，手性瞬态辅基导向策略[7]可以避免底物进行导向基的安装和脱除，极大地扩展了合成产物的后续衍生应用。从 2017 年开始，史炳锋课题组[8]将手性瞬态辅基导向策略应用于钯催化不对称碳氢键活化构建联芳轴手性中，陆续实现了不对称碳氢键烯基化[8a]、炔基化[8b]、烯丙基化[8c]和萘基化反应[8d]。近期，史炳锋课题组又将催化体系扩展到钯/手性磷酸催化体系[9]，分别实现了喹啉[9a]和裸露胺[9b,c]导向的不对称碳氢键官能团化反应来构建轴手性联芳化合物。

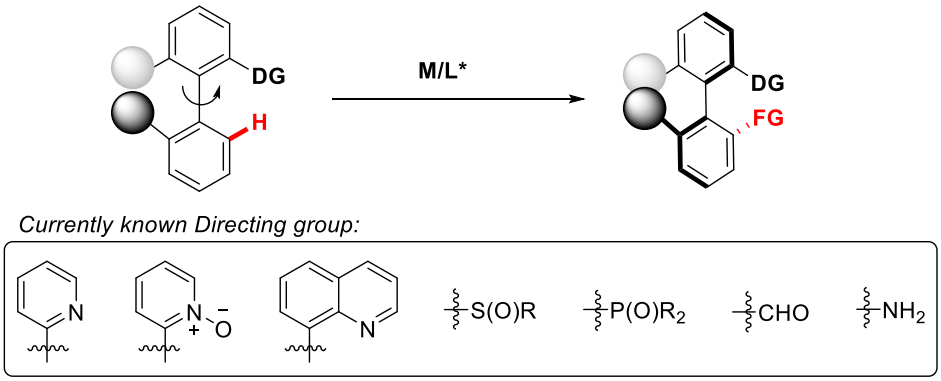


图 2.2 不同导向策略构建轴手性联芳

2.2 课题设计思路

通过以上背景研究，我们意识到在联芳基的邻位引入一个合适的导向基团，不仅可以起到利用空间位阻来稳定手性轴的作用，还可以进行导向的选择性碳氢键活化官能团化过程。虽然科学家们已经发展了多种导向催化体系来解决轴手性化合物的构建问题，但是这些催化体系都存在着一些限制，因此发展一种更高效的导向催化体系来实现多样化的轴手性联芳结构仍然具有非凡的实践价值。

近年来，醚类基团导向的碳氢键官能团化反应取得了不错的进展[10]。我们设想在联芳底物中引入一个氧族原子，通过导向不对称跨环碳氢键官能团化反应来构建联芳轴手性。不同氧族原子与过渡金属有着不同的配位能力，相比弱配位性的氧原子，配位能力更强的

硫原子是一个比较合适的选择[11]。但是因为硫原子的配位能力较强，很容易令金属催化剂中毒而抑制反应的进行。目前所报道的利用硫原子导向的不对称碳氢键官能团化反应仅限于硫代酰胺和硫羰两种导向基团[12]。因此，想要实现钯催化氧族元素导向的不对称碳氢键活化构建联芳轴手性需要克服以下难点：1）需要找到一个原子半径和电子效应均适合的氧族元素作为导向基团，可以与过渡金属进行快速配体和解离；2）取代导向原子的基团位阻大小要合适，需要在保证位阻效应的同时实现良好的反应活性和手性控制；3）寻找一个合适的手性配体，在促进反应发生的同时实现轴手性的诱导。基于以往我们在钯催化不对称碳氢键活化构建联芳轴手性的研究，我们发展了使用硫醚作为导向基团，手性螺环磷酸为手性配体，钯催化不对称碳氢键烯基化和烯丙基化反应构建轴手性联芳化合物。该反应底物的适用范围广阔，产率和对映体比率最高可达 99%和 99% ee(**图 2.3**)。此外，DFT 理论计算不仅指导我们找寻到了一个合适的导向基团，还揭示出手性的来源和反应的具体历程。

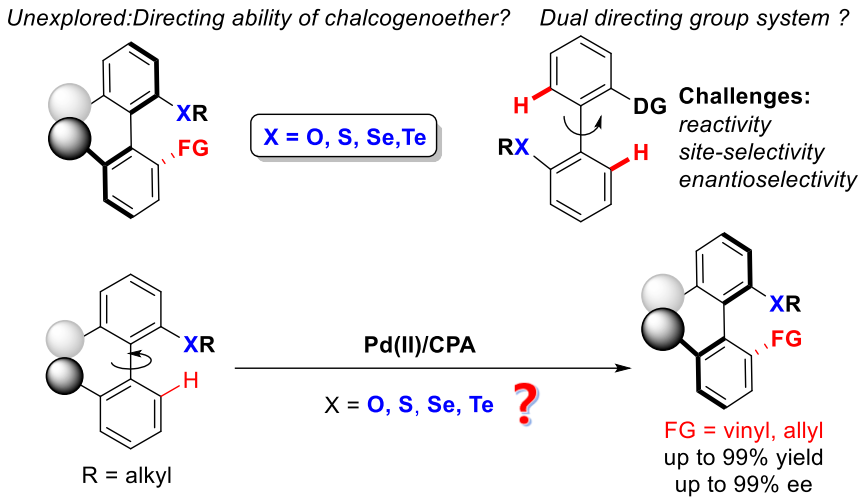
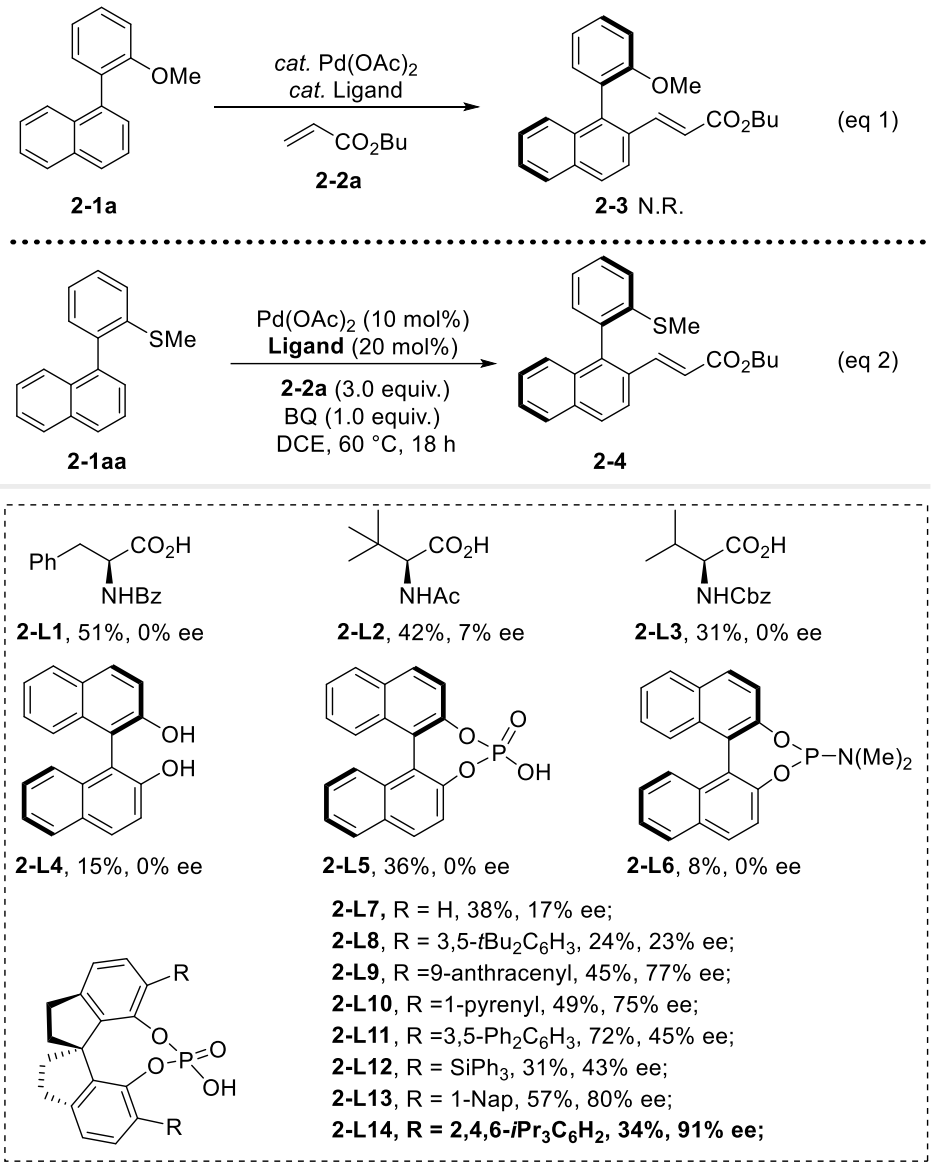


图 2.3 硫族元素导向的不对称碳氢键官能团化反应构建轴手性联芳

2.3 反应条件优化

2.3.1 烯基化反应条件优化

表 2.1 碳氢键烯基化反应的初步尝试和手性配体的筛选 [a]

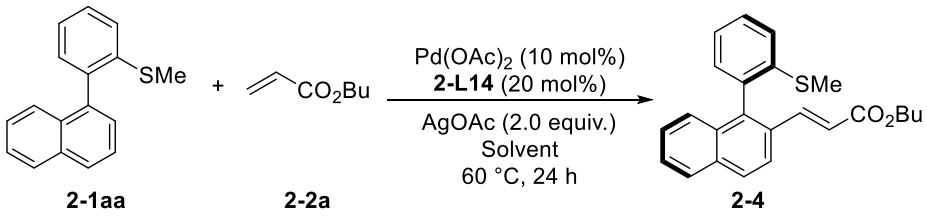


[a] 标准条件: **2-1aa** (0.05 mmol), **2-2a** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), Ligand (20 mol%), BQ (0.1 mmol), in DCE (0.1 M), 60 °C, 24 h.

我们首先对不同氧族原子结构单元作为导向基团的能力进行了初步的探究(**表 2.1, eq1**)，我们将一个氧甲醚取代的联芳底物 **2-1a** 作为我们的模板底物，丙烯酸正丁酯 **2-2a** 为烯基化试剂，醋酸钯为催化剂，筛选了不同配体和反应溶剂。遗憾的是由于氧原子的弱配位能力和过小的原子半径不足以形成六元环钯中间体，我们在这些初始筛选的反应条件下均没有发现目标烯基化的产物。之后，我们将模板底物换成一个硫甲醚取代的联芳底物 **2-1aa**，在醋酸钯催化下，使用 **2-2a** 为烯基化试剂，苯醌作为氧化剂，DCE 为反应溶剂，在 60 °C 下反应过夜，可以顺利地得到目标的跨环烯基化产物 **2-4**。在得到了目标产物之后，我们继续对反应的手性配体，氧化剂以及溶剂等条件进行了系统的筛选。

我们筛选了不同种类的手性配体(**表 2.1, eq2**),首先筛选单保护氨基酸配体(**2-L1**–**2-L3**)。虽然反应可以以中等以上的产率得到目标烯基化产物，但是其手性诱导效果并不理想。之后我们又筛选了手性 BINOL 以及 BINOL 骨架衍生的手性磷酸和手性亚磷酰胺配体(**2-L4**–**2-L6**),可惜的是，这些配体在降低反应活性的同时并不能够诱导出手性。令我们高兴的是，当我们使用手性螺环磷酸 **2-L7** 作用于反应时，我们可以以 38%的产率和 17%的 ee 值分离得到目标烯基化产物 **2-4**。受此结果的鼓舞，我们接着仔细筛选了不同 3,7-位置取代基的手性螺环磷酸(**2-L8**–**2-L14**)，最终确定手性螺环磷酸 **2-L14** 为烯基化反应最优的手性配体，可以诱导出 91%的 ee 值。

表 2.2 碳氢键烯基化反应溶剂的筛选 [a]



2-1aa **2-2a** **2-4**

entry	solvent	yield	ee
1	Toluene	87	92
2	THF	93	94
3	DME	95	95
4	1.4-dioxane	74	95
5	Et_2O	92	97
6	DCE	34	91

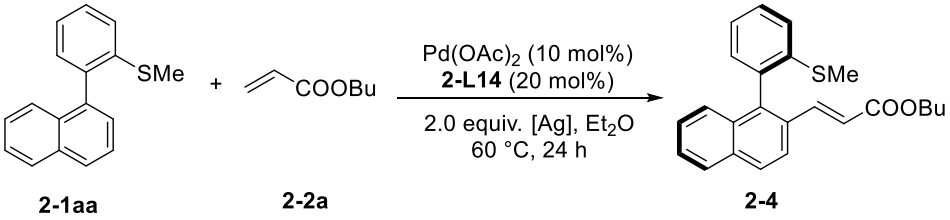
[a] 标准条件: **2-1aa** (0.05 mmol), **2-2a** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), **2-L14** (20 mol%), AgOAc (0.1 mmol), solvent (0.1 M), 60 °C, 24 h.

确定最优的手性配体之后，我们又对反应的溶剂进行了筛选(**表 2.2**)。我们通过筛选发现，小极性的醚类溶剂对反应的产率和对映体比率均有促进作用(**entry 2–5**)。在乙醚中反应 24 小时后，目标产物可以以 92%的产率和 97%的 ee 值被我们分离得到。在甲苯作溶剂时，产物的产率和 ee 值又会有小幅度的下降。

在得到最优的反应溶剂后，我们对反应的氧化剂进行了筛选(**表 2.3**)。我们发现，氧化银和氟化银会抑制反应的发生(**entry 5–6**),碳酸银和硫酸银对反应的活性和手性控制影响不大(**entry 2–3**)。膦酸银可以进一步促进反应的发生，但是手性控制效果会稍有下降(**entry 4**)。如果将反应温度降低至 50 °C，虽然产率会有所上升，但是 ee 值却下降到了 93%(**entry**

7)。综上，确定硫醚导向钯催化不对称碳氢键烯基化的最优反应是: **2-1aa** (0.05 mmol), **2-2a** (3.0 equiv.), $Pd(OAc)_2$ (10 mol%), **2-L14** (20 mol%), AgOAc (2.0 equiv.), Et_2O (0.5 mL), 60 °C 下反应 24 小时。

表 2.3 碳氢键烯基化反应银盐的筛选 [a]



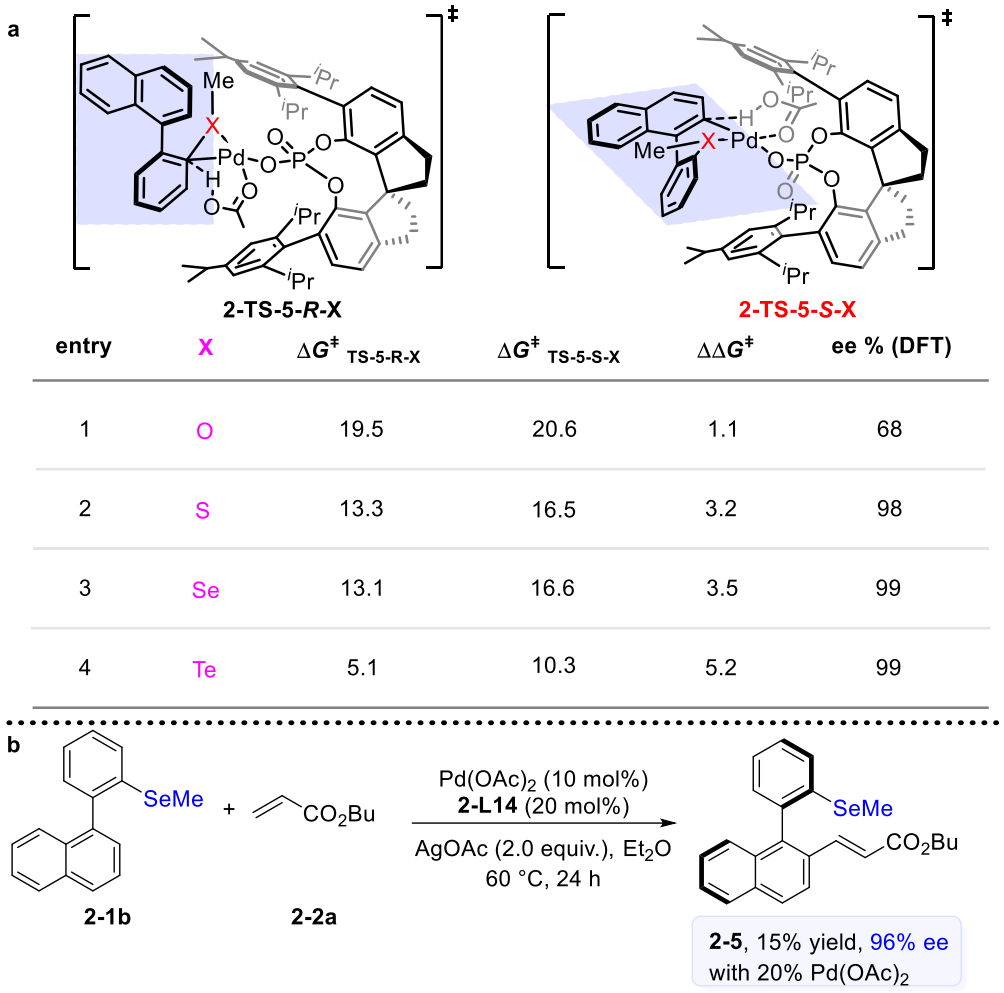
2-1aa **2-2a** **2-4**

entry	[Ag]	yield (%)	ee (%)
1	AgOAc	92	97
2	Ag_2CO_3	70	96
3	Ag_2SO_4	85	95
4	Ag_3PO_4	96	92
5	Ag_2O	NR	--
6	AgF	NR	--
7 [b]	AgOAc	93	93

[a] 标准条件: **2-1aa** (0.05 mmol), **2-2a** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), **2-L14** (20 mol %) AgOAc (2.0 eq), Et_2O (0.5 mL), 60 °C, air, 24 h. [b] 50 °C.

为了进一步理解氧族元素在该不对称烯基化反应中的导向能力，同时为后续实验底物的选择作出指导，我们利用 DFT 理论，对反应历程中不同导向基团作用下协同拔氢过渡态 *R/S* 构型之间的能量进行了计算对比(**图 2.4a**)。结果显示，随着导向基团原子半径的不断增加(X = O, S, Se, Te)，CMD 过程中过渡态 *R/S* 构型的能量差也逐渐增大(**entry 1–4**)。基于计算的数据我们可以推断出不同氧族原子导向作用下烯基化反应可以达到的对映体比率理论值。其中氧甲醚导向作用下最高只能到达 68%的 ee 值。而原子半径更大的硫甲醚，硒甲醚和碲甲醚导向基均可以展现出非常优异的手性控制。因此我们合成了一个联芳基硒甲醚底物 **2-1b**，在最优的烯基化反应条件下进行烯基化反应。我们通过增加催化剂和手性配体的使用量，成功的以 15%的产率和 97%的 ee 值得到了硒甲醚导向下的烯基化产物 **2-5**(**图 2.4b**)。这一结果也证实了该理论计算所得数据的可靠性。因此我们尝试合成一个碲甲醚取代的联芳底物，但是失败了。之后我们又对不同位阻取代的硫原子导向下的碳

氢键活化过渡态 *R/S* 构型的能量差进行了详细的计算(**图 2.5**)。计算结果显示，当硫原子上的取代基位阻逐渐变大时(从甲基到异丙基)，其产物的对映体比率呈现出明显的下降趋势(**2-6**–**2-9**)。此外，我们又考虑到硒甲醚底物合成的复杂性和底物范围的限制性等问题，最终选择硫甲醚作为我们不对称碳氢键烯基化反应的最优导向基团。



entry	X	$\Delta G^{\ddagger}_{\text{TS-5-R-X}}$	$\Delta G^{\ddagger}_{\text{TS-5-S-X}}$	$\Delta\Delta G^{\ddagger}$	ee % (DFT)
1	O	19.5	20.6	1.1	68
2	S	13.3	16.5	3.2	98
3	Se	13.1	16.6	3.5	99
4	Te	5.1	10.3	5.2	99

图 2.4 DFT 计算和实验探究硫族元素导向能力

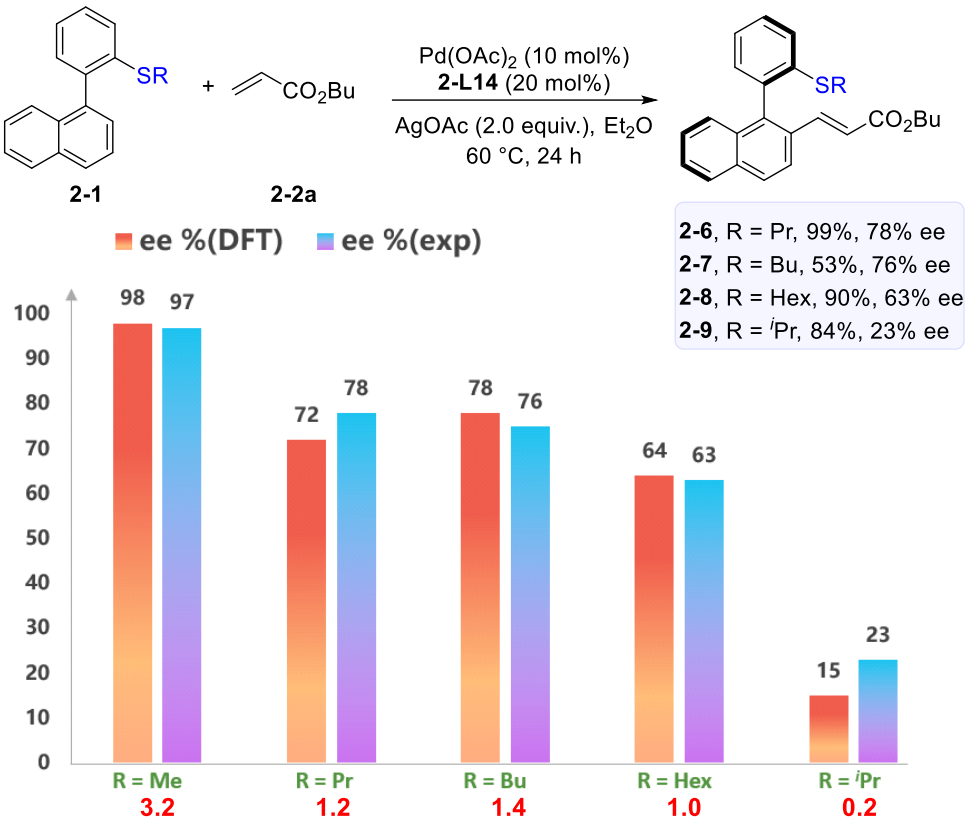
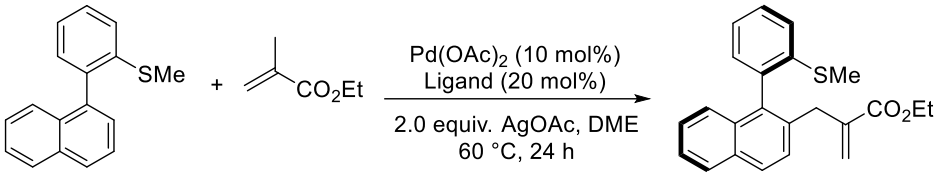


图 2.5 DFT 计算和实验探究不同位阻取代硫醚导向基导向能力

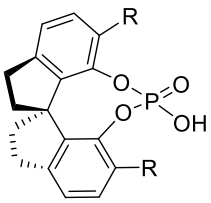
2.3.2 烯丙基化反应条件优化

鉴于烯丙基结构单元在有机反应中的重要性，我们试图将反应推广到钯催化不对称碳氢键烯丙基化反应中。我们通过使用 **2-1aa** 为模板底物，**2-82a** 为烯丙基化试剂，使用醋酸钯为催化剂，醋酸银为氧化剂，DME 为反应溶剂，在 60 ºC 下首先对反应的手性配体进行了筛选(**表 2.4**)。基于烯基化反应的成功，我们首先使用手性螺环磷酸作为烯丙基化反应的手性配体，结果果然如我们所料，不同取代基取代的手性螺环磷酸均可以促使反应以中等左右的产率和可观的对映体比率生成目标烯丙基化产物(**2-L7–2-L18**)。但是手性螺环磷酸诱导出来的 ee 值仍然不够理想，因此我们进一步筛选了不同取代基和电子效应的手性磷酸配体(**2-L19–2-L32**)。我们发现当 BINOL 衍生的手性磷酸的 3,3'-位取代基是大位阻的 2,4,6-(*i*Pr)$_3$C$_6$H$_2$ 时，反应可以以 34%的产率和 78%的 ee 值得到烯丙基化产物。最后，我们通过进一步增大手性配体位阻的同时降低反应的温度，反应可以以 52%的产率和 91%的 ee 值得到目标产物(**2-L32**)。

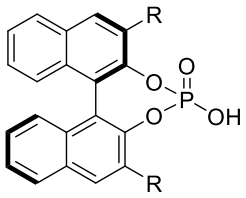
表 2.4 碳氢键烯丙基化反应条件筛选 [a]



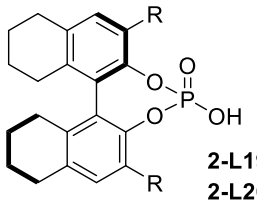
2-1aa **2-82a** **2-83**



2-L7, R = H, 48%, 13% ee;
2-L8, R = 3,5-*t*Bu$_2$C$_6$H$_3$, 51%, 4% ee;
2-L14, R = 2,4,6-*i*Pr$_3$, , 35%, 31% ee;
2-L14[b], R = 2,4,6-*i*Pr$_3$, 21%, 31% ee;
2-L15, R = 3,5-Me$_2$C$_6$H$_3$, 37%, 11% ee;
2-L16, R = 3,5-diCF$_3$C$_6$H$_3$, 41%, 25% ee;
2-L17, R = 2-nap, 46%, 36% ee;
2-L18, R = I, 16%, 3% ee;



2-L5, R = H, 21%, 9% ee;
2-L21, R = Me, 10%, 0% ee;
2-L22, R = Ph, 14%, 4% ee;
2-L23, R = 2-nap, 35, 21% ee;
2-L24, R =1-pyrenyl, 15%, 2% ee;
2-L25, R =1-nap, 31%, 26% ee;
2-L26, R = 3,5-diCF$_3$C$_6$H$_3$, 12%, 34% ee;
2-L27, R = 3,5-*t*Bu$_2$-4-OMeC$_6$H$_2$, 19%, 20% ee;
2-L28, R = SiPh$_3$, 13%, 0% ee;
2-L29, R = 9-phenanthrenyl, 14%, 11% ee;
2-L30, R = 9-anthracenyl, 23%, 60% ee;
2-L31, R = 2,4,6-*i*Pr$_3$, 34%, 78% ee;
2-L32, **R = 2,4,6-Cy$_3$, 52%, 91% ee** [b]

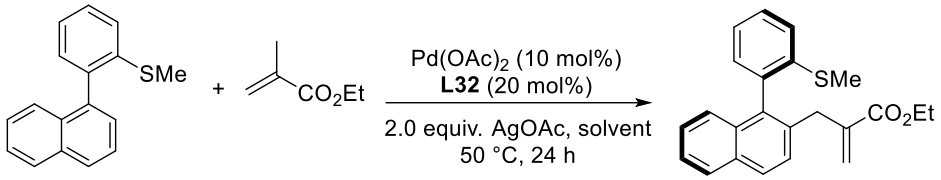


2-L19, R = 3,5-Me$_2$C$_6$H$_3$, 37%, 55% ee;
2-L20, R = 2,4,6-*i*Pr$_3$, 35%, 60% ee;

[a] 标准条件: **2-1aa** (0.05 mmol), **2-82a** (0.15 mmol), Pd(OAc)$_2$ (10 mol%), Ligand (20 mol%), AgOAc (2.0 equiv.), DME (0.5 mL), 60 °C, air, 24 h. [b] 50 °C.

在获得最优的烯丙基化反应手性配体后，我们接着对反应的溶剂进行了筛选(**表 2.5**)。跟烯基化反应一样，醚类溶剂对反应的活性和手性控制都比较友好。当使用乙醚作为反应溶剂时，产物的 ee 值可以达到 93%，但是不论是增加反应时间还是上升反应温度，其产率基本上维持在 50%左右(**entry 3–5**)。将反应溶剂换成苯甲醚时，虽然产率有了明显的提高，但是其 ee 值下降到了 75%(**entry 7**)。进一步筛选醚类溶剂，我们发现使用异丙基醚为反应溶剂时，反应可以以 85%的产率和 93%的 ee 值得到目标烯丙基化产物(**entry 8**)。通过上升温度到 60 °C，反应产率可以得到进一步的提升并几乎不消耗 ee 值(**entry 9**)。综上，确定硫醚导向钯催化不对称碳氢键烯丙基化的最优反应条件是:**2-1aa** (0.05 mmol), **2-82a** (3.0 equiv.), Pd(OAc)$_2$ (10 mol%), **2-L14** (20 mol%), AgOAc (2.0 equiv.), *i*Pr$_2$O (0.5 mL), 60 °C 下反应 48 小时。

表 2.5 碳氢键烯丙基化反应溶剂的筛选 [a]



2-1aa **2-82a** **2-83**

entry [a]	solvent	yield (%)	ee (%)
1	DME	52	91
2	THF	48	89
3	Et_2O	41	93
4 [b]	Et_2O	44	93
5 [b,c]	Et_2O	47	93
6 [b]	MeO^tBu	23	89
7 [b]	PhOMe	72	75
8	$^iPr_2O$	85	93
9 [b,c]	$^iPr_2O$	93	90

[a] 反应条件: **2-1aa** (0.05 mmol), **2-82a** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), AgOAc (2.0 equiv), **2-L32** (20 mol%) in solvent (0.1 M) at 50 °C for 24 h under air. [b]60 °C. [c]48 h.

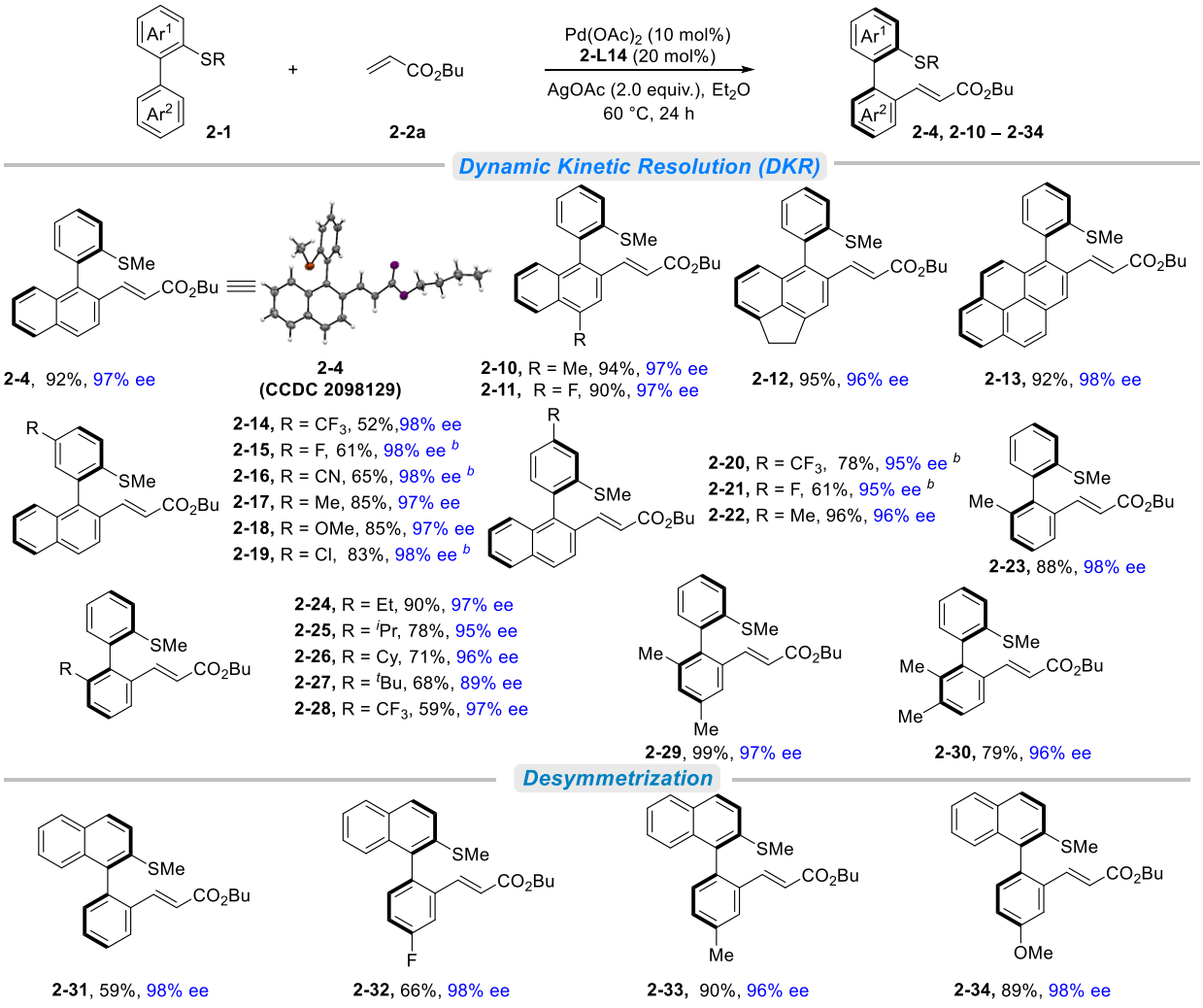
2.4 反应底物扩展

2.4.1 硫醚底物的扩展研究

我们首先对联芳基硫醚底物进行了扩展(**表 2.6a,b**)，萘环上不同位置取代基的底物在标准反应条件下可以以很好的产率和 ee 值转化成相应的烯基化产物(**2-10**–**2-12**, 90–95% yield，96–97% ee)。一个稠环芳烃芘环结构的硫醚底物也可以以 92%的产率和 98%的 ee 值进行烯基化反应。之后，我们考察了苯环上不同取代基对反应的影响。不管苯环的对位或间位拥有何种电子效应的基团，我们发现反应均可以以中等以上的产率和大于 90%的 ee 值得到对应的联芳轴手性产物(**2-14**–**2-22**, 52–96% yield，95–98% ee)。不同取代的联苯类底物也可以很好的适用于烯基化反应条件，高效地得到相应的烯基化产物(**2-23**–**2-30**, 49–99% yield，89–98% ee)。值得一提的是，该烯基化反应还可以进行去对称化过程(**2-31**–**2-34**, 59–90% yield，96–98% ee)。此外，一些杂芳环底物也能在标准反应条件下取得很好的反应效果(**2-35**–**2-38**)。比如苯并呋喃、二苯并呋喃以及吲哚结构的底物都可以取得大于 90%的对映体比率。基于我们计算和实验的验证，硫醚导向基的位阻效应是影响反应对映体选择性的重要因素，因此我们对硫醚导向基的大小进行了一些微调。结果发现乙基和三

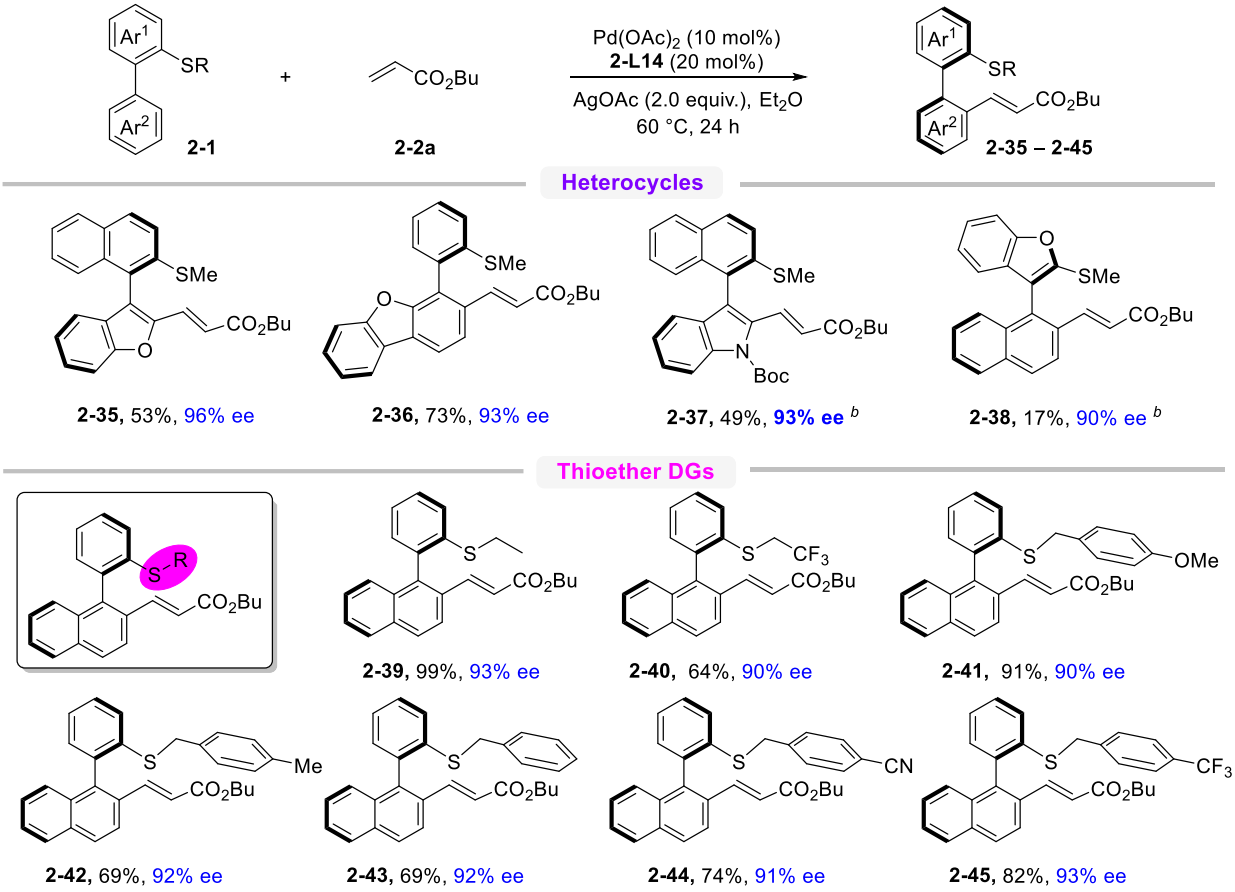
氟乙基取代的硫醚底物可以很好的适用该不对称反应(**2-39**–**2-40**, 90–93% ee)。另外不同取代基效应的苄基硫醚底物也能够顺利进行烯基化反应，得到大于 90%对映体选择性的轴手性产物(**2-41**–**2-45**, 69–91% yield, 90–93% ee)。其中产物 **2-4** 通过单晶衍射实验确定绝对构型为 *R* 构型。

表 2.6a 联芳底物扩展 [a]



[a] 反应条件: **2-1** (0.05 mmol), **2-2a** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), **2-L14** (20 mol%), AgOAc (2.0 equiv) in Et_2O under 60 °C for 24 h. [b]72 h.

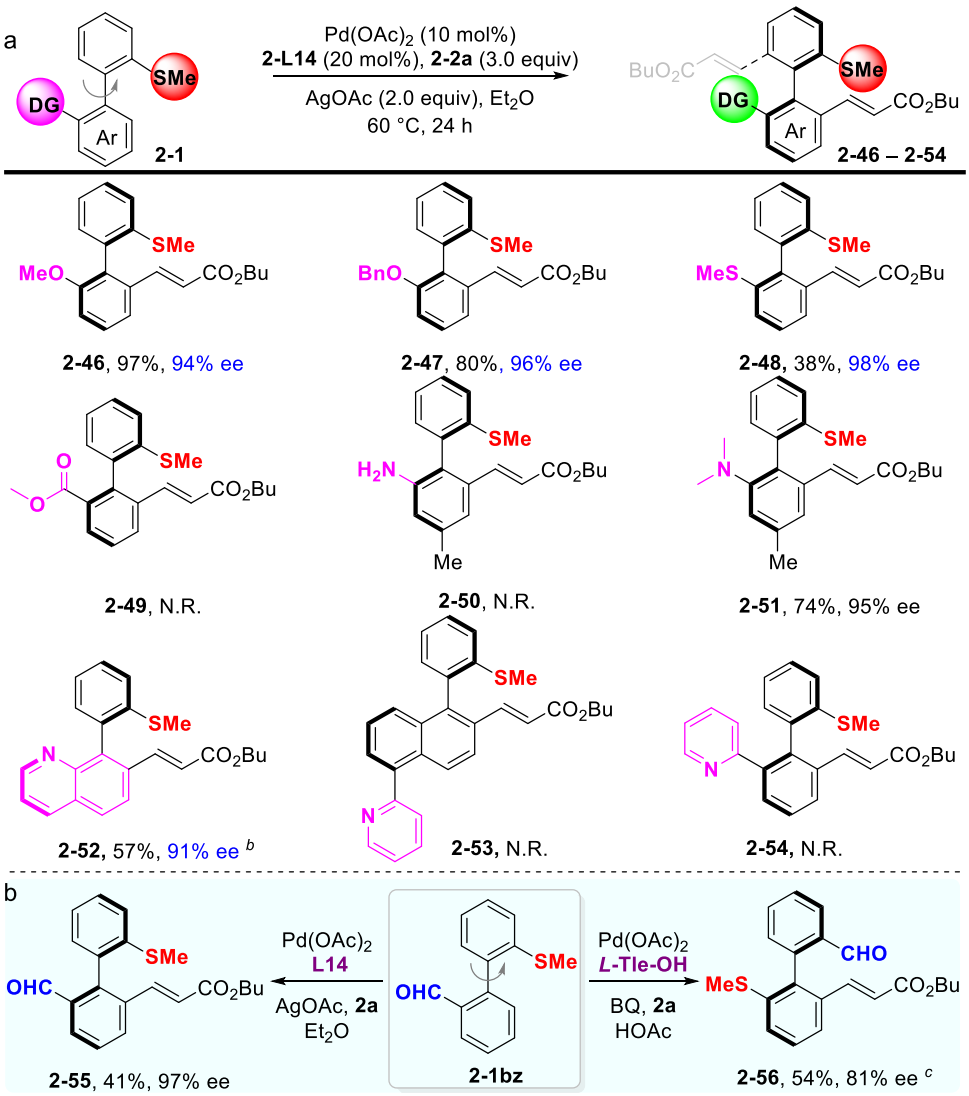
表 2.6b 联芳底物的扩展 [a]



[a] 反应条件: **2-1** (0.05 mmol), **2-2a** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), **2-L14** (20 mol%), AgOAc (2.0 equiv) in Et_2O under 60 °C for 24 h. [b] $Pd(OAc)_2$ (20 mol%)

紧接着，我们对同时拥有两个潜在导向能力取代基的联芳基底物进行实验(**表 2.7**)。当联芳基底物同时拥有氧醚和硫醚导向基时，在标准反应条件下只有顺利得到硫醚导向的碳氢键活化烯基化产物(**2-46**, **2-47**, 80–97% yield, 94–96% ee)。这也再次证明了硫醚作为导向基的优越性。但是当底物中同时出现两个硫甲醚导向基时，我们只能以 38%的产率和 98%的 ee 值得到单烯基化的轴手性产物(**2-48**)。值得注意的是，含有酯基或裸露氨的联芳底物并不适用该反应(**2-49, 2-50**)。有趣的是当裸露的氨基被甲基取代之后的硫醚底物却可以以 74%的产率和 95%的 ee 值得到相应的烯基化产物(**2-51**)。随后，我们发现烯基化反应可以容忍底物中含有喹啉结构单元(**2-52**, 57%,91% ee)。但是一个强配体能力的吡啶结构则会完全抑制烯基化反应的发生(**2-53**, **2-54**)。

表 2.7 含两个导向能力基团底物的扩展 [a]

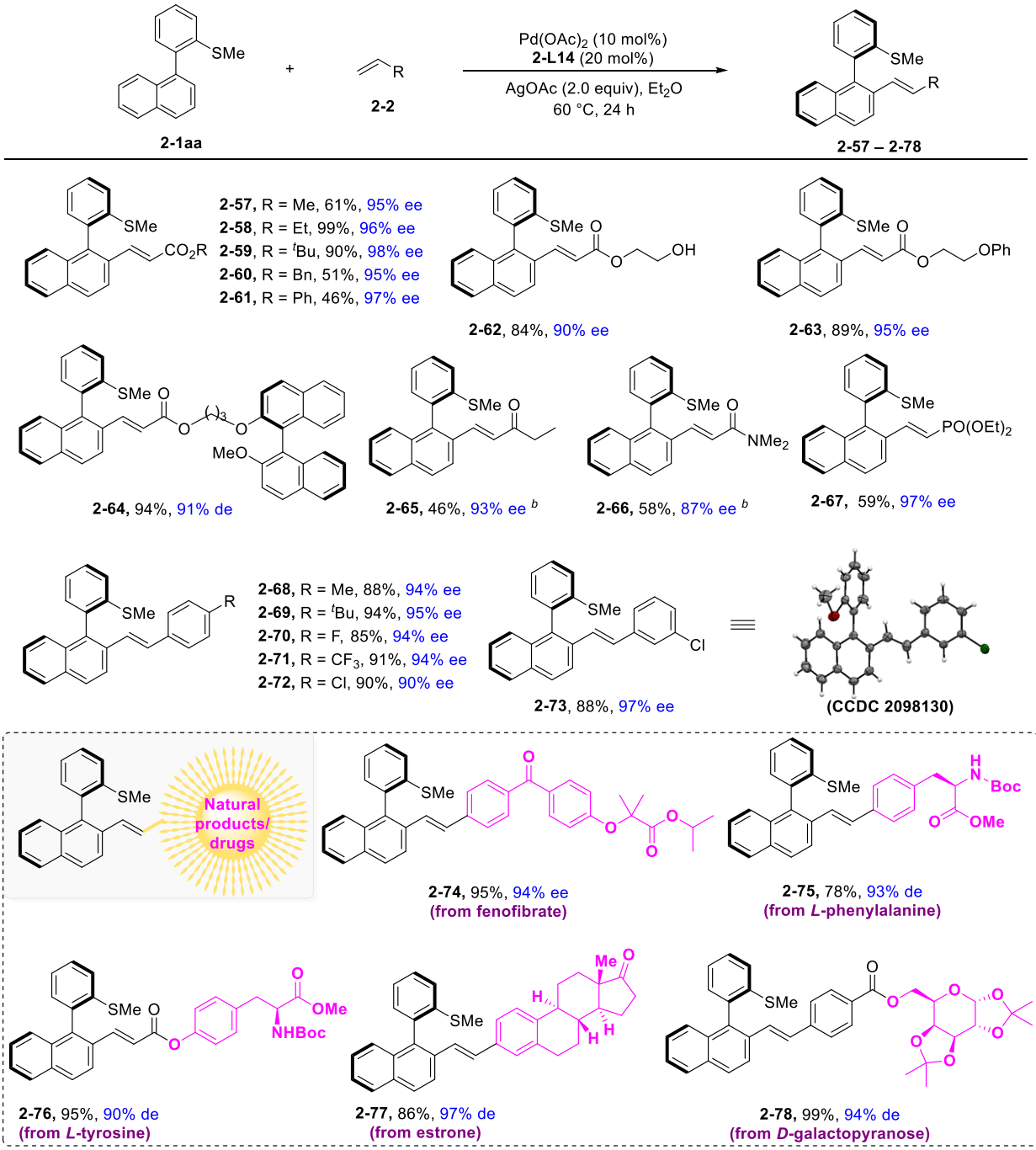


[a] 反应条件: **2-1** (0.05 mmol), **2-2a** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), **2-L14** (20 mol%), AgOAc (2.0 equiv) in Et_2O under 60 °C for 24 h. [b]72 h. [c]**2-1bz** (0.1 mmol), **2-2a** (0.3 mmol), $Pd(OAc)_2$ (10 mol%), *L*-Tle-OH (30 mol%), BQ (0.1 equiv) in HOAc under 50 °C for 72 h.

为了进一步探究烯基化反应的兼容性，我们合成了一个同时带有硫醚导向基和醛导向基的联苯底物 **2-1bz**。当使用标准的硫醚导向烯基化反应条件时，我们可以以 41%的产率和 97%的 ee 值得到单一硫醚导向的碳氢键烯基化产物 **2-55**。而使用叔亮氨酸作为瞬态手性辅基时，反应也可以以 54%的产率和 81%的 ee 值得到单一导向作用的碳氢键烯基化产物 **2-56**。这种可选择性多样化地构建联芳轴手性的方法为合成复杂联芳轴手性化合物提供了可行性的策略。

2.4.2 烯烃底物的扩展研究

表 2.8 烯烃的扩展 [a]



[a] 反应条件: **2-1aa** (0.05 mmol), **2-2** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), AgOAc (2.0 equiv), **2-L14** (20 mol%) in Et_2O under 60 °C for 24 h. [b] 40 °C, 72 h.

我们对反应使用的烯基化试剂进行了扩展性研究，发现反应可以容忍各种各样的丙烯酸酯，得到对应的烯基化产物(**表 2.8**, **2-57**–**2-64**, 46–99% yield, 90–98% ee)。一些活泼的烯烃底物，比如丙烯酮、丙烯酰胺和烯烃磷酸酯都可以在标准烯基化反应条件下顺利进行烯基化转化得到对应轴手性产物(**2-65**–**2-67**, 46–59% yield, 87–97% ee)。我们又测试了苯乙烯类型的烯基化试剂，发现反应可以很好的忍受各种对位取代基的苯乙烯底物，以 90%以上的对映体比率得到烯基化产物(**2-68**–**2-73**)。为了进一步探究该反应的合成应用潜力，我们将反应的烯基化试剂扩展到一些基于药物分子和天然产物分子骨架的烯烃，比如(fenofibrace)**2-2s**、(氨基酸衍生物)**2-2t** 和 **2-2u**，以及一些天然产物分子(estrone, **2-2v**; *D*-galactopyranose, **2-2w**)。令我们高兴的是，这些活性分子衍生出来的烯基化试剂都可以在烯基化反应条件下顺利发生反应，以良好到优秀的产率和优秀的非对映体选择性产生轴手性化合物(**2-74**–**2-78**, 78–99% yield, 90–97% de)。其中产物 **2-73** 的绝对构型由单晶衍射实验确定为 *R* 构型，其他产物通过类比得到。

2.4.2 多手性轴化合物的研究

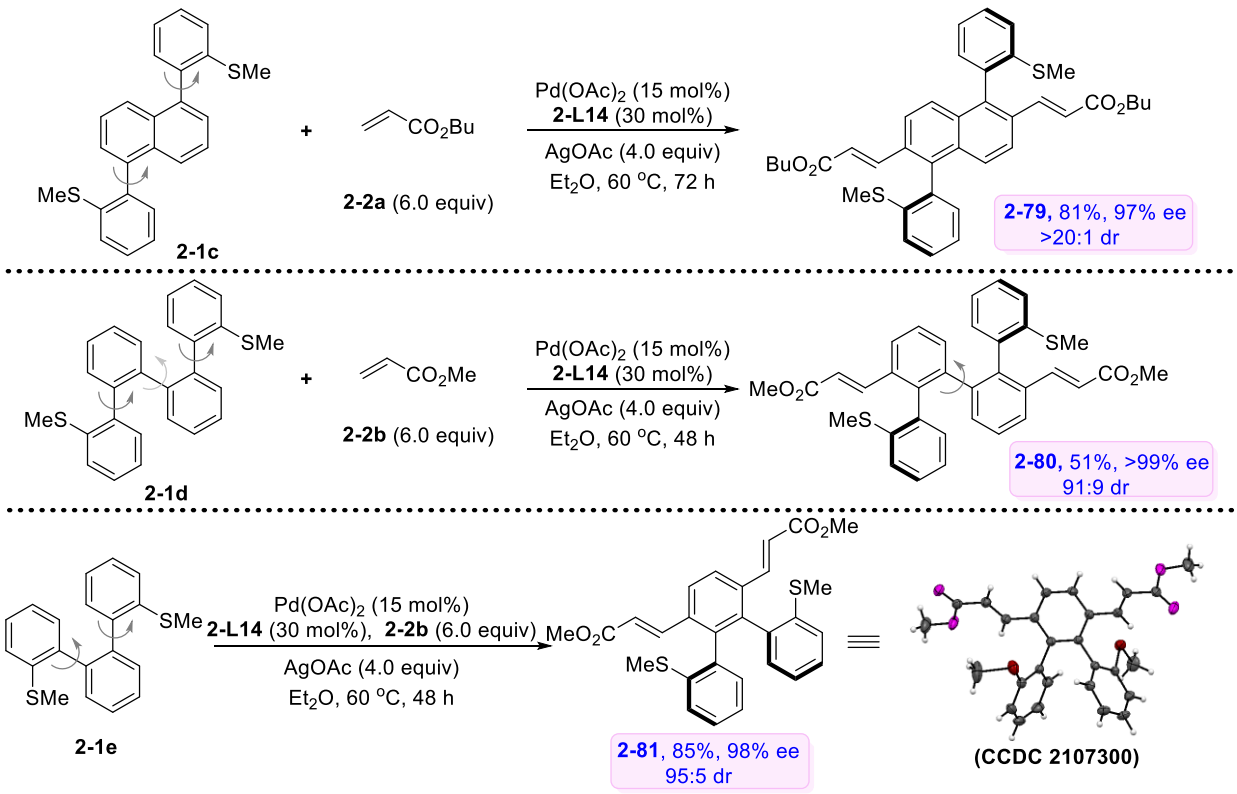


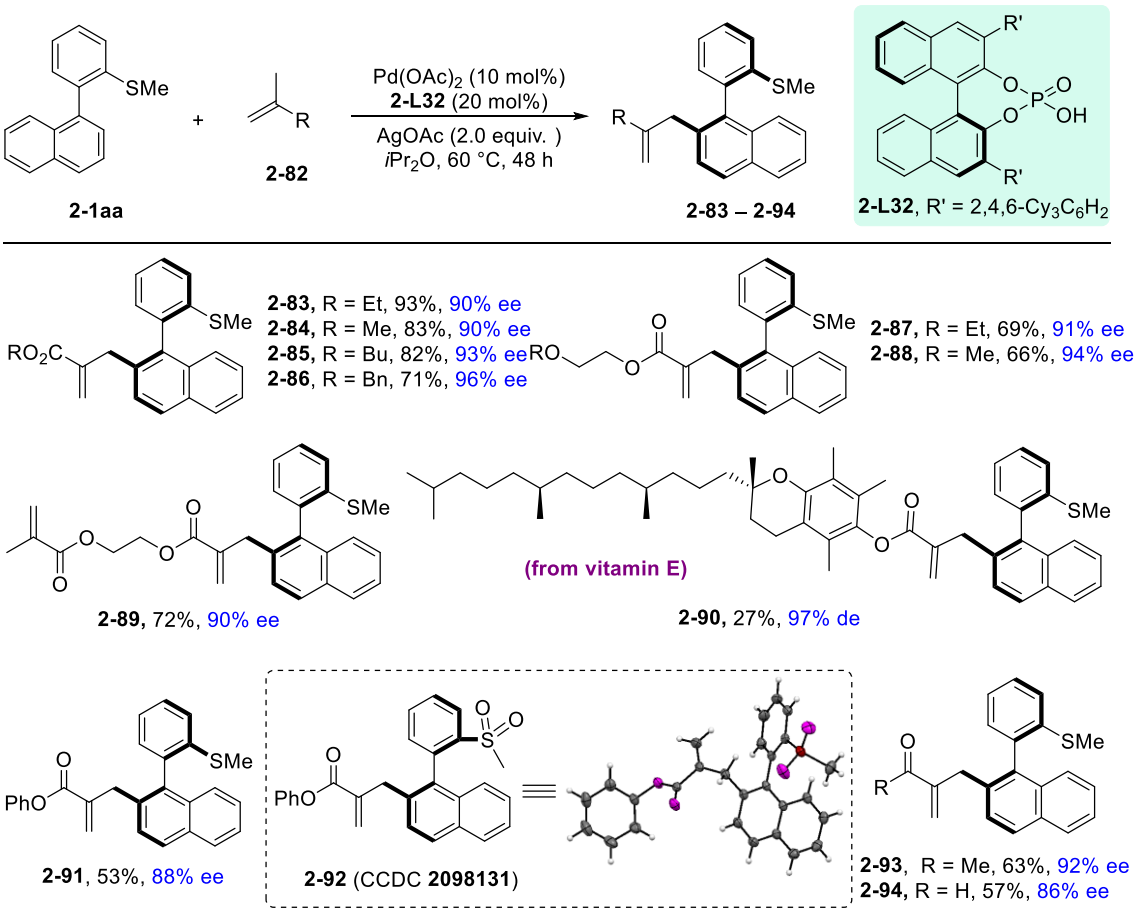
图 2.6 双手性轴联芳化合物的合成

含有多个手性轴的化合物拥有着复杂的拓扑结构，因此高对映体选择性地催化合成该

类多轴手性骨架是充满挑战性的。我们接下来使用硫醚导向不对称碳氢键烯基化策略，尝试进行多轴化合物的构建工作(**图 2.6**)。我们顺利合成了几个带有多个前手性轴的硫醚底物**2-1c**–**2-1e**，通过对标准反应进行微调，同时增加催化剂和手性配体的使用量并延长反应的时间，成功合成了 1,4-双轴手性化合物(**2-79**, **2-80**)和 1,2-双轴手性化合物(**2-81**)。反应的对映体选择性最高达到 99% ee，非对映体选择性大于 20:1。

2.4.3 烯丙基试剂的扩展研究

表 2.9 钯催化不对称碳氢键烯丙基化反应研究 [a]



[a] 反应条件: **2-1aa** (0.05 mmol), **2-82** (0.15 mmol), $Pd(OAc)_2$ (10 mol%), AgOAc (2.0 equiv.), **2-L32** (20 mol%) in iPr_2O (0.1 M) at 60 °C for 48 h under air.

我们对烯丙基化反应进行了底物的扩展研究(**表 2.9**)。许多甲基丙烯酸烷基酯都是很好的烯丙基化反应试剂，反应以良好到优秀的产率和优秀的对映体选择性得到相应烯丙基化产物(**2-83**–**2-88**, 66–93% yield, 90–96% ee)。一个乙二醇衍生的甲基丙烯酸酯试剂也可以在反应中顺利得到单烯丙基化反应的产物(**2-89**, 72% yield, 90% ee)。之后我们又尝试了一个

维他命 *E* 分子衍生的丙烯酸酯作为反应的偶联试剂，虽然反应的产率不是很理想，只有27%，但是可以以 97%的 de 值得到轴手性产物 **2-90**。另外甲基丙烯酮类化合物也是该反应一种良好的偶联试剂(**2-93**–**2-94**, 57–63% yield, 86–92% ee)。

2.5 合成应用

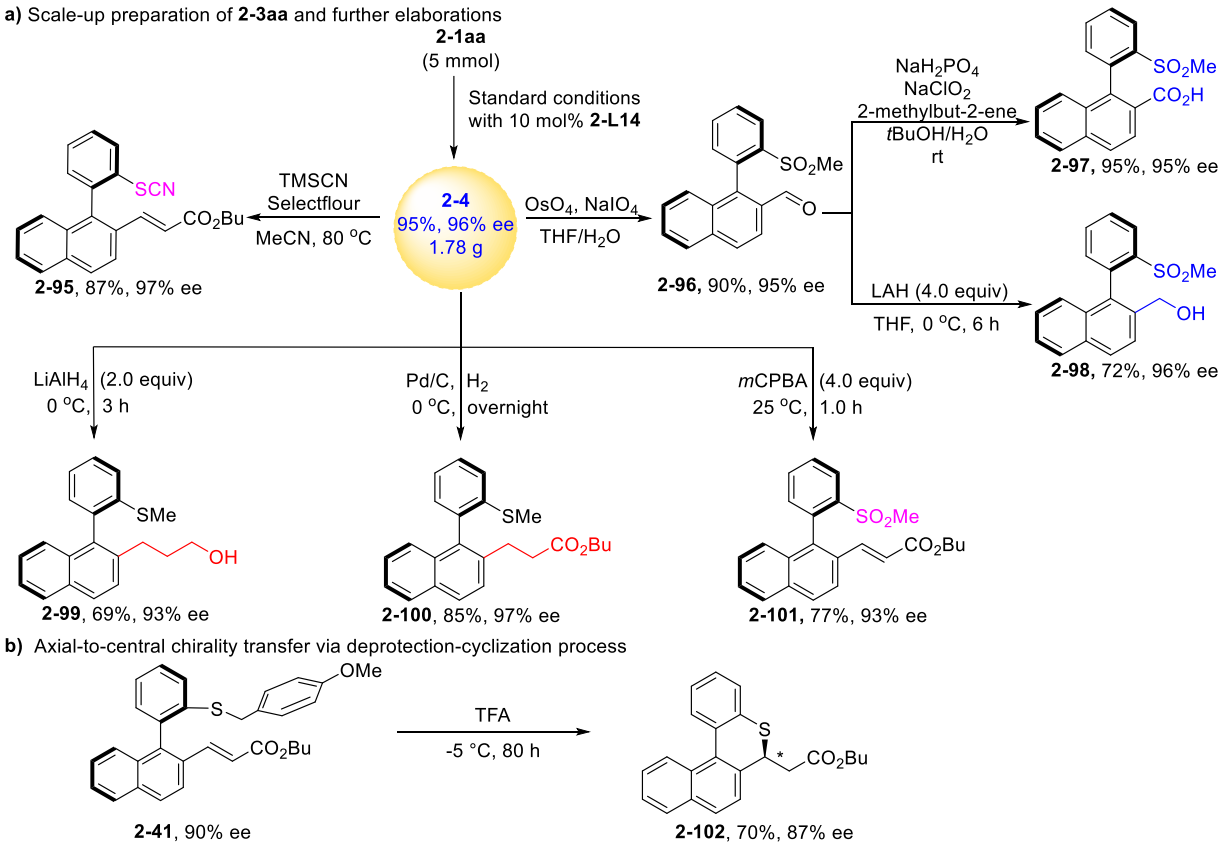


图 2.6 克级规模扩大反应和衍生化反应

为了探究该方法的合成应用性，我们进行了克级规模的放大反应和一些后续衍生化探究(**图 2.6**)。底物 **2-1aa** 可以以 95%的产率和 96%的 ee 值进行克级规模的放大反应，得到目标烯基化产物 **2-4**(5.0 mmol, 1.78 g)。接着我们将得到的烯基化产物进行了简单的转化(**图 2.11a**)。通过与 TMSCN 和 selectflour 反应，可以以 87%的产率和 97%的 ee 值得硫氰基取代的联芳轴手性化合物 **2-95**。**2-4** 可以被四氧化锇/高碘酸钠氧化体系顺利氧化成轴手性醛化合物 **2-96**(90% yield, 95% ee)，烯烃结构单元被氧化的同时，硫甲醚导向基团也会在该氧化体系中被氧化成芳基甲基砜。我们将得到的化合物 **2-96** 进行再一步的氧化和还原反应，反应均可以在不损耗对映体比率的情况下得到相对应的产物(**2-97**, 95%, 95% ee;

2-98, 72%, 96% ee)。当使用四氢铝锂作为氢化试剂时，**2-4** 可以被最终还原成轴手性结构的醇类化合物 **2-99**(69% yield, 93% ee)。而使用钯/C 氢化条件时，反应可以在不影响酯基的同时选择性氢化烯烃结构，得到氢化产物 **2-100**(85% yield, 97% ee)。相比四氧化锇/高碘酸钠氧化体系，使用 *m*-CPBA 作为氧化剂时，反应可以在保证烯烃结构完整的同时氧化硫醚导向基，顺利以 77%的产率和 95%的 ee 值得到芳基甲基砜化合物 **2-101**。值得一提的是，当我们对产物 **2-41** 进行硫醚导向基的去保护转化时，发现脱除烷基链后的芳基硫酚产物会在酸作用下对分子内的不饱和烯烃进行 Michael 加成反应，得到中心手性产物 **2-102**(70%, 87% ee)。该过程实现了手性从轴到中心的传递，也为合成手性化合物的串联反应提供了新思路。

2.6 反应机理研究

2.6.1 KIE 实验

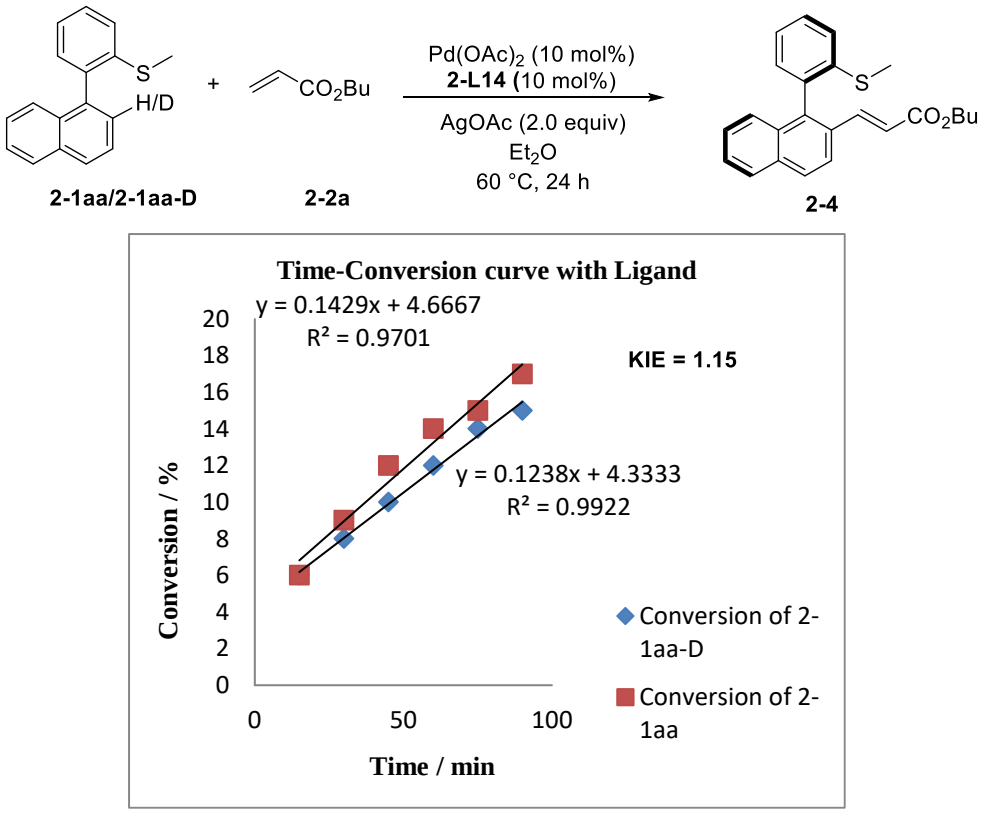


图 2.7 KIE 实验结果

为了探究反应的机理，我们首先进行了正常底物和氘代底物的动力学效应实验(**图 2.7**)。

实验测定的 KIE 数值是 1.15，这表明反应过程中碳氢键活化步骤不是反应的决速步骤。

2.6.2 理论计算

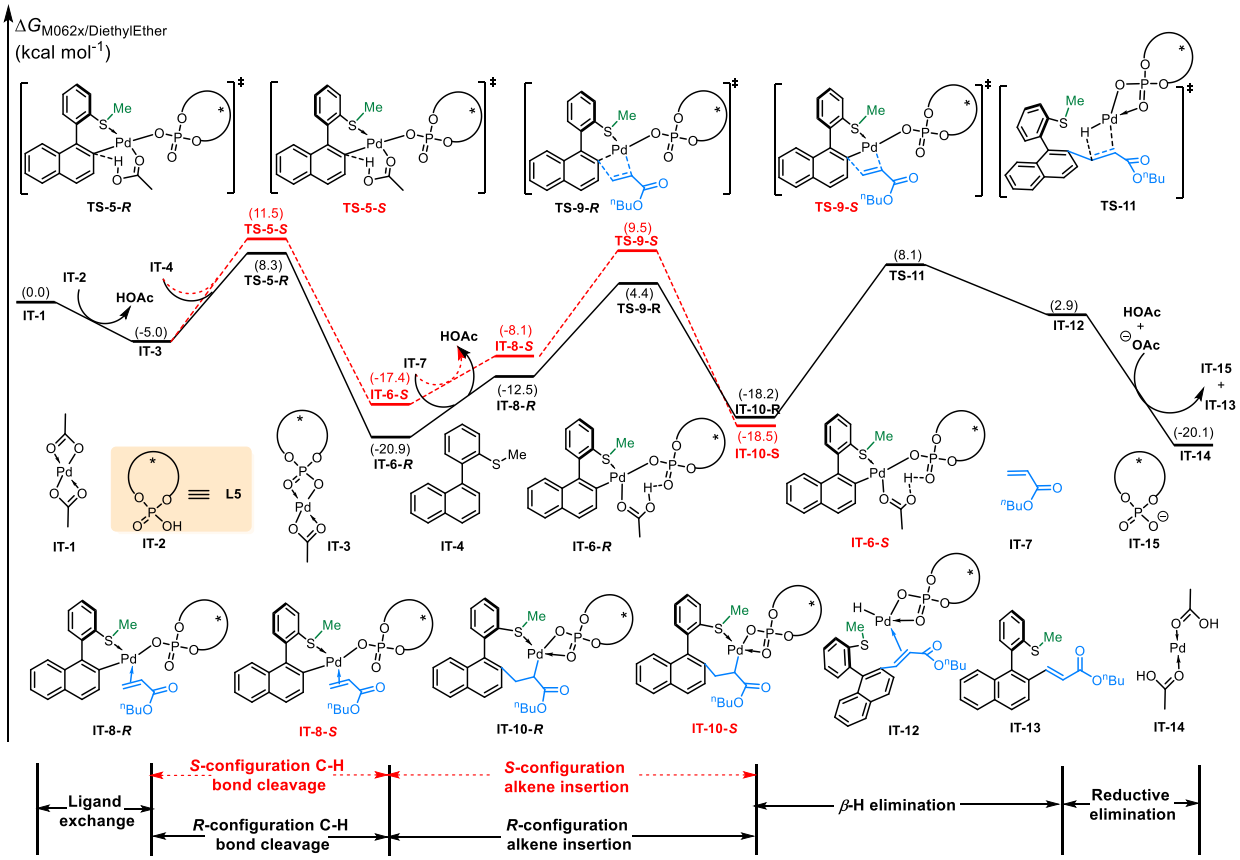


图 2.8 钯催化不对称烯基化反应计算相对自由能示意图。

为了进一步了解钯催化硫醚导向不对称碳氢键烯基化反应的机理，我们通过与蓝宇老师课题组合作，在张涛博士的帮助下，对反应进行了详细的理论计算。我们将底物 **2-1aa** 作为模板底物，醋酸钯为催化剂，螺环手性磷酸 **2-L14** 为手性配体，乙醚作为溶剂化介质，根据 DFT 理论对钯催化不对称碳氢键烯基化反应过程中可能的过渡态和中间体进行了详细的能量计算得到了一条合理的反应路径(**图 2.8**)。反应从活性的醋酸钯催化剂 **2-IT1** 开始，经过配体交换过程生成中间体 **2-IT3**。之后中间体 **2-IT3** 与硫醚底物结合，通过硫醚的导向作用，对萘环邻位进行金属协同去质子化作用，生成碳氢键活化过渡态 **2-TS5-*R***。之后该过渡态稳定成六元环钯中间体 **2-IT6**，该中间体紧接着与烯烃底物 **2-IT7** 进行配体交换，生成中间体 **2-IT8**。然后进行烯烃插入过程，历经四元环过渡态 **2-TS9-*R*** 后得到中间体 **2-IT10**。中间体 **2-IT10** 随着进行 *β*-H 消除反应经过过渡态 **2-TS11** 后得到中间体 **2-**

IT12。最后 **2-IT12** 通过配体的解离和催化剂离去，得到最终烯基化产物 **2-IT13** 的同时催化剂在氧化剂的作用下回到活性的醋酸钯状态。

2.7 本章小结

我们通过理论计算和实验相结合的方法，探究了氧族元素在钯催化不对称碳氢键官能团化反应中的导向能力。结果表明硫醚基团在钯/手性磷酸催化体系中表现出良好的导向能力，在反应活性和对映体选择性控制方面均要优于氧醚和硒醚导向基。值得注意的是，我们首次使用硒醚作为进行不对称碳氢键活化的导向基团。此外，理论计算为反应条件的优化提供了方便，并进一步启发我们对反应机理的理解。我们最终通过硫醚导向钯催化不对称碳氢键烯基化和烯丙基化反应合成了一系列高产率高对映体选择性的联芳轴手性化合物以及含两个手性轴骨架的阻转异构体(up to 99% ee, >20:1 dr)。

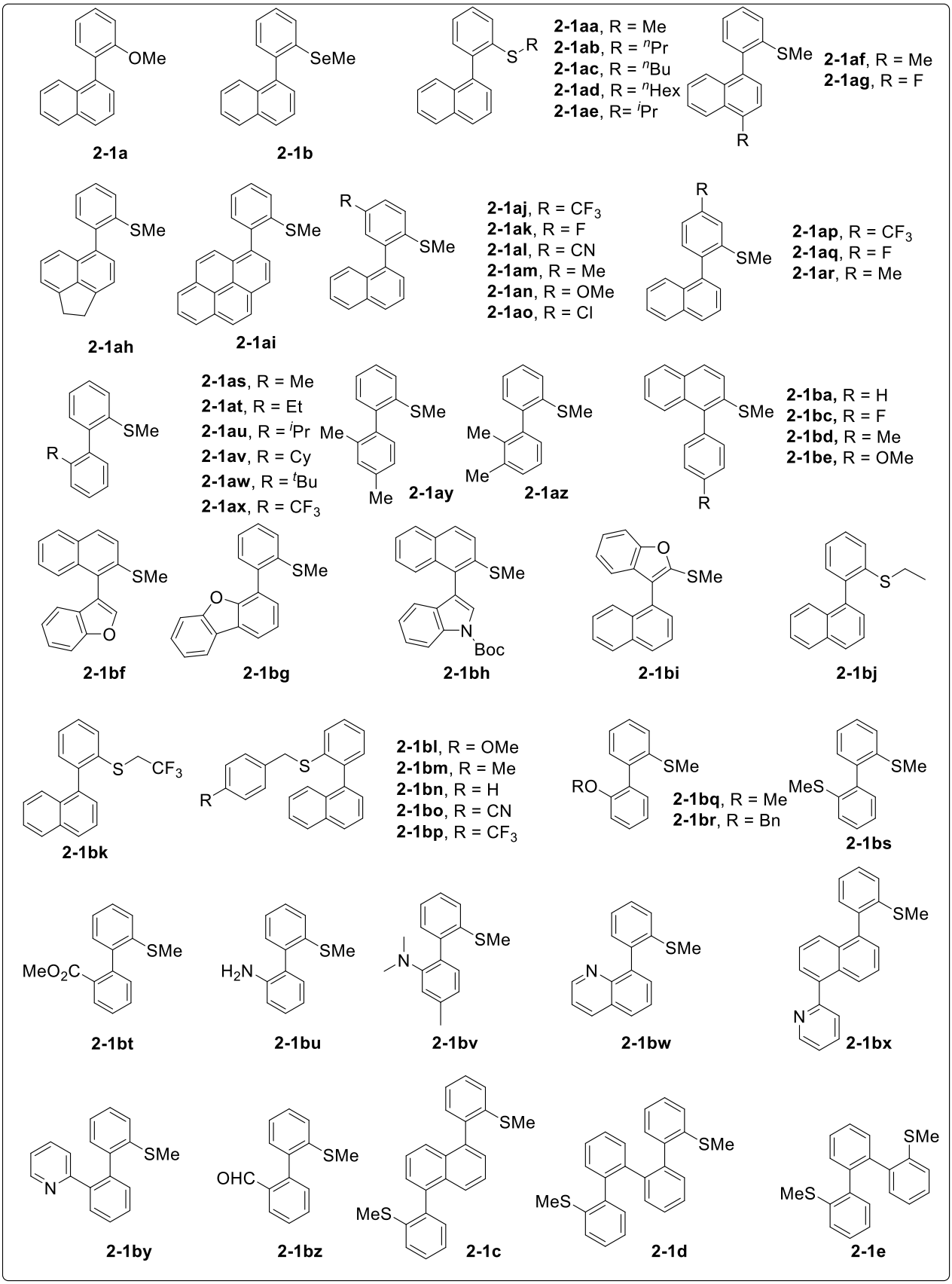
2.8 实验部分

2.8.1 仪器与试剂

测试仪器：Bruker Avance 400 M 核磁共振仪用于样品的 ^{1}H NMR、^{13}C NMR 和 ^{19}F NMR 检测。Waters TOF-MS GCT Premier 质谱仪用于高分辨质谱(EI)的测试，Bruker Apex 111 傅里叶变换离子回旋共振质谱仪用于高分辨质谱(ESI)的测试。Shimadzu HPLC LC-20A 液相色谱仪用于手性样品对映体比率的测定。有机反应用薄层层析法(TLC)跟踪，紫外灯，高锰酸钾显色剂和磷钼酸显色剂进行显色检测。

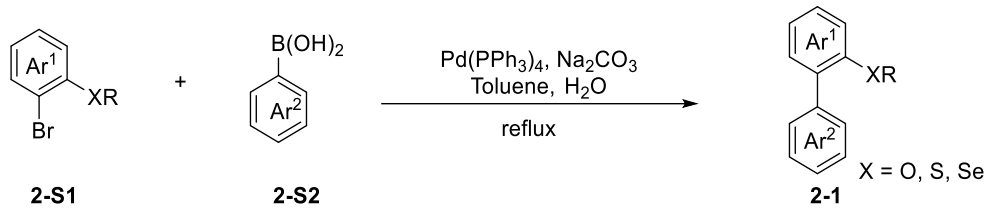
原料和试剂：一般原料试剂均由商业采购之后未经过纯化直接使用，所用无水溶剂由商业购买或者根据《Purification of Laboratory Chemicals, 6th Ed》做后处理之后再进行使用。醋酸钯由小辣椒公司进行购买。

2.8.2 联芳基硫醚底物的合成



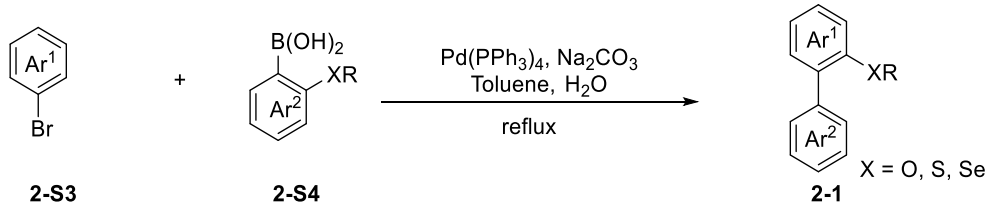
2-1a, **2-1aa**, **2-1bs, 2-1bt, 2-1bu, 2-1bx** 和 **2-1by** 都是已经存在并被文献报道的化合物[13]。

通用方法 A:在 250 mL 干燥的圆底烧瓶中加入相应的溴代芳基硫醚化合物(**2-S1**，10 mmol)，$Pd(PPh_3)_4$ (5 mol%)，芳基硼酸(**2-S2**, 1.5 equiv)，碳酸钠(5.0 equiv)和甲苯/水(2/1, 90 mL)，用干燥的氮气充换烧瓶三次，使其充满氮气。将烧瓶加热到回流状态并保持 12 小时。等原料反应完全后，冷却至室温，反应混合物用水稀释(30 mL)，然后用乙酸乙酯萃取三次。收集有机相液体，用无水硫酸钠干燥，再经过减压浓缩后经柱层析分离得到相对应的联芳基醚化合物(**2-1**)。



2-S1 **2-S2** **2-1**

通用方法 B:在 250 mL 干燥的圆底烧瓶中加入相应的芳基溴代物(**2-S3**，10 mmol)，$Pd(PPh_3)_4$ (5 mol%)，芳基硼酸(**2-S4**, 1.5 equiv)，碳酸钠(5.0 equiv)和甲苯/水(2/1, 90 mL)，用干燥的氮气充换烧瓶三次，使其充满氮气。将烧瓶加热到回流状态并保持 12 小时。等原料反应完全后，冷却至室温，反应混合物用水稀释(30 mL)，然后用乙酸乙酯萃取三次。收集有机相液体，用无水硫酸钠干燥，再经过减压浓缩后经柱层析分离得到相对应的联芳基醚化合物(**2-1**)。



2-S3 **2-S4** **2-1**

2.8.3 钯催化不对称碳氢键烯基化反应

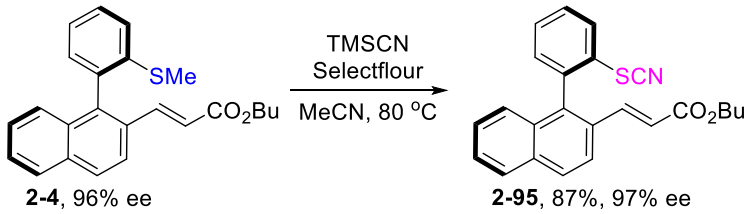
通用方法 C:在 10 mL Schlenk 反应管中依次加入醋酸钯(1.1 mg，0.005 mmol)，**2-L14**(7.2 mg，0.01 mmol)，联芳基底物 **2-1**(0.05 mmol)，烯基化试剂(0.15 mmol)，醋酸银(16.7 mg，0.1 mmol)，最后加入乙醚(0.5 mL)。在空气氛围下，60 ºC 中反应 24 小时。冷却到室温后，用乙酸乙酯稀释反应体系，通过硅藻土过滤，减压浓缩后经制备硅胶板分离后得到相对应的烯基化产物。

2.8.4 钯催化不对称碳氢键烯丙基化反应

通用方法 D:在 10 mL Schlenk 反应管中依次加入醋酸钯(1.1 mg，0.005 mmol)，**2-L32**(9.9 mg，0.01 mmol)，联芳基底物 **2-1**(0.05 mmol)，烯丙基化试剂(0.15 mmol)，醋酸银(16.7 mg，0.1 mmol)，最后加入异丙醚(0.5 mL)。在空气氛围下，60 ºC 中反应 48 小时。冷却到室温后，用乙酸乙酯稀释反应体系，通过硅藻土过滤，减压浓缩后经制备硅胶板分离后得到相对应的烯丙基化产物。

2.8.5 产物衍生化

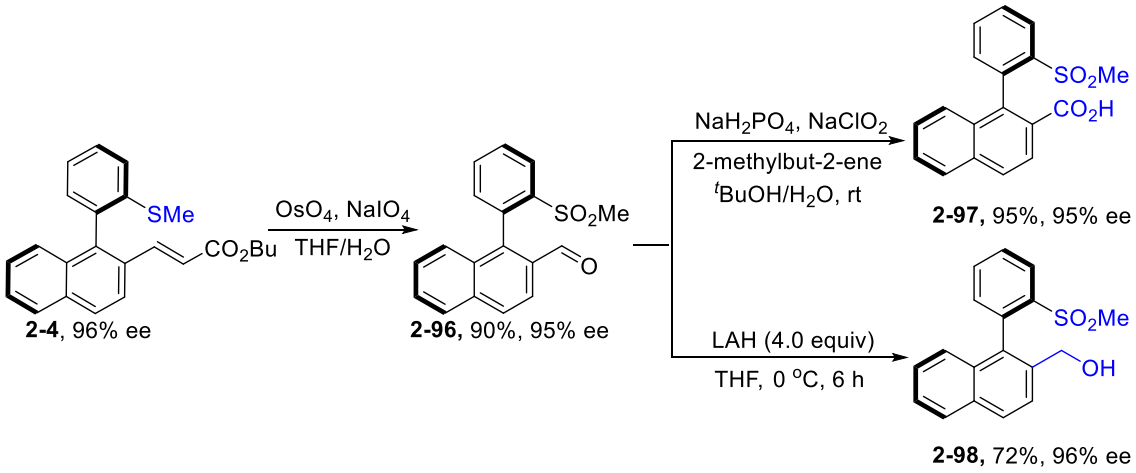
2.8.5.1 化合物 **2-95** 的合成



2-4, 96% ee　　**2-95**, 87%, 97% ee

氮气氛围下在 25 mL 圆底烧瓶中依次加入**(*R*)2-4**(0.1 mmol)，TMSCN(37 μL, 0.3 mmol, 3.0 equiv)，selectfluor(89 mg, 0.25 mmol, 2.5 equiv)，干燥的乙腈(1.0 mL)。将反应置于 80 ºC 下反应 12 小时后，减压浓缩后经柱层析分离提纯得到化合物 **2-95**(33.7 mg，87% yield，97% ee)。对映体比率由手性 HPLC 测定。

2.8.5.2 化合物 **2-96**、**2-97** 和 **2-98** 的合成



2-4, 96% ee　　**2-96**, 90%, 95% ee　　**2-97**, 95%, 95% ee　　**2-98**, 72%, 96% ee

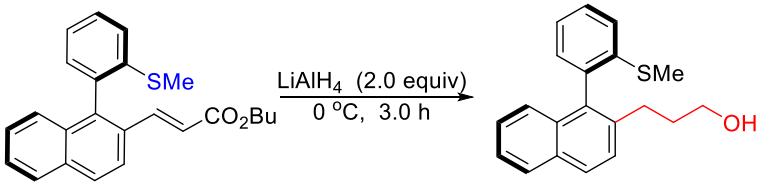
在 10 mL Schlenk 反应管中依次加入**(*R*)2-4**(0.1 mmol)，OsO_4(36 μl, 0.005 mmol)，$NaIO_4$(107.0 mg, 0.5 mmol)，THF/H_2O(2/1, 3.0 mL)。反应在 40 ºC 中搅拌过夜。冷却到室

温后，用饱和亚硫酸钠溶液淬灭反应，乙酸乙酯萃取，收集有机相，用无水硫酸钠干燥，减压浓缩后经制备硅胶板分离后得到化合物 **2-96**(27.9 mg, 90%, 95% ee)。对映体比率由手性 HPLC 测定。

在 10 mL Schlenk 反应管中依次加入 **2-96**(0.1 mmol)，*t*-BuOH(3.0 mL)和含有 2-methylbut-2-ene(13.0 equiv.), $NaClO_2$(3.7 equiv.), NaH_2PO_4(5.0 equiv.)的水溶液(1.0 mL)。反应在室温下搅拌两小时，减压浓缩后经制备硅胶板分离后得到化合物 **2-97**(31.0 mg, 95%, 95% ee)。对映体比率由手性 HPLC 测定。

氮气氛围下在 10 mL Schlenk 反应管中依次加入 **2-96**(0.1 mmol)和干燥的四氢呋喃(1.0 mL)。将反应置于冰浴中，缓慢滴加 $LiAlH_4$(18.6 mg, 0.4 mmol)，滴加完成后，将反应在 0 ºC 下搅拌大约六小时。反应完全后小心的加水淬灭，之后用乙酸乙酯萃取，收集有机相，用无水硫酸钠干燥，减压浓缩后经制备硅胶板分离后得到化合物 **2-98**(22.5 mg, 72%, 96% ee)。对映体比率由手性 HPLC 测定。

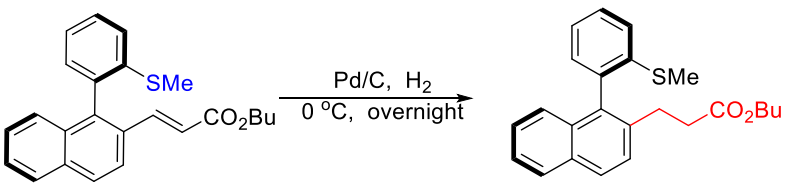
2.8.5.3 化合物 **2-99** 的合成



2-4, 96% ee　　**2-99**, 69%, 93% ee

氮气氛围下在 10 mL Schlenk 反应管中依次加入**(*R*)2-4**(0.1 mmol)和干燥的四氢呋喃(1.0 mL)。将反应置于冰浴中，缓慢滴加 $LiAlH_4$(9.3 mg, 0.2 mmol)，滴加完成后，将反应在 0 ºC 下搅拌大约三小时。反应完全后小心的加水淬灭，之后用乙酸乙酯萃取，收集有机相，用无水硫酸钠干燥，减压浓缩后经制备硅胶板分离后得到化合物 **2-99**(21.3 mg, 69%, 93% ee)。对映体比率由手性 HPLC 测定。

2.8.5.4 化合物 **2-100** 的合成

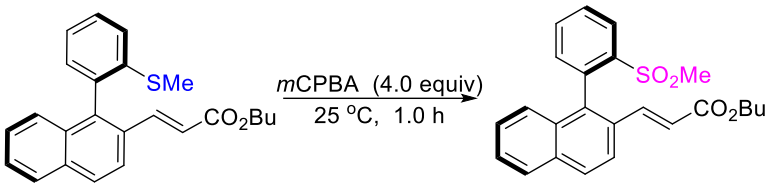


2-4, 96% ee　　**2-100**, 85%, 97% ee

氢气氛围下在 50 mL Schlenk 反应管中依次加入**(*R*)2-4**(0.1 mmol)，干燥的甲醇(1.0 mL)

和 Pd/C(5.0 mg)，将反应置于室温下搅拌过夜。反应完全后用乙酸乙酯稀释，再经过一小段硅藻土过滤，将滤液减压浓缩后经制备硅胶板分离后得到化合物 **2-100**(32.2 mg, 85%, 97% ee)。对映体比率由手性 HPLC 测定。

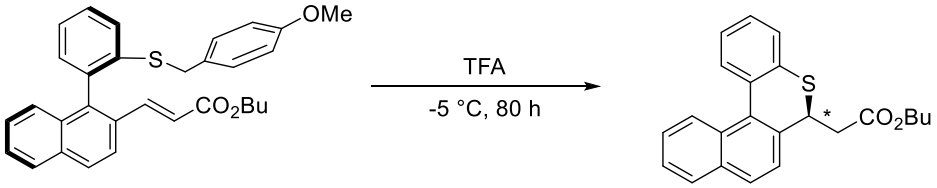
2.8.5.5 化合物 **2-101** 的合成



2-4, 96% ee　　**2-101**, 77%, 93% ee

在 10 mL Schlenk 反应管中依次加入**(*R*)2-4**(0.1 mmol)，*m*-CPBA(0.4 mmol)和二氯甲烷(1.0 mL)，将反应置于室温下搅拌大约一小时。反应完全后用饱和碳酸氢钠水溶液淬灭，再用乙酸乙酯萃取，收集有机相之后用无水硫酸钠干燥，减压浓缩后经制备硅胶板分离后得到化合物 **2-101**(31.4 mg, 77%, 93% ee)。对映体比率由手性 HPLC 测定。

2.8.5.6 化合物 **2-102** 的合成



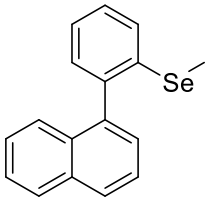
2-41, 90% ee　　**2-102**, 70%, 87% ee

氮气氛围下在 10 mL Schlenk 反应管中依次加入**(*R*)2-41**(0.1 mmol)和三氟乙酸(2.0 mL)，将反应置于-5 °C 下搅拌大约 80 小时。反应完全后用二氯甲烷稀释，混合物减压浓缩后经制备硅胶板分离后得到化合物 **2-102**(25.4 mg, 70%, 87% ee)。对映体比率由手性 HPLC 测定。

2.9 结构表征

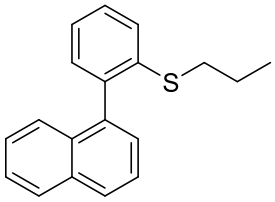
2.9.1 底物结构表征

methyl(2-(naphthalen-1-yl)phenyl)selane (2-1b)



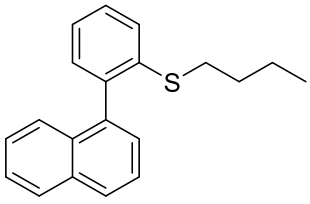
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到黄色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, *J* = 8.0 Hz, 2H), 7.56 – 7.35 (m, 7H), 7.34 – 7.25 (m, 2H), 2.14 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.96, 139.11, 133.72, 133.61, 131.79, 130.64, 128.36, 128.29, 128.23, 128.04, 127.17, 126.10, 125.96, 125.92, 125.35, 125.26, 6.72. HRMS (EI-TOF) calcd for $C_{17}H_{14}Se$ ($M+H^+$): 298.0256, found: 298.0257.

(2-(naphthalen-1-yl)phenyl)(propyl)sulfane (2-1ab)



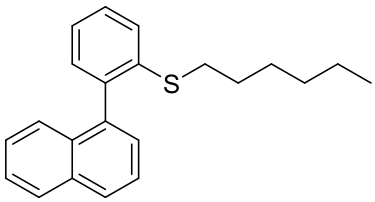
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (dd, *J* = 8.1, 2.1 Hz, 2H), 7.57 – 7.50 (m, 1H), 7.50 – 7.42 (m, 3H), 7.42 – 7.35 (m, 3H), 7.29 – 7.26 (m, 1H), 2.69 (t, *J* = 7.4 Hz, 2H), 1.55 – 1.47 (m, 2H), 0.85 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.36, 138.69, 137.48, 133.63, 132.10, 131.14, 128.35, 128.21, 128.10, 127.37, 127.33, 126.21, 126.05, 125.89, 125.36, 125.05, 35.01, 22.24, 13.61. HRMS (ESI-TOF) calcd for $C_{19}H_{18}S$ ($M+H^+$): 279.1202, found: 279.1202.

butyl(2-(naphthalen-1-yl)phenyl)sulfane (2-1ac)



根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δδ 7.89 (dd, *J* = 8.3, 3.7 Hz, 2H), 7.55 – 7.50 (m, 1H), 7.50 – 7.42 (m, 3H), 7.42 – 7.35 (m, 3H), 7.35 – 7.31 (m, 1H), 7.29 – 7.26 (m, 1H), 2.72 (t, *J* = 7.4 Hz, 2H), 1.52 – 1.41 (m, 2H), 1.32 – 1.21 (m, 2H), 0.81 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.31, 138.67, 137.58, 133.63, 132.09, 131.13, 128.34, 128.22, 128.10, 127.38, 127.27, 126.22, 126.04, 125.89, 125.36, 125.03, 32.73, 30.93, 22.12, 13.71. HRMS (ESI-TOF) calcd for $C_{20}H_{20}S$ ($M+H^+$): 293.1358, found: 293.1359.

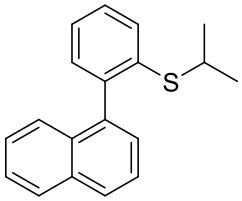
hexyl(2-(naphthalen-1-yl)phenyl)sulfane (2-1ad)



根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到黄色液体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (dd, *J* = 8.1, 3.2 Hz, 2H), 7.61 – 7.57 (m, 1H), 7.56 – 7.48 (m, 3H), 7.48 – 7.40 (m, 3H), 7.33 – 7.29 (m, 2H), 2.77 (t, *J* = 7.3 Hz, 2H), 1.58 – 1.50 (m, 2H), 1.34 – 1.21 (m, 6H), 0.89 (t, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.31, 138.67, 137.57, 133.62, 132.08, 131.12, 128.34, 128.20, 128.09, 127.38, 127.30, 126.21,

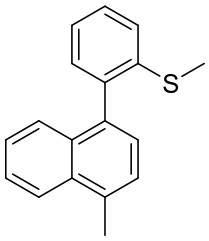
126.04, 125.88, 125.35, 125.02, 33.06, 31.43, 28.81, 28.68, 22.61, 14.13. HRMS (ESI-TOF) calcd for $C_{22}H_{24}S$ ($M+H^+$): 321.1671, found: 321.1673.

isopropyl(2-(naphthalen-1-yl)phenyl)sulfane (2-1ae)



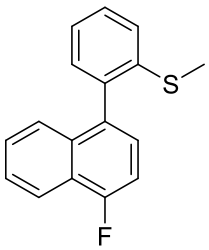
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 – 7.84 (m, 2H), 7.56 – 7.49 (m, 2H), 7.49 – 7.43 (m, 2H), 7.43 – 7.34 (m, 3H), 7.32 – 7.25 (m, 2H), 3.32 – 3.16 (m, 1H), 1.18 – 1.05 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.71, 138.97, 136.62, 133.57, 132.19, 131.34, 130.08, 128.30, 128.13, 127.97, 127.37, 126.29, 125.99, 125.83, 125.76, 125.26, 37.20, 22.96, 22.93. HRMS (ESI-TOF) calcd for $C_{19}H_{18}S$ ($M+H^+$): 279.1202, found: 279.1201.

methyl(2-(4-methylnaphthalen-1-yl)phenyl)sulfane (2-1af)



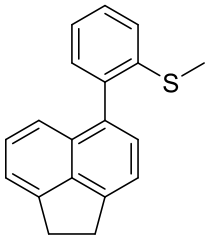
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.07 (d, *J* = 8.4 Hz, 1H), 7.56 – 7.48 (m, 2H), 7.47 – 7.38 (m, 3H), 7.33 (d, *J* = 7.9 Hz, 1H), 7.30 (d, *J* = 7.1 Hz, 1H), 7.26 – 7.23 (m, 2H), 2.77 (s, 3H), 2.32 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.18, 138.96, 136.61, 134.61, 132.75, 131.98, 130.93, 128.29, 127.04, 126.67, 126.26, 125.83, 125.80, 124.58, 124.58, 124.47, 19.78, 15.74. HRMS (ESI-TOF) calcd for $C_{18}H_{16}S$ ($M+H^+$): 265.1045, found: 265.1045.

(2-(4-fluoronaphthalen-1-yl)phenyl)(methyl)sulfane (2-1ag)



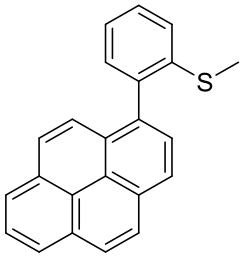
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.17 (d, *J* = 8.3 Hz, 1H), 7.57 – 7.52 (m, 1H), 7.50 – 7.42 (m, 3H), 7.36 – 7.30 (m, 2H), 7.26 – 7.18 (m, 3H), 2.32 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 158.69 (d, J_{CF} = 252.0 Hz), 139.06, 138.20, 134.24 (d, J_{CF} = 4.3 Hz), 133.33 (d, J_{CF} = 4.6 Hz), 130.99, 128.58, 127.18 (d, J_{CF} = 8.3 Hz), 127.08, 126.11 (d, J_{CF} = 2.6 Hz), 124.68, 124.55, 123.86 (d, J_{CF} = 16.5 Hz), 120.93 (d, J_{CF} = 5.6 Hz), 109.09 (d, J_{CF} = 19.9 Hz), 15.71. ^{19}F NMR (376 MHz, $CDCl_3$) δ -123.1605. HRMS (EI-TOF) calcd for $C_{17}H_{13}FS$ ($M+H^+$): 269.0795, found: 269.0797.

(2-(1,2-dihydroacenaphthylen-5-yl)phenyl)(methyl)sulfane (2-1ah)



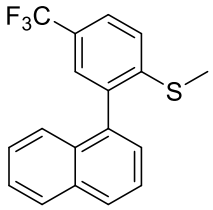
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到黄色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.47 – 7.33 (m, 5H), 7.32 – 7.26 (m, 3H), 7.26 – 7.23 (m, 1H), 3.46 (s, 4H), 2.34 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.28, 146.24, 139.44, 138.79, 138.74, 133.68, 130.91, 130.31, 129.06, 128.19, 128.03, 124.88, 124.50, 121.10, 119.51, 118.96, 30.66, 30.35, 15.92. HRMS (ESI-TOF) calcd for $C_{19}H_{16}S$ ($M+H^+$): 277.1046, found: 277.1045.

methyl(2-(pyren-1-yl)phenyl)sulfane (2-1ai)



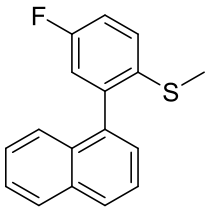
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 7.8 Hz, 1H), 8.21 (d, *J* = 7.6 Hz, 1H), 8.17 (d, *J* = 7.5 Hz, 1H), 8.12 (s, 2H), 8.05 – 7.98 (m, 2H), 7.95 (d, *J* = 7.8 Hz, 1H), 7.77 (d, *J* = 9.2 Hz, 1H), 7.56 – 7.47 (m, 1H), 7.44 – 7.31 (m, 3H), 2.32 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.38, 139.06, 135.71, 131.48, 131.15, 131.15, 131.15), 129.27, 128.51, 127.75, 127.67, 127.65, 127.59, 126.11, 125.41, 125.29, 125.20, 124.98, 124.88, 124.77, 124.67, 124.60, 15.76. HRMS (ESI-TOF) calcd for $C_{23}H_{16}S$ ($M+H^+$): 325.1045, found: 325.1046.

methyl(2-(naphthalen-1-yl)-4-(trifluoromethyl)phenyl)sulfane (2-1aj)



根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.04 – 7.86 (m, 2H), 7.70 (d, *J* = 8.3 Hz, 1H), 7.58 (t, *J* = 7.6 Hz, 1H), 7.55 – 7.48 (m, 2H), 7.48 – 7.35 (m, 4H), 2.37 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 144.45, 138.88, 136.68, 133.73, 131.60, 128.94, 128.57, 127.52, 127.27 (q, J_{CF} = 3.2 Hz), 126.53, 126.52 (q, J_{CF} = 32.6 Hz), 126.23, 125.59, 125.47, 125.12 (q, J_{CF} = 3.8 Hz), 124.48 (q, J_{CF} = 273.7 Hz), 123.90, 15.32. ^{19}F NMR (376 MHz, $CDCl_3$) δ -61.99. HRMS (EI-TOF) calcd for $C_{18}H_{13}F_3S$ (M^+): 318.0685, found: 318.0686.

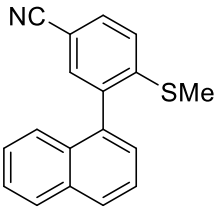
(4-fluoro-2-(naphthalen-1-yl)phenyl)(methyl)sulfane (2-1ak)



根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 (d, *J* = 8.3 Hz, 2H), 7.60 – 7.48 (m, 3H), 7.47 – 7.38 (m, 2H), 7.36 – 7.33 (m, 1H), 7.18 (td, *J* = 8.5, 2.9 Hz, 1H), 7.06 (dd, *J* = 9.0, 2.8 Hz, 1H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 160.68 (d, J_{CF} = 245.4 Hz) 141.35 (d, J_{CF} = 7.6 Hz), 137.26, 133.89 (d, J_{CF} = 3.2 Hz),

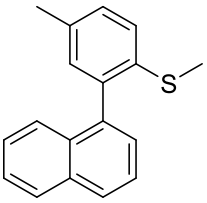
133.63, 131.68, 128.62, 128.47, 127.45 (d, J_{CF} = 7.9 Hz), 127.23, 126.37, 126.11, 125.79, 125.35, 118.06 (d, J_{CF} = 21.8 Hz), 115.37 (d, J_{CF} = 21.6 Hz), 16.73; ^{19}F NMR (376 MHz, $CDCl_3$) δ -123.87. HRMS (EI-TOF) calcd for $C_{17}H_{13}FS$ (M^+): 268.0717, found: 268.0716.

4-(methylthio)-3-(naphthalen-1-yl)benzonitrile (2-1al)



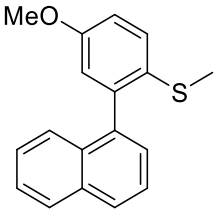
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 5/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (t, J = 8.0 Hz, 2H), 7.71 (dd, J = 8.3, 1.9 Hz, 1H), 7.59 – 7.49 (m, 3H), 7.46 – 7.41 (m, 1H), 7.41 – 7.32 (m, 3H), 2.36 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.89, 139.18, 135.66, 133.71, 133.44, 131.78, 131.37, 129.20, 128.62, 127.49, 126.64, 126.33, 125.43, 125.28, 123.91, 119.09, 107.51, 15.11. HRMS (EI-TOF) calcd for $C_{18}H_{13}NS$ (M^+): 275.0764, found: 275.0761.

methyl(4-methyl-2-(naphthalen-1-yl)phenyl)sulfane (2-1am)



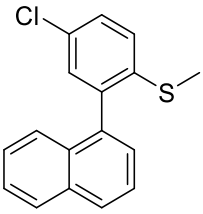
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 – 7.85 (m, 2H), 7.57 – 7.44 (m, 3H), 7.43 – 7.34 (m, 2H), 7.28 – 7.25 (m, 2H), 7.09 (s, 1H), 2.38 (s, 3H), 2.28 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.34, 138.58, 135.14, 134.52, 133.66, 132.07, 131.70, 129.17, 128.40, 128.15, 127.28, 126.20, 126.10, 125.94, 125.64, 125.42, 20.97, 16.31. HRMS (ESI-TOF) calcd for $C_{18}H_{16}S$ ($M+H^+$): 265.1045, found: 265.1046.

(4-methoxy-2-(naphthalen-1-yl)phenyl)(methyl)sulfane (2-1an)



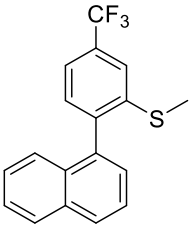
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 4/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, J = 8.1 Hz, 2H), 7.58 – 7.51 (m, 2H), 7.51 – 7.45 (m, 1H), 7.44 – 7.34 (m, 3H), 7.01 (dd, J = 8.7, 2.8 Hz, 1H), 6.88 (d, J = 2.9 Hz, 1H), 3.82 (s, 3H), 2.23 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.75, 141.70, 138.58, 133.59, 131.99, 129.25, 128.89, 128.39, 128.22, 127.13, 126.18, 126.18, 125.98, 125.34, 116.58, 114.49, 55.60, 17.58. HRMS (ESI-TOF) calcd for $C_{18}H_{16}OS$ ($M+H^+$): 281.0995, found: 281.0996.

(4-chloro-2-(naphthalen-1-yl)phenyl)(methyl)sulfane (2-1ao)



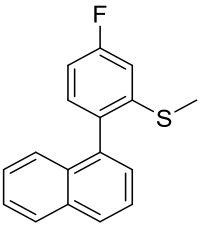
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, *J* = 8.2 Hz, 2H), 7.57 – 7.44 (m, 3H), 7.44 – 7.39 (m, 2H), 7.37 (dd, *J* = 7.0, 1.2 Hz, 1H), 7.24 (d, *J* = 5.8 Hz, 1H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.52, 137.67, 136.94, 133.66, 131.66, 130.66, 130.43, 128.73, 128.50, 128.40, 127.34, 126.42, 126.16, 126.10, 125.78, 125.40, 15.97. HRMS (EI-TOF) calcd for $C_{17}H_{13}ClS$ (M^+): 284.0421, found: 284.0418.

methyl(2-(naphthalen-1-yl)-5-(trifluoromethyl)phenyl)sulfane (2-1ap)



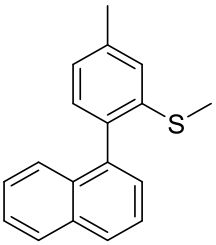
根据通用方法 A 合成，通过柱层析分离(石油醚为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 – 7.91 (m, 2H), 7.60 – 7.48 (m, 4H), 7.46 – 7.41 (m, 2H), 7.41 – 7.35 (m, 2H), 2.37 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.27, 140.83, 136.86, 133.70, 131.50, 131.05, 130.80 (q, J_{CF} = 32.1 Hz), 128.87, 128.55, 127.25, 126.49, 126.24, 125.63, 125.43, 124.31 (q, J_{CF} = 273.7 Hz), 121.16 (q, J_{CF} = 3.6 Hz), 120.93 (q, J_{CF} = 3.7 Hz), 15.51. ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.50. HRMS (EI-TOF) calcd for $C_{18}H_{13}F_3S$ ($M+H^+$): 318.0685, found: 318.0685.

(5-fluoro-2-(naphthalen-1-yl)phenyl)(methyl)sulfane (2-1aq)



根据通用方法 A 合成，通过柱层析分离(石油醚为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (d, *J* = 7.7 Hz, 2H), 7.62 – 7.45 (m, 3H), 7.45 – 7.36 (m, 2H), 7.21 (dd, *J* = 8.3, 6.0 Hz, 1H), 7.04 (dd, *J* = 9.9, 2.5 Hz, 1H), 6.95 (td, *J* = 8.3, 2.5 Hz, 1H), 2.32 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 163.00 (d, J_{CF} = 247.2 Hz), 141.61 (d, J_{CF} = 8.0 Hz), 137.18, 134.40 (d, J_{CF} = 3.3 Hz), 133.72, 132.08, 131.99 (d, J_{CF} = 8.6 Hz), 128.52, 128.47, 127.74, 126.27, 126.06, 125.85, 125.43, 111.34 (d, J_{CF} = 24.9 Hz), 111.09 (d, J_{CF} = 21.6 Hz), 15.55. ^{19}F NMR (376 MHz, $CDCl_3$) δ -113.91. HRMS (EI-TOF) calcd for $C_{17}H_{13}FS$ (M^+): 268.0717, found: 268.0719.

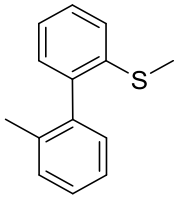
methyl(5-methyl-2-(naphthalen-1-yl)phenyl)sulfane (2-1ar)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (dd, *J* = 8.2, 3.8 Hz, 2H), 7.58 – 7.50 (m, 2H), 7.50 – 7.43 (m, 1H), 7.42 – 7.36 (m, 2H), 7.20 – 7.12 (m, 2H), 7.08 (d, *J* = 7.7 Hz, 1H), 2.47 (s, 3H), 2.31 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.42, 138.32, 138.14, 136.24, 133.69, 132.21, 130.70, 128.38, 128.14, 127.55, 126.19, 126.06, 125.92, 125.57, 125.44, 125.43, 21.60, 15.86. HRMS

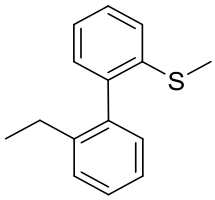
(EI-TOF) calcd for $C_{18}H_{16}S$ ($M+H^+$): 265.1045, found: 265.1044.

methyl(2'-methyl-[1,1'-biphenyl]-2-yl)sulfane (2-1as)



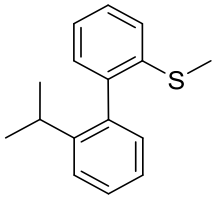
根据通用方法 B 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 (td, *J* = 7.7, 1.6 Hz, 1H), 7.31 – 7.26 (m, 2H), 7.28 – 7.21 (m, 3H), 7.19 (td, *J* = 7.4, 1.3 Hz, 1H), 7.14 (d, *J* = 7.3 Hz, 2H), 7.10 (dd, *J* = 7.5, 1.6 Hz, 1H), 2.36 (s, 3H), 2.11 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.27, 140.12, 137.93, 136.54, 130.02, 129.71, 129.56, 128.02, 127.99, 125.74, 124.48, 124.31, 19.92, 15.42. HRMS (EI-TOF) calcd for $C_{14}H_{14}S$ (M^+): 214.0811, found: 214.0810.

(2'-ethyl-[1,1'-biphenyl]-2-yl)(methyl)sulfane (2-1at)



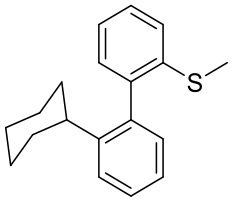
根据通用方法 B 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.39 – 7.31 (m, 3H), 7.28 – 7.22 (m, 2H), 7.19 (td, *J* = 7.3, 1.2 Hz, 1H), 7.13 (d, *J* = 7.5 Hz, 2H), 2.57 – 2.44 (m, 1H), 2.44 – 2.29 (m, 4H), 1.08 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.48, 140.03, 139.53, 138.16, 129.95, 129.86, 128.33, 128.23, 127.97, 125.66, 124.26, 124.16, 26.25, 15.42, 15.24. HRMS (EI-TOF) calcd for $C_{15}H_{16}S$ (M^+): 228.0968, found: 228.0969.

(2'-isopropyl-[1,1'-biphenyl]-2-yl)(methyl)sulfane (2-1au)



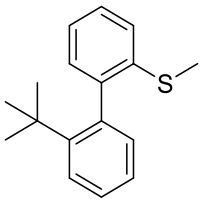
根据通用方法 B 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 – 7.34 (m, 3H), 7.29 – 7.23 (m, 2H), 7.20 (td, *J* = 7.3, 1.2 Hz, 1H), 7.13 (m, 2H), 2.72 (hept, *J* = 6.9 Hz, 1H), 2.38 (s, 3H), 1.24 (d, *J* = 6.9 Hz, 3H), 1.10 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 147.26, 140.08, 138.87, 138.42, 129.89, 129.87, 128.42, 127.91, 125.51, 125.49, 124.17, 124.05, 30.16, 24.88, 23.38, 15.42. HRMS (EI-TOF) calcd for $C_{16}H_{18}S$ (M^+): 242.1124, found: 242.1122.

(2'-cyclohexyl-[1,1'-biphenyl]-2-yl)(methyl)sulfane (2-1av)



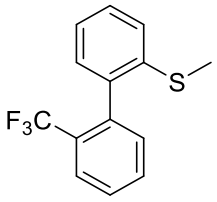
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 – 7.32 (m, 3H), 7.26 – 7.20 (m, 2H), 7.17 (td, *J* = 7.4, 1.2 Hz, 1H), 7.14 – 7.06 (m, 2H), 2.36 (s, 3H), 2.33 – 2.23 (m, 1H), 1.87 (d, *J* = 13.0 Hz, 1H), 1.79 – 1.59 (m, 4H), 1.55 – 1.42 (m, 1H), 1.36 – 1.27 (m, 1H), 1.24 – 1.00 (m, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.32, 140.21, 139.16, 138.35, 129.96, 129.88, 128.24, 127.86, 126.28, 125.45, 124.29, 124.21, 40.82, 35.38, 33.50, 26.98, 26.98, 26.31, 15.59. HRMS (ESI-TOF) calcd for $C_{19}H_{22}S$ ($M+H^+$): 283.1515, found:. 283.1517.

(2'-(tert-butyl)-[1,1'-biphenyl]-2-yl)(methyl)sulfane (2-1aw)



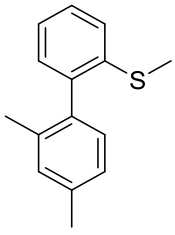
根据通用方法 B 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (d, *J* = 8.1 Hz, 1H), 7.38 – 7.30 (m, 2H), 7.23 – 7.16 (m, 3H), 7.16 – 7.08 (m, 1H), 6.97 (d, *J* = 7.5 Hz, 1H), 2.38 (s, 3H), 1.20 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.15, 143.11, 138.87, 138.87, 132.64, 130.56, 127.90, 127.72, 127.72, 125.39, 123.83, 123.40, 36.83, 32.24, 15.38. HRMS (EI-TOF) calcd for $C_{17}H_{20}S$ (M^+): 256.1281, found: 256.1281.

methyl(2'-(trifluoromethyl)-[1,1'-biphenyl]-2-yl)sulfane (2-1ax)



根据通用方法 B 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78 (d, *J* = 7.8 Hz, 1H), 7.58 (t, *J* = 7.4 Hz, 1H), 7.51 (t, *J* = 7.7 Hz, 1H), 7.43 – 7.36 (m, 1H), 7.33 (d, *J* = 7.5 Hz, 1H), 7.29 (d, *J* = 7.9 Hz, 1H), 7.23 – 7.13 (m, 2H), 2.38 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.08, 138.00, 137.92, 132.38, 131.35, 129.85, 128.99 (q, J_{CF} = 30.2 Hz) 128.69, 128.04, 126.33 (q, J_{CF} = 5.1 Hz), 125.06, 124.11, 124.06 (q, J_{CF} = 273.9 Hz), 15.95. ^{19}F NMR (376 MHz, $CDCl_3$) δ -58.79. HRMS (EI-TOF) calcd for $C_{14}H_{11}F_3S$ (M^+): 268.0529, found: 268.0530.

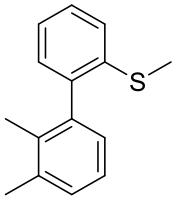
(2',4'-dimethyl-[1,1'-biphenyl]-2-yl)(methyl)sulfane (2-1ay)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.36 (td, J = 7.6, 1.6 Hz, 1H), 7.25 (dd, J = 6.9, 1.1 Hz, 1H), 7.19 (td, J = 7.3, 1.2 Hz, 1H), 7.14 – 7.03 (m, 4H), 2.40 (s, 3H), 2.38 (s, 3H), 2.10 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.23, 138.10, 137.65, 137.22, 136.29, 130.85, 129.76, 129.59, 127.88, 126.49, 124.43, 124.18, 21.40, 19.84,

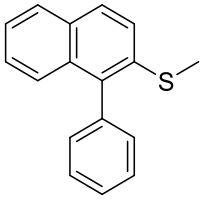
15.40. HRMS (ESI-TOF) calcd for $C_{15}H_{16}S$ ($M+H^+$): 269.1051, found: 269.1051.

(2',3'-dimethyl-[1,1'-biphenyl]-2-yl)(methyl)sulfane (2-1az)



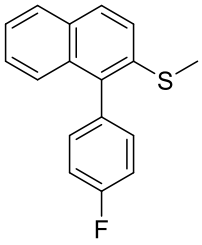
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.35 (td, *J* = 7.6, 1.6 Hz, 1H), 7.25 (d, *J* = 7.2 Hz, 1H), 7.23 – 7.13 (m, 3H), 7.11 (dd, *J* = 7.5, 1.6 Hz, 1H), 7.01 (d, *J* = 7.2 Hz, 1H), 2.36 (s, 3H), 2.35 (s, 3H), 2.01 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.92, 140.22, 138.10, 137.00, 135.11, 129.73, 129.52, 127.84, 127.49, 125.34, 124.42, 124.22, 20.71, 16.52, 15.45. HRMS (EI-TOF) calcd for $C_{15}H_{16}S$ ($M+H^+$): 229.1045, found: 229.1046.

methyl(1-phenylnaphthalen-2-yl)sulfane (2-1ba)



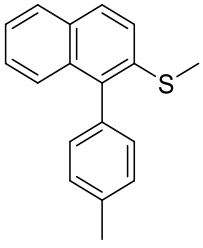
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 (d, *J* = 8.7 Hz, 1H), 7.84 (d, *J* = 8.2 Hz, 1H), 7.57 – 7.46 (m, 4H), 7.44 – 7.38 (m, 1H), 7.38 – 7.30 (m, 4H), 2.46 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.61, 137.14, 134.85, 132.94, 131.29, 130.56, 128.66, 128.30, 127.98, 127.88, 126.64, 125.73, 125.11, 123.25, 16.37. HRMS (ESI-TOF) calcd for $C_{17}H_{14}S$ ($M+H^+$): 251.0889, found: 251.0884.

(1-(4-fluorophenyl)naphthalen-2-yl)(methyl)sulfane (2-1bc)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (d, *J* = 8.7 Hz, 1H), 7.84 (d, *J* = 7.5 Hz, 1H), 7.48 (d, *J* = 8.8 Hz, 1H), 7.44 – 7.39 (m, 1H), 7.39 – 7.32 (m, 2H), 7.32 – 7.26 (m, 2H), 7.26 – 7.19 (m, 2H), 2.46 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.61, 137.14, 134.85, 132.94, 131.29, 130.56, 128.66, 128.30, 127.98, 127.88, 126.64, 125.73, 125.11, 123.25, 16.37. ^{19}F NMR (376 MHz, $CDCl_3$) δ -114.31. HRMS (EI-TOF) calcd for $C_{17}H_{13}FS$ (M^+): 268.0717, found: 268.0720.

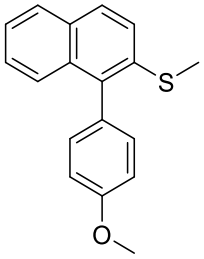
methyl(1-(p-tolyl)naphthalen-2-yl)sulfane (2-1bd)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.78 (t, *J* = 8.8 Hz, 2H), 7.43 (d, *J* = 8.7 Hz, 1H), 7.39 – 7.24 (m, 5H), 7.18 (d, *J* = 7.7 Hz, 2H), 2.42 (s, 3H), 2.39 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.24, 138.98, 136.63, 134.59, 132.77, 132.01, 130.94, 128.29, 127.05, 126.68, 126.25, 125.82, 125.79, 124.66,

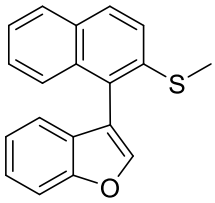
124.56, 124.48, 19.75, 15.75. HRMS (ESI-TOF) calcd for $C_{18}H_{16}S$ ($M+H^+$): 265.1045, found: 265.1048.

(1-(4-methoxyphenyl)naphthalen-2-yl)(methyl)sulfane (2-1be)



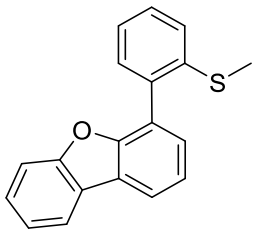
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 =4/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (t, *J* = 9.0 Hz, 2H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.45 – 7.38 (m, 2H), 7.39 – 7.31 (m, 1H), 7.28 – 7.22 (m, 2H), 7.18 – 7.04 (m, 2H), 3.91 (s, 3H), 2.46 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.24, 138.98, 136.63, 134.59, 132.77, 132.01, 130.94, 128.29, 127.05, 126.68, 126.25, 125.82, 125.79, 124.66, 124.56, 124.48, 19.75, 15.75. HRMS (ESI-TOF) calcd for $C_{18}H_{16}S$ (M+H+): 281.0995, found: 281.0996.

3-(2-(methylthio)naphthalen-1-yl)benzofuran (2-1bf)



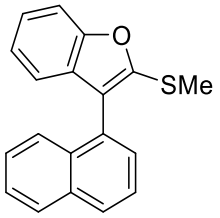
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =10/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 (d, *J* = 8.8 Hz, 1H), 7.87 (d, *J* = 8.1 Hz, 1H), 7.75 (s, 1H), 7.64 (d, *J* = 8.3 Hz, 1H), 7.55 (t, *J* = 8.3 Hz, 2H), 7.46 – 7.40 (m, 1H), 7.40 – 7.32 (m, 2H), 7.23 – 7.15 (m, 2H), 2.46 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.41, 144.42, 137.41, 133.54, 131.29, 131.29, 129.10, 128.17, 126.96, 125.70, 125.52, 125.30, 124.70, 123.20, 122.97, 120.98, 117.71, 111.84, 16.28. HRMS (ESI-TOF) calcd for $C_{19}H_{14}OS$ ($M+H^+$): 291.0838, found: 291.0841.

4-(2-(methylthio)phenyl)dibenzo[b,d]furan (2-1bg)



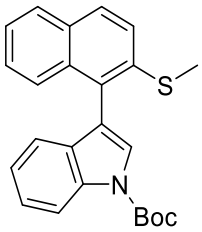
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =10/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.00 (d, *J* = 7.4 Hz, 2H), 7.54 (d, *J* = 8.2 Hz, 1H), 7.50 – 7.38 (m, 6H), 7.38 – 7.28 (m, 2H), 2.38 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.35, 153.78, 138.46, 135.67, 130.77, 128.86, 128.70, 127.29, 126.10, 124.99, 124.87, 124.59, 124.49, 122.83, 122.67, 120.81, 120.38, 112.07, 16.34. HRMS (ESI-TOF) calcd for C19H14OS ($M+H^+$): 291.0838, found: 291.0835.

2-(methylthio)-3-(naphthalen-1-yl)benzofuran (2-1bh)



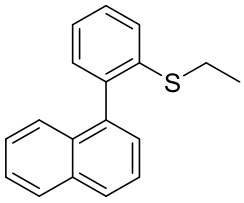
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 (d, *J* = 8.1 Hz, 2H), 7.73 (d, *J* = 8.4 Hz, 1H), 7.61 – 7.47 (m, 4H), 7.47 – 7.36 (m, 1H), 7.35 – 7.28 (m, 1H), 7.24 – 7.08 (m, 2H), 2.46 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.61, 149.17, 133.97, 132.21, 130.05, 129.40, 128.75, 128.63, 128.59, 126.20, 126.17, 126.13, 125.62, 124.64, 123.11, 121.85, 120.45, 111.05, 17.16. HRMS (EI-TOF) calcd for $C_{19}H_{14}OS$ (M^+): 290.0760, found: 290.0759.

tert-butyl 3-(2-(methylthio)naphthalen-1-yl)-1H-indole-1-carboxylate (2-1bi)



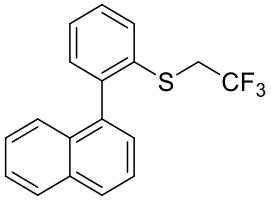
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.45 (s, 1H), 8.00 (d, *J* = 8.7 Hz, 1H), 7.95 (d, *J* = 7.9 Hz, 1H), 7.88 (s, 1H), 7.69 (d, *J* = 7.6 Hz, 1H), 7.63 (d, *J* = 8.7 Hz, 1H), 7.56 – 7.47 (m, 2H), 7.47 – 7.39 (m, 1H), 7.27 (d, *J* = 20.8 Hz, 2H), 2.55 (s, 3H), 1.83 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 149.77, 137.20, 133.61, 131.18, 130.60, 128.79, 128.01, 127.62, 126.70, 125.86, 125.62, 125.08, 124.65, 122.97, 122.83, 120.41, 117.81, 115.42, 83.82, 28.24, 16.10. HRMS (EI-TOF) calcd for $C_{24}H_{23}NO_2S$ (M+H^+): 389.1444, found: 389.1444.

ethyl(2-(naphthalen-1-yl)phenyl)sulfane (2-1bj)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (dd, *J* = 7.7, 2.5 Hz, 2H), 7.54 (t, *J* = 7.6 Hz, 1H), 7.48 (t, *J* = 7.8 Hz, 2H), 7.45 – 7.35 (m, 4H), 7.29 – 7.26 (m, 2H), 2.77 (q, *J* = 7.3 Hz, 2H), 1.18 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.22, 138.63, 137.34, 133.64, 132.08, 131.14, 128.38, 128.24, 128.14, 127.38, 127.04, 126.20, 126.09, 125.92, 125.37, 125.05, 26.93, 13.96. HRMS (ESI-TOF) calcd for $C_{18}H_{16}S$ (M+H^+): 265.1045, found: 265.1048.

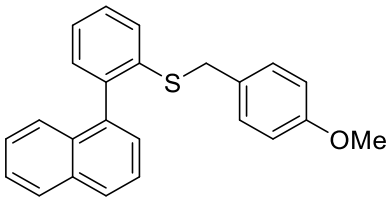
(2-(naphthalen-1-yl)phenyl)(2,2,2-trifluoroethyl)sulfane (2-1bk)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 =9/1 为洗脱剂)得到无色液体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, *J* = 8.2 Hz, 2H), 7.67 (dd, *J* = 7.6, 1.5 Hz, 1H), 7.58 (dd, *J* = 8.3, 7.0 Hz, 1H), 7.55 – 7.50 (m, 1H), 7.50 – 7.39 (m, 5H), 7.36 (dd, *J* = 7.3, 1.8 Hz, 1H), 3.16 (q, *J* = 9.7 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 142.44, 138.13, 133.78, 133.63, 132.06, 131.65,

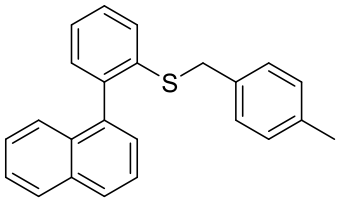
131.14, 128.70, 128.46, 128.43, 127.67, 127.43, 126.39, 126.09, 125.93, 125.35 (q, J_{CF} = 276.7 Hz), 125.30, 36.90 (q, J_{CF} = 32.7 Hz). ^{19}F NMR (376 MHz, $CDCl_3$) δ -65.83. HRMS (EI-TOF) calcd for $C_{18}H_{13}F_3S$ (M^+): 318.0685, found: 318.0687.

(4-methoxybenzyl)(2-(naphthalen-1-yl)phenyl)sulfane (2-1bl)



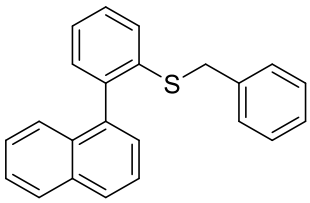
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 19/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) 7.88 (dd, *J* = 8.3, 5.3 Hz, 2H), 7.53 – 7.41 (m, 4H), 7.39 – 7.33 (m, 2H), 7.33 – 7.26 (m, 2H), 7.26 – 7.23 (m, 1H), 7.04 (d, *J* = 8.5 Hz, 2H), 6.72 (d, *J* = 8.7 Hz, 2H), 3.88 (s, 2H), 3.74 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 158.77, 140.71, 138.50, 137.06, 133.60, 132.11, 131.14, 130.06, 129.02, 128.52, 128.32, 128.22, 128.11, 127.41, 126.21, 126.08, 125.87, 125.66, 125.31, 113.86, 77.48, 77.16, 76.84, 55.36, 37.78. HRMS (EI-TOF) calcd for $C_{24}H_{20}OS$ (M^+): 356.1230, found:.356.1227.

(4-methylbenzyl)(2-(naphthalen-1-yl)phenyl)sulfane (2-1bm)



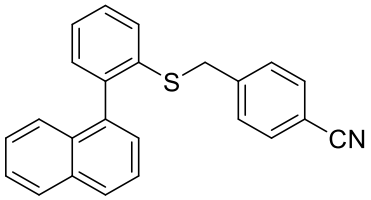
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88 (t, *J* = 6.8 Hz, 2H), 7.54 – 7.41 (m, 4H), 7.41 – 7.33 (m, 2H), 7.33 – 7.29 (m, 1H), 7.29 – 7.25 (m, 2H), 7.06 – 6.95 (m, 4H), 3.90 (s, 2H), 2.27 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.63, 138.50, 137.19, 136.83, 133.99, 133.63, 132.13, 131.14, 129.17, 128.86, 128.36, 128.33, 128.24, 128.12, 127.43, 126.23, 126.08, 125.88, 125.61, 125.33, 38.04, 21.20. HRMS (ESI-TOF) calcd for $C_{24}H_{20}S$ ($M+H^+$): 341.1358, found: 341.1361.

benzyl(2-(naphthalen-1-yl)phenyl)sulfane (2-1bn)



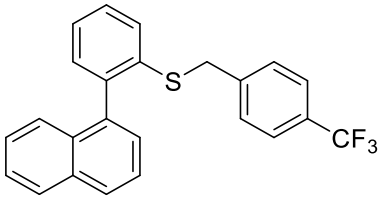
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 =9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88 (dd, *J* = 8.3, 5.1 Hz, 2H), 7.55 – 7.41 (m, 4H), 7.41 – 7.32 (m, 2H), 7.32 – 7.26 (m, 2H), 7.26 – 7.23 (m, 1H), 7.23 – 7.15 (m, 3H), 7.12 (dd, *J* = 7.4, 2.2 Hz, 2H), 3.92 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.92, 138.44, 137.49, 135.19, 133.62, 132.66, 132.10, 131.96, 131.36, 130.44, 129.50, 129.20, 128.46, 128.37, 128.19, 127.65, 127.49, 127.40, 126.40, 126.13, 125.91, 125.29. HRMS (ESI-TOF) calcd for $C_{23}H_{18}S$ ($M+H^+$): 327.1202, found: 327.1204.

4-(((2-(naphthalen-1-yl)phenyl)thio)methyl)benzonitrile (2-1bo)



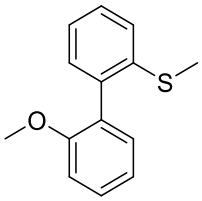
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 1/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (dd, *J* = 8.2, 4.4 Hz, 2H), 7.54 – 7.47 (m, 2H), 7.46 – 7.40 (m, 3H), 7.40 – 7.34 (m, 3H), 7.34 – 7.30 (m, 1H), 7.28 (dd, *J* = 7.4, 1.8 Hz, 2H), 7.24 (d, *J* = 1.2 Hz, 1H), 7.14 (d, *J* = 8.3 Hz, 2H), 3.87 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.15, 141.82, 138.25, 135.14, 133.57, 132.20, 132.04, 131.45, 129.98, 129.56, 128.42, 128.39, 128.27, 127.39, 126.73, 126.20, 126.00, 125.94, 125.23, 118.89, 110.91, 38.57. HRMS (EI-TOF) calcd for $C_{24}H_{17}NS$ (M^+): 351.1077, found: 351.1076.

(2-(naphthalen-1-yl)phenyl)(4-(trifluoromethyl)benzyl)sulfane (2-1bp)



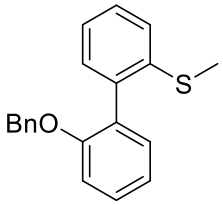
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 9/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (s, 2H), 7.51 – 7.30 (m, 8H), 7.26 – 7.03 (m, 5H), 3.85 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.56, 141.50, 138.34, 135.73, 133.56, 132.07, 131.33, 129.46, 129.16, 128.37, 128.21, 127.35, 126.41, 126.18, 126.02, 125.96, 124.25 (q, *J* = 272.7 Hz), 125.37, 125.34, 125.27, 38.24. ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.4678. HRMS (ESI-TOF) calcd for $C_{24}H_{17}F_3S$ ($M+H^+$): 395.1076, found: 395.1081.

(2'-methoxy-[1,1'-biphenyl]-2-yl)(methyl)sulfane (2-1bq)



根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 =9/1 为洗脱剂)得到无色液体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.40 – 7.28 (m, 3H), 7.24 – 7.13 (m, 3H), 7.06 – 6.94 (m, 2H), 3.77 (s, 3H), 2.35 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.02, 138.35, 137.94, 131.23, 130.43, 129.54, 129.39, 128.05, 125.51, 124.71, 120.54, 111.18, 55.81, 16.21. HRMS (EI-TOF) calcd for $C_{14}H_{14}OS$ (M^+): 231.0838, found: 231.0838.

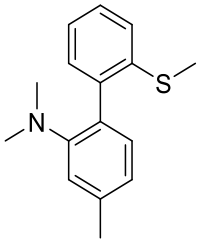
(2'-(benzyloxy)-[1,1'-biphenyl]-2-yl)(methyl)sulfane(2-1br)



根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 9/1 为洗脱剂)得到无色液体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.24 (m, 5H), 7.24 – 7.17 (m, 6H), 7.07 – 6.97 (m, 2H), 5.05 (s, 2H), 2.34 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 156.07, 138.31, 137.88, 137.54, 131.27, 130.45, 130.31, 129.24, 128.35, 127.98, 127.45, 126.75, 125.28, 124.56, 120.99, 113.42, 70.49, 16.08. HRMS

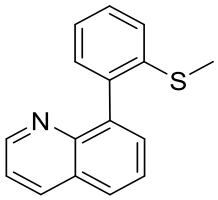
(EI-TOF) calcd for $C_{20}H_{18}OS$ (M^+): 306.1073, found: 306.1071.

N,N,4-trimethyl-2'-(methylthio)-[1,1'-biphenyl]-2-amine (2-1bv)



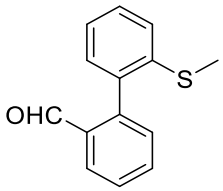
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 10/1，1%三乙胺为洗脱剂)得到无色液体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.32 – 7.27 (m, 2H), 7.25 – 7.23 (m, 1H), 7.21 – 7.13 (m, 1H), 7.04 (d, *J* = 7.6 Hz, 1H), 6.86 (s, 1H), 6.82 (d, *J* = 7.6 Hz, 1H), 2.52 (s, 6H), 2.37 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 151.64, 140.58, 138.48, 137.99, 131.62, 130.40, 129.92, 127.25, 125.33, 124.61, 121.68, 118.49, 43.12, 21.67, 16.21. HRMS (EI-TOF) calcd for $C_{16}H_{19}NS$ (M^+): 257.1233, found: 257.1235.

8-(2-(methylthio)phenyl)quinoline (2-1bw)



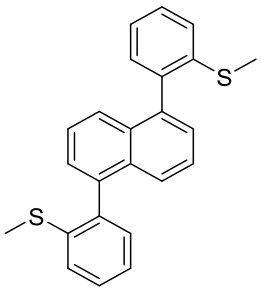
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 6/1 为洗脱剂)得到淡黄色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.95 – 8.87 (m, 1H), 8.20 (d, *J* = 8.3 Hz, 1H), 7.88 (d, *J* = 8.1 Hz, 1H), 7.67 (d, *J* = 7.2 Hz, 1H), 7.61 (td, *J* = 7.6, 2.3 Hz, 1H), 7.45 – 7.36 (m, 3H), 7.34 – 7.26 (m, 2H), 2.32 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 150.58, 146.75, 139.99, 139.17, 138.36, 136.33, 130.96, 130.80, 128.56, 128.40, 128.26, 126.13, 125.76, 124.74, 121.19, 16.40. HRMS (ESI-TOF) calcd for $C_{16}H_{13}NS$ ($M+H^+$): 252.0841, found: 252.0840.

2'-(methylthio)-[1,1'-biphenyl]-2-carbaldehyde (2-1bz)



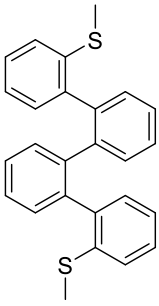
根据通用方法 A 合成，通过柱层析分离(石油醚/乙酸乙酯 = 9/1 为洗脱剂)得到淡黄色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 – 7.80 (m, 3H), 7.55 – 7.43 (m, 3H), 7.41 – 7.32 (m, 3H), 7.30 (td, *J* = 7.4, 1.2 Hz, 1H), 7.15 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.49 (d, *J* = 16.0 Hz, 1H), 4.12 (t, *J* = 6.5 Hz, 2H), 2.30 (s, 3H), 1.64 – 1.57 (m, 2H), 1.41 – 1.30 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.13, 142.97, 139.65, 139.24, 135.78, 134.25, 132.61, 131.08, 130.55, 128.98, 128.74, 128.19, 127.16, 127.04, 126.87, 124.91, 124.83, 122.79, 119.25, 64.31, 30.81, 19.30, 15.57, 13.88. HRMS (EI-TOF) calcd for $C_{14}H_{12}OS$ (M^+): 228.0604, found: 228.0605.

1,5-bis(2-(methylthio)phenyl)naphthalene (2-1c)



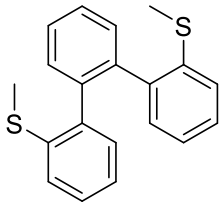
根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 4/1 为洗脱剂)得到黄色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.54 (d, *J* = 8.2 Hz, 2H), 7.48 – 7.31 (m, 9H), 7.30 – 7.26 (m, 3H), 2.36 – 2.29 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.23, 138.82, 138.52, 138.45, 132.22, 132.12, 131.01, 130.91, 128.40, 128.37, 127.49, 127.40, 126.33, 125.46, 124.81, 124.67, 124.52, 124.46, 15.81, 15.77. HRMS (EI-TOF) calcd for C24H20S ($M+H^+$): 373.1079, found: 373.1077.

2,2'''-bis(methylthio)-1,1':2',1'':2'',1'''-quaterphenyl (2-1d)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 =4/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.29 – 7.12 (m, 10H), 7.12 – 7.02 (m, 2H), 6.97 – 6.72 (m, 4H), 2.43 (s, 4H), 2.20 (s, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 140.11, 139.51, 138.70, 138.60, 132.34, 131.46, 131.02, 130.11, 127.57, 127.22, 126.98, 126.65, 126.31, 125.12, 124.20, 124.02, 16.14, 15.70. HRMS (ESI-TOF) calcd for $C_{26}H_{22}S_2$ (M+H+): 399.1236, found: 399.1238.

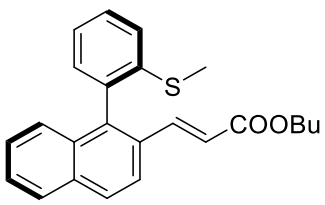
2,2''-bis(methylthio)-1,1':2',1''-terphenyl (2-1e)



根据通用方法 A 合成，通过柱层析分离(石油醚/二氯甲烷 = 4/1 为洗脱剂)得到白色固体。^{1}H NMR (400 MHz, $CDCl_3$) 7.48 – 7.27 (m, 4H), 7.24 – 7.00 (m, 6H), 6.86 (t, J = 7.2 Hz, 2H), 2.44 – 2.24 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.55, 139.25, 137.50, 130.90, 130.01, 129.51, 128.54, 127.60, 127.27, 124.92, 124.53, 123.87, 123.80, 15.60. HRMS (EI-TOF) calcd for $C_{14}H_{12}OS$ (M^+): 322.0845, found: 322.0846.

2.9.2 产物结构表征

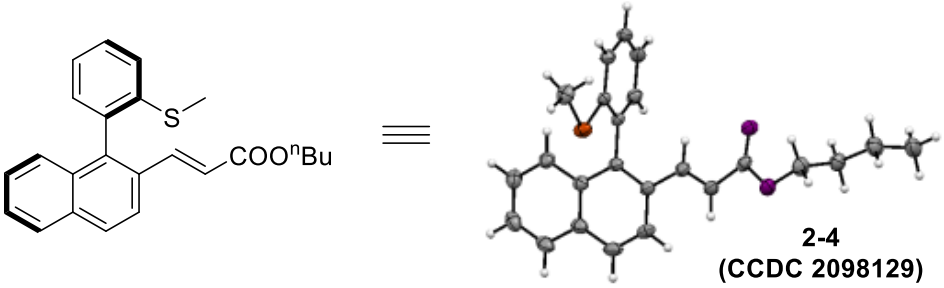
butyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-4)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.3 mg, 92%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 – 7.80 (m, 3H), 7.55 – 7.43 (m, 3H), 7.41 – 7.32 (m, 3H), 7.30 (td, *J* = 7.4, 1.2 Hz, 1H), 7.15 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.49 (d, *J* = 16.0 Hz, 1H), 4.12 (t, *J* = 6.5 Hz, 2H), 2.30 (s, 3H), 1.64 – 1.57 (m, 2H), 1.41 – 1.30 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.13, 142.97, 139.65, 139.24,

135.78, 134.25, 132.61, 131.08, 130.55, 128.98, 128.74, 128.19, 127.16, 127.04, 126.87, 124.91, 124.83, 122.79, 119.25, 64.31, 30.81, 19.30, 15.57, 13.88. HRMS (ESI-TOF) calcd for $C_{24}H_{24}O_2S$ ($M+Na^+$): 399.1389, found: 399.1390. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 8.6 min, t (major) = 7.4 min, 97% ee. $[\alpha]_D^{20}$ = -99.9 (c = 1.0, $CHCl_3$).

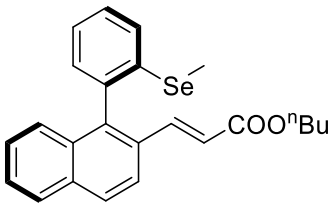
***X-ray* Data of 2-4**



Empirical formula	$C_{24}H_{24}O_2S$
Formula weight	376.49
Temperature/K	170.0
Crystal system	orthorhombic
Space group	$P2_12_12_1$
a/Å	7.6531(17)
b/Å	10.470(2)
c/Å	25.341(6)
α/°	90
β/°	90
γ/°	90
Volume/Å^3	2030.5(8)
Z	4
ρ_{calc}g/cm^3	1.232
μ/mm^{-1}	0.175
F(000)	800.0
Crystal size/mm^3	0.49 × 0.36 × 0.32
Radiation	MoKα (λ = 0.71073)
2Θ range for data collection/°	5.048 to 54.192

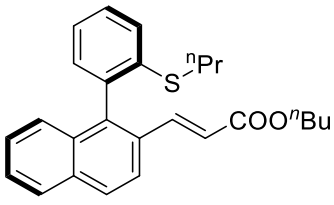
Index ranges	$-9 \le h \le 9, -13 \le k \le 13, -32 \le l \le 32$
Reflections collected	26855
Independent reflections	4479 [R_{int} = 0.0327, R_{sigma} = 0.0214]
Data/restraints/parameters	4479/0/246
Goodness-of-fit on F^2	1.083
Final R indexes [I>=2σ (I)]	R_1 = 0.0268, wR_2 = 0.0683
Final R indexes [all data]	R_1 = 0.0283, wR_2 = 0.0696
Largest diff. peak/hole / e $Å^{-3}$	0.14/-0.25
Flack parameter	-0.015(17)

butyl (*E*)-3-(1-(2-(methylselanyl)phenyl)naphthalen-2-yl)acrylate (2-5)



根据通用方法 C 使用 20 mol%的醋酸钯经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(3.2 mg, 15%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 – 7.85 (m, 2H), 7.82 (d, *J* = 8.7 Hz, 1H), 7.53 – 7.40 (m, 4H), 7.40 – 7.31 (m, 3H), 7.16 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.48 (d, *J* = 16.0 Hz, 1H), 4.11 (t, *J* = 6.5 Hz, 2H), 2.14 (s, 3H), 1.65 – 1.59 (m, 2H), 1.38 – 1.31 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.04, 142.82, 137.92, 134.15, 131.01, 130.39, 128.93, 128.71, 128.40, 128.09, 127.11, 127.01, 126.82, 125.77, 122.70, 119.22, 64.26, 30.72, 19.22, 13.80, 6.60. HRMS (ESI-TOF) calcd for $C_{24}H_{24}O_2Se$ (M^+): 424.0937, found: 424.0936. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 6.3 min, t (major) = 5.4 min, 96% ee. $[\alpha]_D^{20}$ = -71.5 (c = 0.8, $CHCl_3$).

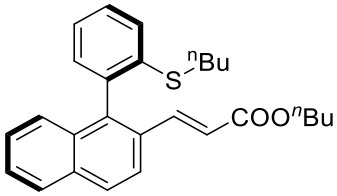
butyl (*E*)-3-(1-(2-(propylthio)phenyl)naphthalen-2-yl)acrylate (2-6)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(20.0 mg, 99%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (t, *J* = 9.1 Hz, 2H), 7.82 (d, *J* = 8.7 Hz, 1H), 7.55 – 7.39 (m, 4H), 7.39 – 7.32 (m, 2H), 7.32 – 7.26 (m, 1H), 7.14 (d, *J* = 7.2 Hz, 1H), 6.46 (d, *J* = 16.0 Hz, 1H), 4.10 (t, *J* = 6.5 Hz, 2H), 2.78 – 2.63 (m, 2H), 1.64 – 1.58 (m, 2H), 1.54 – 1.43 (m, 2H), 1.38 – 1.29 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H), 0.83 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.12, 143.14, 140.09, 137.90, 137.17, 134.19, 132.73, 131.39, 130.38, 128.78, 128.59, 128.15, 127.31, 127.17, 127.08, 126.78, 125.32, 122.76, 119.11,

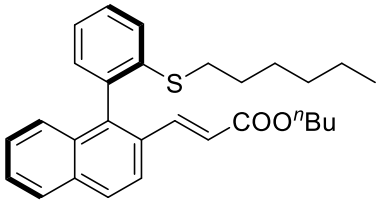
64.28, 34.65, 30.82, 22.26, 19.30, 13.88, 13.53. HRMS (ESI-TOF) calcd for $C_{26}H_{28}O_2S$ ($M+Na^+$): 427.1702, found: 427.1702. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 7.3 min, t (major) = 6.6 min, 78% ee. $[\alpha]_D^{20}$ = -127.6 (c = 1.2, $CHCl_3$).

butyl (*E*)-3-(1-(2-(butylthio)phenyl)naphthalen-2-yl)acrylate (2-7)



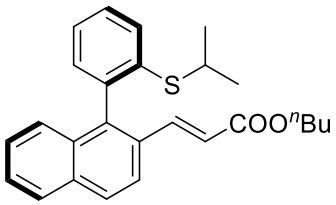
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(11.1 mg, 53%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (t, *J* = 9.0 Hz, 2H), 7.82 (d, *J* = 8.8 Hz, 1H), 7.52 – 7.42 (m, 4H), 7.38 – 7.27 (m, 3H), 7.14 (d, *J* = 7.5 Hz, 1H), 6.46 (d, *J* = 16.0 Hz, 1H), 4.10 (t, *J* = 6.5 Hz, 2H), 2.79 – 2.68 (m, 2H), 1.63 – 1.58 (m, 2H), 1.50 – 1.41 (m, 2H), 1.37 – 1.30 (m, 2H), 1.28 – 1.23 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H), 0.79 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.12, 143.15, 140.10, 138.02, 137.12, 134.19, 132.73, 131.37, 130.39, 128.79, 128.59, 128.15, 127.28, 127.19, 127.08, 126.78, 125.31, 122.77, 119.10, 64.29, 32.41, 30.96, 30.82, 22.07, 19.31, 13.89, 13.66. HRMS (ESI-TOF) calcd for $C_{27}H_{30}O_2S$ ($M+Na^+$): 441.1859, found: 441.1861. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 98/2, v = 0.5 mL·min^{-1}, λ = 254 nm, t (minor) = 16.4 min, t (major) = 15.4 min, 76% ee. $[\alpha]_D^{20}$ = -77.4 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(1-(2-(hexylthio)phenyl)naphthalen-2-yl)acrylate (2-8)



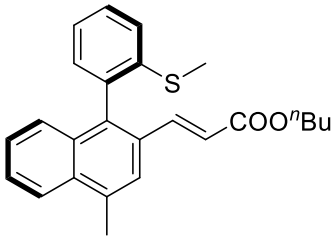
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(20.2 mg, 90%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (t, *J* = 9.0 Hz, 2H), 7.82 (d, *J* = 8.8 Hz, 1H), 7.57 – 7.39 (m, 4H), 7.39 – 7.26 (m, 3H), 7.14 (d, *J* = 7.5 Hz, 1H), 6.46 (d, *J* = 16.0 Hz, 1H), 4.10 (t, *J* = 6.5 Hz, 2H), 2.72 (td, *J* = 7.2, 2.3 Hz, 2H), 1.63 – 1.57 (m, 2H), 1.50 – 1.41 (m, 2H), 1.39 – 1.30 (m, 2H), 1.25 – 1.10 (m, 6H), 0.91 (t, *J* = 7.3 Hz, 3H), 0.82 (t, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.12, 143.15, 140.12, 138.03, 137.14, 134.20, 132.73, 131.38, 130.40, 128.80, 128.59, 128.16, 127.34, 127.20, 127.09, 126.78, 125.32, 122.77, 119.09, 64.30, 32.78, 31.40, 30.82, 28.87, 28.67, 22.62, 19.31, 14.12, 13.89. HRMS (ESI-TOF) calcd for $C_{29}H_{34}O_2S$ ($M+Na^+$): 469.2172, found: 469.2173. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 4.8 min, t (major) = 4.5 min, 63% ee. $[\alpha]_D^{20}$ = -33.0 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(1-(2-(isopropylthio)phenyl)naphthalen-2-yl)acrylate (2-9)



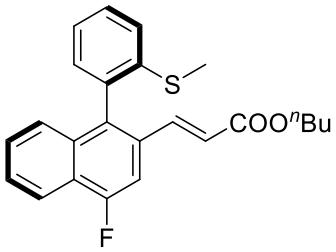
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.0 mg, 84%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 – 7.83 (m, 2H), 7.81 (d, *J* = 8.8 Hz, 1H), 7.53 (d, *J* = 7.6 Hz, 1H), 7.50 – 7.42 (m, 3H), 7.38 – 7.28 (m, 3H), 7.15 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.45 (d, *J* = 16.0 Hz, 1H), 4.15 – 4.03 (m, 2H), 3.43 – 3.28 (m, 1H), 1.62 – 1.54 (m, 2H), 1.38 – 1.27 (m, 3H), 1.16 – 1.08 (m, 6H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.10, 143.20, 140.35, 138.20, 137.39, 134.12, 132.82, 131.52, 130.20, 129.46, 128.72, 128.48, 128.12, 127.24, 127.03, 126.72, 125.83, 122.71, 119.00, 64.26, 36.74, 30.80, 23.06, 22.76, 19.28, 13.87. HRMS (ESI-TOF) calcd for $C_{26}H_{28}O_2S$ ($M+Na^+$): 427.1702, found: 427.1703. 手性 HPLC 分离条件：a Daicel Chiralpak IB, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 6.5 min, t (major) = 6.0 min, 23% ee. $[\alpha]_D^{20}$ = -43.7 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(4-methyl-1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-10)



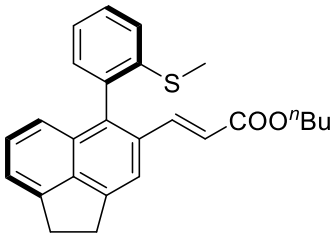
根据通用方法 C 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(18.4 mg, 94%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (d, *J* = 8.3 Hz, 1H), 7.59 – 7.53 (m, 1H), 7.52 – 7.46 (m, 2H), 7.46 – 7.39 (m, 2H), 7.37 – 7.32 (m, 2H), 7.28 (td, *J* = 7.4, 1.2 Hz, 1H), 7.12 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.42 (d, *J* = 15.9 Hz, 1H), 4.11 (t, *J* = 6.5 Hz, 2H), 2.31 (s, 3H), 1.64 – 1.58 (m, 2H), 1.41 – 1.29 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.20, 143.06, 139.39, 138.15, 135.94, 135.01, 133.64, 132.67, 131.28, 130.06, 128.88, 127.64, 127.04, 126.53, 124.80, 124.77, 124.45, 123.37, 118.99, 77.48, 77.16, 76.84, 64.29, 30.83, 19.91, 19.32, 15.56, 13.89. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_2S$ ($M+Na^+$): 413.1546, found: 413.1548. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 5.2 min, t (major) = 4.5 min, 97% ee. $[\alpha]_D^{20}$ = -129.5 (c = 0.8, $CHCl_3$).

butyl (*E*)-3-(4-fluoro-1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-11)



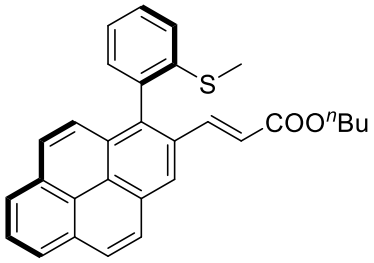
根据通用方法 C 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.8 mg, 90%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.13 (d, *J* = 8.3 Hz, 1H), 7.59 – 7.53 (m, 1H), 7.52 – 7.46 (m, 2H), 7.46 – 7.39 (m, 2H), 7.37 – 7.32 (m, 2H), 7.28 (td, *J* = 7.4, 1.2 Hz, 1H), 7.12 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.42 (d, *J* = 15.9 Hz, 1H), 4.11 (t, *J* = 6.5 Hz, 2H), 2.31 (s, 3H), 1.64 – 1.58 (m, 2H), 1.41 – 1.29 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.87, 158.90 (d, J_{CF} = 252.4 Hz), 142.13 (d, J_{CF} = 2.7 Hz), 139.54, 135.79 (d, J_{CF} = 3.8 Hz), 135.04, 134.11 (d, J_{CF} = 5.2 Hz), 131.34, 131.03 (d, J_{CF} = 8.2 Hz), 129.18, 127.87, 127.46 (d, J_{CF} = 1.7 Hz), 127.03 (d, J_{CF} = 3.0 Hz), 124.86, 120.92 (d, J_{CF} = 5.2 Hz), 119.93, 106.11 (d, J_{CF} = 21.1 Hz) , 64.44, 30.79, 19.30, 15.51, 13.87. ^{19}F NMR (376 MHz, $CDCl_3$) δ -122.60. HRMS (ESI-TOF) calcd for $C_{24}H_{23}FO_2S$ ($M+Na^+$): 417.1295, found: 417.1297. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL · min^{-1}, λ = 254 nm, t (minor) = 5.9 min, t (major) = 4.4 min, 97% ee. $[\alpha]_D^{20}$ = -132.9 (c = 0.7, $CHCl_3$).

butyl (*E*)-3-(5-(2-(methylthio)phenyl)-1,2-dihydroacenaphthylen-4-yl)acrylate (2-12)



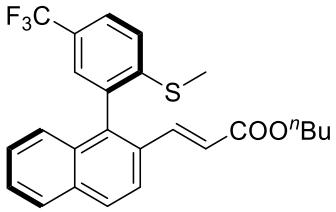
根据通用方法 C 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(19.1 mg, 95%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.66 (s, 1H), 7.55 (d, *J* = 16.0 Hz, 1H), 7.46 (td, *J* = 7.7, 1.5 Hz, 1H), 7.39 – 7.30 (m, 3H), 7.30 – 7.26 (m, 1H), 7.14 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.06 (d, *J* = 8.0 Hz, 1H), 6.48 (d, *J* = 15.9 Hz, 1H), 4.11 (t, *J* = 6.5 Hz, 2H), 3.45 (s, 4H), 2.31 (s, 3H), 1.66 – 1.59 (m, 2H), 1.40 – 1.31 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.29, 146.59, 145.97, 143.84, 140.16, 139.28, 135.94, 135.72, 132.21, 131.22, 130.85, 128.81, 128.75, 124.94, 124.79, 122.12, 121.00, 118.77, 116.13, 64.24, 30.82, 30.64, 30.30, 19.31, 15.67, 13.89. HRMS (ESI-TOF) calcd for $C_{26}H_{26}O_2S$ ($M+Na^+$): 425.1546, found: 425.1546. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 92/8, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 7.9 min, t (major) = 7.3 min, 96% ee. $[\alpha]_D^{20}$ = -107.2 (c = 0.8, $CHCl_3$).

butyl (*E*)-3-(1-(2-(methylthio)phenyl)pyren-2-yl)acrylate (2-13)



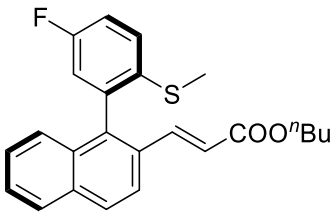
根据通用方法 C 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 =9/1 为展开剂)(20.7 mg, 92%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.54 (s, 1H), 8.18 (dd, *J* = 7.6, 1.2 Hz, 1H), 8.14 (dd, *J* = 7.7, 1.1 Hz, 1H), 8.10 (s, 2H), 8.00 (t, *J* = 7.6 Hz, 1H), 7.97 (d, *J* = 9.2 Hz, 1H), 7.71 (d, *J* = 16.0 Hz, 1H), 7.59 (d, *J* = 9.2 Hz, 1H), 7.57 – 7.51 (m, 1H), 7.42 (dd, *J* = 8.1, 1.2 Hz, 1H), 7.35 (td, *J* = 7.4, 1.2 Hz, 1H), 7.26 – 7.22 (m, 1H), 6.67 (d, *J* = 15.9 Hz, 1H), 4.15 (t, *J* = 6.5 Hz, 2H), 2.31 (s, 3H), 1.68 – 1.59 (m, 2H), 1.43 – 1.34 (m, 2H), 0.94 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.08, 143.72, 139.56, 136.28, 136.12, 131.69, 131.46, 131.33, 131.21, 131.10, 130.19, 129.09, 128.36, 128.26, 127.65, 126.73, 125.72, 125.69, 125.63, 125.60, 124.92, 124.89, 124.70, 122.31, 120.05, 64.39, 30.85, 19.34, 15.59, 13.91. HRMS (ESI-TOF) calcd for $C_{30}H_{26}O_2S$ ($M+Na^+$): 473.1546, found: 473.1545. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL · min^{-1}, λ = 254 nm, t (minor) = 6.4 min, t (major) = 5.6 min, 98% ee. $[\alpha]_D^{20}$ = +34.2 (c = 1.1, $CHCl_3$).

butyl(*E*)-3-(1-(2-(methylthio)-5-(trifluoromethyl)phenyl)naphthalen-2-yl)acrylate (2-14)



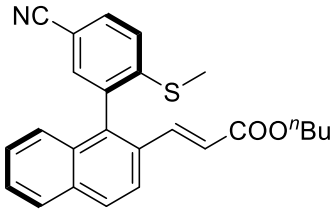
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(11.7 mg, 52%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (d, *J* = 8.8 Hz, 1H), 7.89 (d, *J* = 8.1 Hz, 2H), 7.84 (d, *J* = 8.7 Hz, 1H), 7.74 (dd, *J* = 8.7, 1.9 Hz, 1H), 7.56 – 7.50 (m, 1H), 7.46 – 7.34 (m, 4H), 7.26 (d, *J* = 8.3 Hz, 1H), 6.51 (d, *J* = 15.9 Hz, 1H), 4.12 (td, *J* = 6.5, 1.2 Hz, 2H), 2.36 (s, 3H), 1.65 – 1.59 (m, 2H), 1.40 – 1.31 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.92, 144.97, 142.11, 137.59, 135.78, 134.31, 132.21, 130.82, 129.40, 128.38, 127.59 (q, J_{CF} = 3.6 Hz), 126.85 (q, J_{CF} = 33.1 Hz), 125.76 (q, J_{CF} = 4.0 Hz), 124.35 (q, J_{CF} = 272.7 Hz), 127.39, 127.28, 126.44, 124.03, 122.83, 120.08, 64.43, 30.79, 19.30, 15.14, 13.83. ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.01. HRMS (ESI-TOF) calcd for $C_{25}H_{23}F_3O_2S$ ($M+Na^+$): 467.1263, found: 467.1265. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 7.2 min, t (major) = 6.4 min, 98% ee. $[\alpha]_D^{20}$ = -75.9 (c = 1.2, $CHCl_3$).

butyl (*E*)-3-(1-(5-fluoro-2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-15)



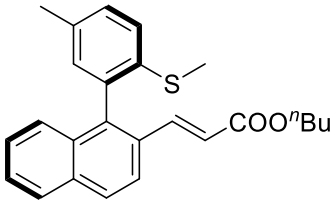
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(12.0 mg, 61%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 8.8 Hz, 1H), 7.88 (d, *J* = 8.2 Hz, 1H), 7.83 (d, *J* = 8.8 Hz, 1H), 7.55 – 7.49 (m, 1H), 7.46 (d, *J* = 15.9 Hz, 1H), 7.43 – 7.38 (m, 1H), 7.38 – 7.30 (m, 2H), 7.22 (td, *J* = 8.5, 2.8 Hz, 1H), 6.94 (dd, *J* = 8.8, 2.8 Hz, 1H), 6.50 (d, *J* = 15.9 Hz, 1H), 4.13 (t, *J* = 6.5 Hz, 2H), 2.27 (s, 3H), 1.67 – 1.59 (m, 2H), 1.41 – 1.31 (m, 2H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.02, 160.80 (d, J_{CF} = 246.4 Hz), 142.47, 138.32 (d, J_{CF} = 1.5 Hz), 138.18 (d, J_{CF} = 7.4 Hz), 134.47 (d, J_{CF} = 3.1 Hz), 127.58 (d, J_{CF} = 8.1 Hz), 134.22, 132.30, 130.47, 129.09, 128.29, 127.29, 127.11, 126.71, 122.76, 119.74, 118.38 (d, J_{CF} = 21.9 Hz), 116.13 (d, J_{CF} = 21.5 Hz), 64.42, 30.81, 19.32, 16.44, 13.86. ^{19}F NMR (376 MHz, $CDCl_3$) δ -117.99. HRMS (ESI-TOF) calcd for $C_{24}H_{23}FO_2S$ ($M+Na^+$): 417.1295, found: 417.1293. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 8.8 min, t (major) = 7.4 min, 98% ee. $[\alpha]_D^{20}$ = -90.7 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(1-(5-cyano-2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-16)



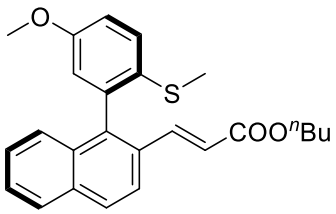
根据通用方法 C 反应 72 小时后经过制备级 TLC 分离得到淡黄无色液体(石油醚/乙酸乙酯 = 4/1 为展开剂)(13.1 mg, 65%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 (d, *J* = 8.7 Hz, 1H), 7.89 (d, *J* = 8.1 Hz, 1H), 7.83 (d, *J* = 8.8 Hz, 1H), 7.76 (dd, *J* = 8.3, 1.9 Hz, 1H), 7.57 – 7.48 (m, 1H), 7.45 – 7.31 (m, 4H), 7.22 (d, *J* = 8.4 Hz, 1H), 6.51 (d, *J* = 15.9 Hz, 1H), 4.14 (td, *J* = 6.6, 1.1 Hz, 2H), 2.35 (s, 3H), 1.68 – 1.60 (m, 2H), 1.43 – 1.31 (m, 2H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.84, 147.30, 141.77, 136.45, 136.17, 134.26, 133.82, 132.35, 131.94, 129.65, 128.44, 127.48, 127.39, 126.11, 123.99, 122.83, 120.34, 107.90, 64.51, 30.76, 19.30, 14.93. HRMS (ESI-TOF) calcd for $C_{25}H_{23}NO_2S$ ($M+Na^+$): 424.1342, found: 424.1342. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 75/25, v = 1.4 mL · min^{-1}, λ = 254 nm, t (minor) = 40.1 min, t (major) = 46.7 min, 98% ee. $[\alpha]_D^{20}$ = -20.0 (c = 1.1, $CHCl_3$).

butyl (*E*)-3-(1-(5-methyl-2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-17)



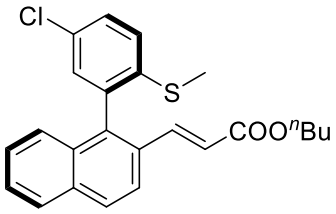
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(16.6 mg, 85%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 – 7.81 (m, 3H), 7.56 – 7.46 (m, 2H), 7.42 – 7.35 (m, 2H), 7.29 (s, 2H), 6.98 (s, 1H), 6.50 (d, *J* = 16.0 Hz, 1H), 4.13 (t, *J* = 6.5 Hz, 2H), 2.38 (s, 3H), 2.27 (s, 3H), 1.62 (dd, *J* = 8.1, 7.0 Hz, 2H), 1.38 (dt, *J* = 14.8, 7.4 Hz, 2H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.10, 135.97, 135.50, 134.70, 134.21, 131.74, 130.37, 129.78, 128.57, 128.13, 127.13, 127.10, 126.78, 125.61, 122.68, 119.03, 64.27, 30.79, 20.98, 15.98, 13.87. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_2S$ ($M+Na^+$): 413.1546, found: 413.1547. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 7.8 min, t (major) = 6.2 min, 97% ee. $[\alpha]_D^{20}$ = -46.5 (c = 0.9, $CHCl_3$).

butyl (*E*)-3-(1-(5-methoxy-2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-18)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 4/1 为展开剂)(17.3 mg, 85%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 – 7.81 (m, 3H), 7.56 – 7.46 (m, 2H), 7.42 – 7.35 (m, 2H), 7.29 (d, *J* = 0.9 Hz, 2H), 6.98 (d, *J* = 1.3 Hz, 1H), 6.50 (d, *J* = 16.0 Hz, 1H), 4.13 (t, *J* = 6.5 Hz, 2H), 2.38 (s, 3H), 2.27 (s, 3H), 1.62 (m, *J* = 8.0, 6.5 Hz, 2H), 1.42 – 1.32 (m, 2H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.11, 157.87, 142.97, 139.86, 138.46, 134.15, 132.57, 130.24, 129.63, 129.02, 128.64, 128.15, 127.14, 127.12, 126.87, 122.66, 119.20, 116.72, 115.05, 64.31, 55.54, 30.79, 19.29, 17.23, 13.87. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_3S$ ($M+Na^+$): 429.1495, found: 429.1495. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 9.9 min, t (major) = 7.7 min, 97% ee. $[\alpha]_D^{20}$ = -26.2 (c = 0.9, $CHCl_3$).

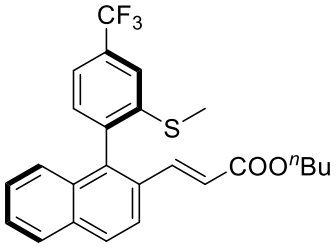
butyl (*E*)-3-(1-(5-chloro-2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-19)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.1 mg, 83%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 8.8 Hz, 1H), 7.88 (d, *J* = 8.1 Hz, 1H), 7.83 (d, *J* = 8.8 Hz, 1H), 7.55 – 7.49 (m, 1H), 7.49 – 7.43 (m, 2H), 7.43 – 7.38 (m, 1H), 7.33 (d, *J* = 8.4 Hz, 1H), 7.28 (d, *J* = 8.6 Hz, 1H), 7.17 (d, *J* = 2.3 Hz, 1H), 6.51 (d, *J* = 15.9 Hz, 1H), 4.14 (t, *J* = 6.5 Hz, 2H), 2.29 (s, 3H), 1.68 – 1.60 (m, 2H), 1.43 – 1.32 (m, 2H), 0.94

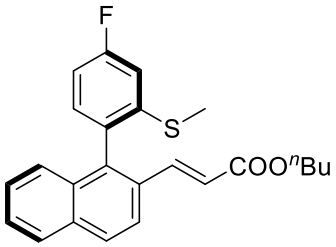
(t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.00, 142.39, 138.16, 137.94, 137.27, 134.22, 132.24, 130.83, 130.69, 130.56, 129.16, 129.05, 128.28, 127.31, 127.14, 126.64, 126.04, 122.72, 119.77, 64.41, 30.79, 19.31, 15.65, 13.88. HRMS (ESI-TOF) calcd for $C_{24}H_{23}ClO_2S$ ($M+Na^+$): 433.0999, found: 433.0999. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 6.9 min, t (major) = 5.9 min, 98% ee. $[\alpha]_D^{20}$ = -28.3 (c = 1.4, $CHCl_3$).

butyl(*E*)-3-(1-(2-(methylthio)-4-(trifluoromethyl)phenyl)naphthalen-2-yl)acrylate (2-20)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.3 mg, 78%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 (d, *J* = 8.8 Hz, 1H), 7.89 (d, *J* = 8.1 Hz, 2H), 7.84 (d, *J* = 8.8 Hz, 1H), 7.59 – 7.48 (m, 3H), 7.42 – 7.35 (m, 2H), 7.27 (t, *J* = 8.3 Hz, 2H), 6.51 (d, *J* = 15.9 Hz, 1H), 4.13 (t, *J* = 6.5 Hz, 2H), 2.35 (s, 3H), 1.65 – 1.59 (m, 2H), 1.40 – 1.29 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.96, 142.15, 141.38, 139.21, 137.84, 134.25, 132.06, 131.46, 131.40 (q, J_{CF} = 32.4 Hz), 130.53, 129.33, 128.36, 127.40, 127.22, 126.50, 124.18 (q, J_{CF} = 275.6 Hz), 122.80, 121.43 (q, J_{CF} = 3.7 Hz), 120.95 (q, J_{CF} = 3.7 Hz), 119.99, 64.45, 30.77, 19.29, 15.26, 13.77. ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.57. HRMS (ESI-TOF) calcd for $C_{25}H_{23}F_3O_2S$ ($M+Na^+$): 467.1263, found: 467.1264. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 6.4 min, t (major) = 5.8 min, 95% ee. $[\alpha]_D^{20}$ = -97.4 (c = 1.2, $CHCl_3$).

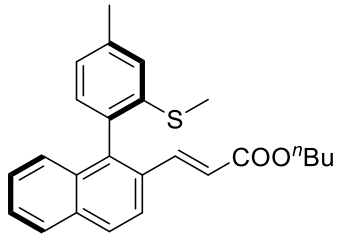
butyl (*E*)-3-(1-(4-fluoro-2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-21)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(12.0 mg, 61%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 – 7.85 (m, 2H), 7.83 (d, *J* = 8.8 Hz, 1H), 7.55 – 7.44 (m, 2H), 7.43 – 7.37 (m, 1H), 7.34 (d, *J* = 8.4 Hz, 1H), 7.11 (dd, *J* = 8.3, 5.9 Hz, 1H), 7.05 (dd, *J* = 9.8, 2.5 Hz, 1H), 6.99 (td, *J* = 8.3, 2.5 Hz, 1H), 6.49 (d, *J* = 16.0 Hz, 1H), 4.14 (t, *J* = 6.5 Hz, 2H), 2.30 (s, 3H), 1.68 – 1.60 (m, 2H), 1.43 – 1.31 (m, 2H), 0.94 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ164.55, 163.32 (d, J_{CF} = 248.3 Hz), 162.09, 142.65, 142.14 (d, J_{CF} = 8.0 Hz), 138.38, 134.27, 132.67, 132.41 (d, J_{CF} = 8.6 Hz), 131.11 (d, J_{CF} = 3.4 Hz), 130.96, 129.01, 128.27, 127.24, 127.01, 126.77, 122.81, 119.54, 111.67, 111.44 (d, J_{CF} = 3.0 Hz), 64.39, 30.82, 19.32, 15.35, 13.84. ^{19}F NMR (376 MHz,

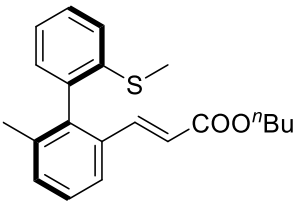
$CDCl_3$) δ -112.87. HRMS (ESI-TOF) calcd for $C_{25}H_{23}F_3O_2S$ ($M+Na^+$): 417.1295, found: 417.1297. 手性 HPLC 分离条件：a Daicel Chiralpak AD, *n*-hexane/2-propanol = 95/5, v = 0.5 mL·min^{-1}, λ = 254 nm, t (minor) = 12.9 min, t (major) = 11.8 min, 95% ee. $[\alpha]_D^{20}$ = -84.4 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(1-(4-methyl-2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-22)



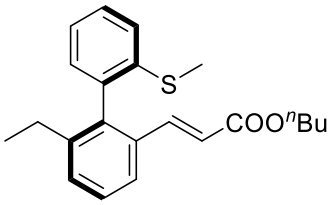
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(18.8 mg, 96%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 – 7.78 (m, 3H), 7.56 – 7.44 (m, 2H), 7.42 – 7.32 (m, 2H), 7.17 (s, 1H), 7.10 (dd, J = 7.6, 1.6 Hz, 1H), 7.03 (d, J = 7.6 Hz, 1H), 6.50 (d, J = 16.0 Hz, 1H), 4.13 (t, J = 6.5 Hz, 2H), 2.49 (s, 3H), 2.30 (s, 3H), 1.69 – 1.58 (m, 2H), 1.45 – 1.33 (m, 2H), 0.93 (t, J = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.22, 143.18, 139.79, 138.68, 134.20, 132.76, 132.73, 130.91, 130.61, 128.58, 128.14, 127.12, 127.10, 126.77, 125.72, 125.52, 122.72, 118.96, 64.27, 30.78, 21.67, 19.28, 15.56, 13.87. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_2S$ ($M+Na^+$): 413.1546, found: 413.1548. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 8.8 min, t (major) = 7.9 min, 96% ee. $[\alpha]_D^{20}$ = -90.4 (c = 1.1, $CHCl_3$).

butyl (*E*)-3-(6-methyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-23)



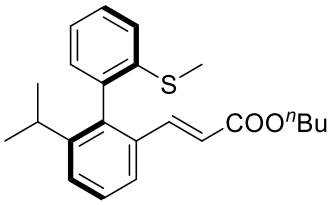
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(15.0 mg, 88%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (dd, *J* = 6.2, 3.1 Hz, 1H), 7.38 (td, *J* = 7.7, 1.5 Hz, 1H), 7.35 – 7.30 (m, 2H), 7.28 (d, *J* = 5.1 Hz, 1H), 7.26 – 7.24 (m, 1H), 7.21 (td, *J* = 7.4, 1.2 Hz, 1H), 7.01 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.30 (d, *J* = 16.0 Hz, 1H), 4.07 (t, *J* = 6.5 Hz, 2H), 2.35 (s, 3H), 2.03 (s, 3H), 1.62 – 1.57 (m, 2H), 1.36 – 1.28 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.11, 143.30, 140.75, 138.10, 137.72, 136.98, 133.49, 131.70, 129.82, 128.54, 128.20, 124.88, 124.45, 123.69, 118.94, 64.23, 30.77, 19.28, 15.24, 13.88. HRMS (ESI-TOF) calcd for $C_{21}H_{24}O_2S$ ($M+Na^+$): 363.1389, found: 363.1390. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 7.5 min, t (major) = 5.0 min, 98% ee. $[\alpha]_D^{20}$ = -82.3 (c =1.1, $CHCl_3$).

butyl (*E*)-3-(6-ethyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-24)



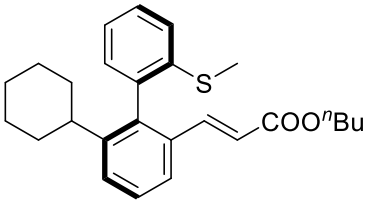
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(15.9 mg, 90%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (dd, *J* = 6.5, 2.6 Hz, 1H), 7.43 – 7.34 (m, 3H), 7.28 – 7.26 (m, 1H), 7.25 – 7.18 (m, 2H), 7.03 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.30 (d, *J* = 15.9 Hz, 1H), 4.06 (t, *J* = 6.5 Hz, 2H), 2.45 – 2.21 (m, 5H), 1.62 – 1.57 (m, 2H), 1.36 – 1.28 (m, 2H), 1.07 (t, *J* = 7.6 Hz, 3H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.12, 143.56, 143.48, 140.15, 138.49, 136.71, 133.57, 130.28, 130.04, 128.55, 128.44, 124.64, 124.41, 123.70, 118.92, 64.22, 30.80, 26.44, 19.29, 15.33, 15.08, 13.88. HRMS (ESI-TOF) calcd for $C_{22}H_{26}O_2S$ ($M+Na^+$): 377.1546, found: 377.1549. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 9.1 min, t (major) = 4.8 min, 97% ee. $[\alpha]_D^{20}$ = -91.0 (c = 0.7, $CHCl_3$).

butyl (*E*)-3-(6-isopropyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-25)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(14.4 mg, 78%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.57 (dd, *J* = 6.9, 2.1 Hz, 1H), 7.45 – 7.36 (m, 3H), 7.28 – 7.25 (m, 1H), 7.24 – 7.17 (m, 2H), 7.02 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.28 (d, *J* = 15.9 Hz, 1H), 4.06 (t, *J* = 6.5 Hz, 2H), 2.63 – 2.51 (m, 1H), 2.35 (s, 3H), 1.58 – 1.51 (m, 2H), 1.37 – 1.27 (m, 2H), 1.19 (d, *J* = 6.9 Hz, 3H), 1.04 (d, *J* = 6.8 Hz, 3H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.13, 148.43, 143.69, 139.36, 136.67, 133.44, 130.27, 128.62, 128.50, 127.47, 124.53, 124.27, 123.63, 118.82, 64.19, 30.77, 30.39, 24.80, 23.52, 19.28, 15.33, 13.89. HRMS (ESI-TOF) calcd for $C_{23}H_{28}O_2S$ ($M+Na^+$): 391.1702, found: 391.1705. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 7.2 min, t (major) = 4.2 min, 95% ee. $[\alpha]_D^{20}$ = -62.8 (c = 0.6, $CHCl_3$).

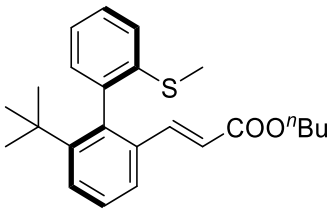
butyl (*E*)-3-(6-cyclohexyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-26)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(14.5 mg, 71%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (dd, *J* = 6.3, 2.7 Hz, 1H), 7.43 – 7.36 (m, 3H), 7.27 (d, *J* = 1.2 Hz, 1H), 7.25 – 7.16 (m, 2H), 6.99 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.27 (d, *J* = 15.9 Hz, 1H), 4.06 (t, *J* = 6.5 Hz, 2H), 2.35 (s, 3H), 2.19 – 2.09 (m, 1H), 1.84 (d, *J* = 12.6 Hz, 1H), 1.72 (d, *J* = 11.7 Hz, 1H), 1.68 – 1.50 (m, 6H), 1.45 (td, *J* = 12.4, 3.4 Hz, 1H),

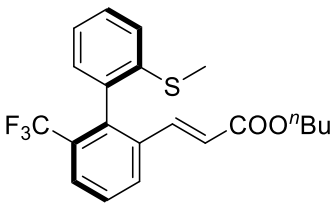
1.35 – 1.23 (m, 3H), 1.21 – 1.06 (m, 2H), 1.06 – 0.96 (m, 1H), 0.89 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ167.13, 147.42, 143.78, 139.67, 138.67, 136.73, 133.42, 130.19, 128.46, 128.44, 128.21, 124.55, 124.39, 123.57, 118.73, 64.18, 41.09, 35.30, 33.61, 30.77, 26.92, 26.90, 26.22, 19.28, 15.48, 13.89. HRMS (ESI-TOF) calcd for $C_{26}H_{32}O_2S$ ($M+Na^+$): 431.2015, found: 431.2016. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 8.0 min, t (major) = 4.3 min, 96% ee. $[\alpha]_D^{20}$ = -51.8 (c = 0.7, $CHCl_3$).

butyl (*E*)-3-(6-(tert-butyl)-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-27)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(13.0 mg, 68%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.64 (dd, J = 8.2, 1.2 Hz, 1H), 7.55 (dd, J = 7.8, 1.2 Hz, 1H), 7.41 – 7.33 (m, 2H), 7.23 – 7.15 (m, 2H), 7.13 – 7.05 (m, 2H), 6.22 (d, J = 15.9 Hz, 1H), 4.04 (td, J = 6.5, 1.7 Hz, 2H), 2.35 (s, 3H), 1.57 – 1.49 (m, 2H), 1.33 – 1.25 (m, 2H), 1.17 (s, 9H), 0.90 (t, J = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.07, 149.01, 144.25, 139.85, 139.21, 139.09, 135.21, 131.22, 129.74, 128.49, 128.18, 124.17, 123.99, 119.03, 64.11, 37.19, 32.37, 30.75, 19.27, 15.38, 13.89. HRMS (ESI-TOF) calcd for $C_{24}H_{30}O_2S$ ($M+Na^+$): 405.1859, found: 405.1861. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 5.2 min, t (major) = 4.0 min, 89% ee. $[\alpha]_D^{20}$ = -79.4 (c = 1.1, $CHCl_3$).

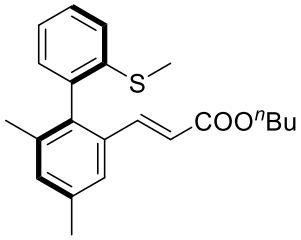
butyl (*E*)-3-(2'-(methylthio)-6-(trifluoromethyl)-[1,1'-biphenyl]-2-yl)acrylate (2-28)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(11.7 mg, 59%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, *J* = 7.9 Hz, 1H), 7.80 (d, *J* = 7.9 Hz, 1H), 7.54 (t, *J* = 7.9 Hz, 1H), 7.46 – 7.37 (m, 1H), 7.30 (d, *J* = 7.9 Hz, 1H), 7.25 – 7.16 (m, 2H), 7.09 (d, *J* = 7.6 Hz, 1H), 6.35 (d, *J* = 16.0 Hz, 1H), 4.08 (td, *J* = 6.5, 2.9 Hz, 2H), 2.37 (s, 3H), 1.61 – 1.57 (m, 2H), 1.36 – 1.28 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.54, 141.50, 139.34 (q, J_{CF} = 1.6 Hz), 138.82, 135.90, 134.48, 130.28 (q, J_{CF} = 29.6 Hz), 130.26, 130.25, 129.40, 129.31, 128.45, 127.69 (q, J_{CF} = 5.2 Hz), 125.27, 124.60, 123.75 (q, J_{CF} = 274.6 Hz), 120.90, 64.46, 30.73, 19.26, 15.93, 13.85. ^{19}F NMR (376 MHz, $CDCl_3$) δ -59.13. HRMS (ESI-TOF) calcd for $C_{21}H_{21}F_3O_2S$ ($M+Na^+$): 417.1107, found: 417.1107. 手性

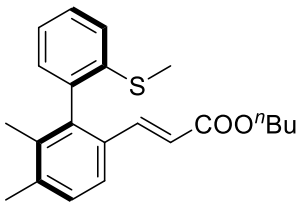
HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 5.8 min, t (major) = 5.3 min, 97% ee. $[\alpha]_D^{20}$ = -107.7 (c = 0.7, $CHCl_3$).

butyl (*E*)-3-(4,6-dimethyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-29)



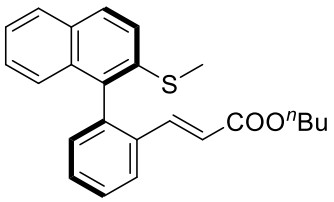
根据通用方法 C 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.6 mg, 99%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.41 (s, 1H), 7.37 (td, *J* = 7.7, 1.5 Hz, 1H), 7.27 (s, 1H), 7.25 – 7.22 (m, 1H), 7.20 (td, *J* = 7.4, 1.2 Hz, 1H), 7.15 (s, 1H), 6.99 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.30 (d, *J* = 15.9 Hz, 1H), 4.06 (t, *J* = 6.5 Hz, 2H), 2.39 (s, 3H), 2.35 (s, 3H), 2.00 (s, 3H), 1.58 – 1.53 (m, 2H), 1.37 – 1.28 (m, 2H), 0.89 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.17, 143.43, 138.33, 138.07, 137.77, 137.50, 137.07, 133.32, 132.76, 130.09, 128.45, 124.85, 124.42, 124.29, 118.70, 64.19, 30.80, 21.41, 20.18, 19.29, 15.26, 13.87. HRMS (ESI-TOF) calcd for $C_{22}H_{26}O_2S$ ($M+Na^+$): 377.1546, found: 377.1547. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 5.7 min, t (major) = 4.9 min, 97% ee. $[\alpha]_D^{20}$ = -97.9 (c = 0.9, $CHCl_3$).

butyl (*E*)-3-(5,6-dimethyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-30)



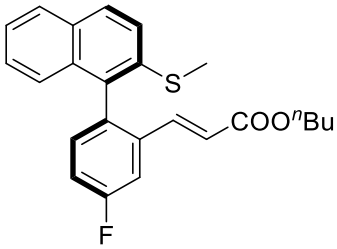
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(14.0 mg, 79%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.51 (d, *J* = 8.0 Hz, 1H), 7.38 (td, *J* = 7.7, 1.5 Hz, 1H), 7.28 – 7.25 (m, 1H), 7.24 – 7.17 (m, 3H), 6.99 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.26 (d, *J* = 15.9 Hz, 1H), 4.06 (t, *J* = 6.5 Hz, 2H), 2.35 (s, 6H), 1.93 (s, 3H), 1.57 – 1.51 (m, 2H), 1.34 – 1.28 (m, 2H), 0.89 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.28, 143.68, 140.79, 139.36, 138.33, 137.67, 136.07, 131.26, 130.05, 129.90, 128.41, 124.81, 124.42, 123.40, 117.86, 64.13, 30.80, 20.94, 19.28, 16.68, 15.27, 13.87. HRMS (ESI-TOF) calcd for $C_{22}H_{26}O_2S$ ($M+Na^+$): 377.1546, found: 377.1546. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 5.0 min, t (major) = 4.5 min, 96% ee. $[\alpha]_D^{20}$ = -87.3 (c = 1.1, $CHCl_3$).

butyl (*E*)-3-(2-(2-(methylthio)naphthalen-1-yl)phenyl)acrylate (2-31)



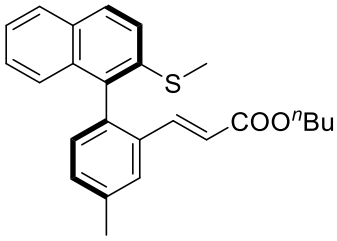
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(11.1 mg, 59%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 – 7.79 (m, 3H), 7.58 – 7.47 (m, 3H), 7.44 – 7.37 (m, 1H), 7.35 – 7.29 (m, 1H), 7.27 – 7.24 (m, 1H), 7.19 (d, *J* = 16.0 Hz, 1H), 7.13 (d, *J* = 8.4 Hz, 1H), 6.37 (d, *J* = 16.0 Hz, 1H), 4.00 (t, *J* = 6.5 Hz, 2H), 2.45 (s, 3H), 1.55 – 1.44 (m, 2H), 1.30 – 1.19 (m, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.94, 142.43, 139.50, 135.57, 134.15, 134.12, 132.96, 131.70, 131.27, 130.42, 128.92, 128.64, 128.16, 126.98, 126.44, 125.28, 125.24, 123.05, 119.25 , 64.21, 30.66, 19.19, 16.11, 13.81. HRMS (ESI-TOF) calcd for $C_{24}H_{24}O_2S$ ($M+Na^+$): 399.1389, found: 399.1390. 手性 HPLC 分离条件：a Daicel Chiralpak AD, *n*-hexane/2-propanol = 90/10, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 5.7 min, t (major) = 6.2 min, 98% ee. $[\alpha]_D^{20}$ = +23.7 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(5-fluoro-2-(2-(methylthio)naphthalen-1-yl)phenyl)acrylate (2-32)



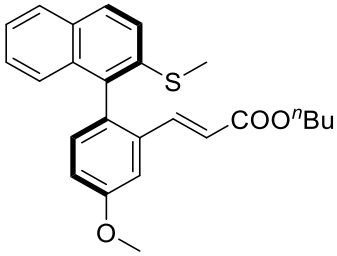
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(13.1 mg, 66%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 (d, *J* = 8.7 Hz, 1H), 7.85 (d, *J* = 8.0 Hz, 1H), 7.54 (dd, *J* = 9.9, 2.3 Hz, 1H), 7.48 (d, *J* = 8.8 Hz, 1H), 7.44 – 7.38 (m, 1H), 7.36 – 7.30 (m, 1H), 7.26 – 7.19 (m, 2H), 7.16 – 7.03 (m, 2H), 6.35 (d, *J* = 16.0 Hz, 1H), 4.00 (t, *J* = 6.5 Hz, 2H), 2.46 (s, 3H), 1.56 – 1.45 (m, 2H), 1.30 – 1.21 (m, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 117.67 (d, J_{CF} = 21.6 Hz), 112.93 (d, J_{CF} = 22.3 Hz) 166.58, 162.75 (d, J_{CF} = 247.3 Hz), 141.36, 141.34, 136.25 (d, J_{CF} = 7.7 Hz), 136.02, 135.31 (d, J_{CF} = 3.1 Hz), 133.46 (d, J_{CF} = 8.1 Hz), 133.04 (d, J_{CF} = 10.0 Hz), 131.27, 129.17, 128.25, 127.14, 125.31, 125.02, 122.92, 120.45, 64.39, 30.63, 19.18, 16.04, 13.80. ^{19}F NMR (376 MHz, $CDCl_3$) δ -113.09. HRMS (ESI-TOF) calcd for $C_{24}H_{23}FO_2S$ ($M+Na^+$): 417.1295, found: 417.1296. 手性 HPLC 分离条件：a Daicel Chiralpak AD, *n*-hexane/2-propanol = 95/5, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 8.6 min, t (major) = 9.5 min, 98% ee. $[\alpha]_D^{20}$ = +28.5 (c = 1.1, $CHCl_3$).

butyl (*E*)-3-(2-(2-(methylthio)naphthalen-1-yl)phenyl)acrylate (2-33)



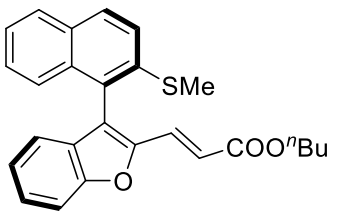
根据通用方法 C 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.6 mg, 90%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, *J* = 8.7 Hz, 1H), 7.84 (d, *J* = 8.0 Hz, 1H), 7.69 (s, 1H), 7.49 (d, *J* = 8.8 Hz, 1H), 7.43 – 7.38 (m, 1H), 7.36 (dd, *J* = 7.8, 1.7 Hz, 1H), 7.34 – 7.29 (m, 1H), 7.22 – 7.07 (m, 3H), 6.37 (d, *J* = 16.0 Hz, 1H), 4.01 (t, *J* = 6.5 Hz, 2H), 2.50 (s, 3H), 2.46 (s, 3H), 1.57 – 1.46 (m, 2H), 1.30 – 1.21 (m, 2H), 0.85 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.99, 142.57, 138.30, 136.63, 135.65, 134.13, 133.83, 133.12, 131.51, 131.44, 131.25, 128.79, 128.12, 126.99, 126.88, 125.33, 125.16, 122.95, 118.92, 64.15, 30.66, 21.58, 19.18, 16.07, 13.80. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_2S$ ($M+Na^+$): 413.1546, found: 413.1547. 手性 HPLC 分离条件：a Daicel Chiralpak AD, *n*-hexane/2-propanol = 85/15, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 8.2 min, t (major) = 4.8 min, 96% ee. $[\alpha]_D^{20}$ = +26.8 (c = 0.9, $CHCl_3$).

butyl (*E*)-3-(5-methoxy-2-(2-(methylthio)naphthalen-1-yl)phenyl)acrylate (2-34)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(18.1 mg, 89%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (d, *J* = 8.8 Hz, 1H), 7.84 (d, *J* = 8.0 Hz, 1H), 7.48 (d, *J* = 8.7 Hz, 1H), 7.42 – 7.37 (m, 1H), 7.36 (d, *J* = 2.6 Hz, 1H), 7.35 – 7.29 (m, 1H), 7.22 – 7.04 (m, 4H), 6.35 (d, *J* = 15.9 Hz, 1H), 4.00 (t, *J* = 6.5 Hz, 2H), 3.93 (s, 3H), 2.45 (s, 3H), 1.56 – 1.46 (m, 2H), 1.27 – 1.18 (m, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.87, 159.59, 142.50, 136.11, 135.15, 133.72, 133.38, 132.75, 131.95, 131.23, 128.83, 128.13, 126.91, 125.30, 125.13, 122.77, 119.30, 116.83, 110.76, 64.24, 55.48, 30.64, 19.17, 16.01, 13.80. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_3S$ ($M+Na^+$): 429.1495, found: 429.1493. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.3 mL·min^{-1}, λ = 254 nm, t (minor) = 5.7 min, t (major) = 6.2 min, 98% ee. $[\alpha]_D^{20}$ = +22.3 (c = 1.1, $CHCl_3$).

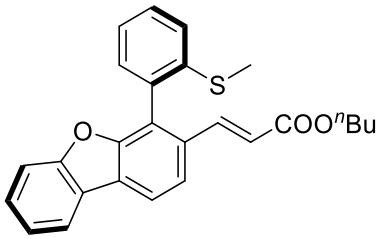
butyl (*E*)-3-(3-(2-(methylthio)naphthalen-1-yl)benzofuran-2-yl)acrylate (2-35)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(11.0 mg, 53%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, *J* = 8.8 Hz, 1H), 7.88 (d, *J* = 8.1 Hz, 1H), 7.59 (d, *J* = 8.3 Hz, 1H), 7.54 (d, *J* = 8.8 Hz, 1H), 7.49 – 7.38 (m, 2H), 7.34

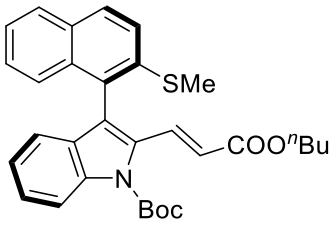
(t, *J* = 4.3 Hz, 2H), 7.23 – 7.04 (m, 3H), 6.63 (d, *J* = 15.7 Hz, 1H), 4.12 (t, *J* = 6.7 Hz, 2H), 2.45 (s, 3H), 1.66 – 1.59 (m, 2H), 1.41 – 1.32 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.97, 155.35, 150.33, 137.78, 133.34, 131.33, 130.23, 129.75, 129.28, 128.31, 127.32, 126.91, 125.45, 125.10, 124.58, 123.51, 123.28, 121.89, 121.46, 119.34, 111.73, 64.62, 30.82, 19.27, 16.17, 13.84. HRMS (ESI-TOF) calcd for $C_{26}H_{24}O_3S$ ($M+Na^+$): 439.1338, found: 439.1339. 手性 HPLC 分离条件：a Daicel Chiralpak IB, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 6.6 min, t (major) = 5.4 min, 96% ee. $[\alpha]_D^{20}$ = -17.6 (c = 0.6, $CHCl_3$).

butyl (*E*)-3-(4-(2-(methylthio)phenyl)dibenzo[b,d]furan-3-yl)acrylate (2-36)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(15.2 mg, 73%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.04 – 7.91 (m, 2H), 7.79 (d, *J* = 8.2 Hz, 1H), 7.57 – 7.47 (m, 3H), 7.47 – 7.39 (m, 2H), 7.38 – 7.29 (m, 2H), 7.28 – 7.26 (m, 1H), 6.47 (d, *J* = 15.9 Hz, 1H), 4.12 (t, *J* = 6.6 Hz, 2H), 2.35 (s, 3H), 1.68 – 1.60 (m, 2H), 1.44 – 1.31 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.07, 157.10, 154.51, 142.40, 139.14, 132.57, 132.35, 131.05, 129.45, 127.89, 125.89, 125.75, 125.69, 125.14, 124.12, 123.11, 121.02, 121.01, 120.39, 119.27, 112.26, 64.36, 30.82, 19.31, 15.96, 13.88. HRMS (ESI-TOF) calcd for $C_{26}H_{24}O_3S$ ($M+Na^+$): 439.1338, found: 439.1339. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 8.6 min, t (major) = 7.4 min, 93% ee. $[\alpha]_D^{20}$ = -57.4 (c = 1.3, $CHCl_3$).

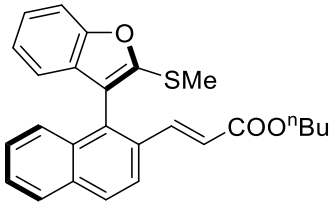
***tert*-butyl(*E*)-2-(3-butoxy-3-oxoprop-1-en-1-yl)-3-(2-(methylthio)naphthalen-1-yl)-1H-indole-1-carboxylate (2-37)**



根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/二氯甲烷 = 1/1 为展开剂)(12.6 mg, 49%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.27 (d, *J* = 8.5 Hz, 1H), 8.11 (d, *J* = 16.0 Hz, 1H), 7.93 (d, *J* = 8.8 Hz, 1H), 7.86 (d, *J* = 8.1 Hz, 1H), 7.52 (d, *J* = 8.8 Hz, 1H), 7.43 – 7.29 (m, 4H), 7.13 (t, *J* = 7.5 Hz, 1H), 6.91 (d, *J* = 7.8 Hz, 1H), 5.46 (d, *J* = 16.0 Hz, 1H), 3.98 (t, *J* = 6.8 Hz, 2H), 2.44 (s, 3H), 1.73 (s, 9H), 1.53 – 1.47 (m, 2H), 1.30 (d, *J* = 7.5 Hz, 2H), 0.86 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.79, 137.03, 136.94, 135.14, 132.93, 132.83, 132.42, 131.44, 129.70, 129.30, 128.33, 127.25, 126.21, 125.37, 125.09, 123.53, 123.21, 121.34, 120.53, 120.42, 115.88, 85.08, 64.33, 30.73, 28.40, 19.19, 15.92, 13.82. HRMS (ESI-

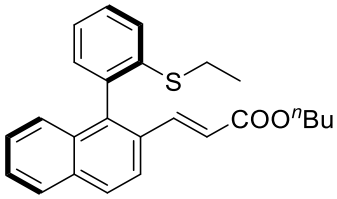
TOF) calcd for $C_{31}H_{33}NO_4S$ ($M+Na^+$): 538.2023, found: 538.2023. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 4.99 min, t (major) = 4.0 min, 93% ee. $[\alpha]_D^{20}$ = -22.1 (c = 0.8, $CHCl_3$).

butyl (E)-3-(1-(2-(methylthio)benzofuran-3-yl)naphthalen-2-yl)acrylate (2-38)



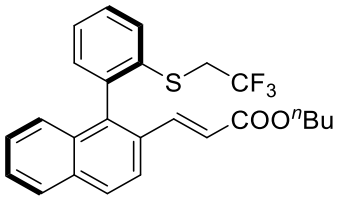
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/二氯甲烷 =9/1 为展开剂)(3.6 mg, 17%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.01 – 7.90 (m, 3H), 7.73 (d, *J* = 15.9 Hz, 1H), 7.63 – 7.53 (m, 3H), 7.45 – 7.34 (m, 2H), 7.19 (t, *J* = 7.6 Hz, 1H), 7.03 (d, *J* = 7.8 Hz, 1H), 6.70 – 6.48 (m, 1H), 4.15 (t, *J* = 6.5 Hz, 2H), 2.50 (s, 3H), 1.65 – 1.63 (m, 2H), 1.40 – 1.33 (m, 2H), 0.94 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.09, 155.80, 150.52, 146.44, 142.99, 134.33, 131.79, 130.66, 129.26, 128.69, 128.38, 127.30, 127.11, 127.04, 124.95, 123.40, 123.14, 120.28, 119.76, 111.22, 64.45, 30.82, 19.28, 16.51, 13.84. HRMS (ESI-TOF) calcd for $C_{26}H_{24}O_3S$ ($M+Na^+$): 439.1338, found: 439.1340. 手性 HPLC 分离条件：a Daicel Chiralpak IB, *n*-hexane/2-propanol = 96/4, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 7.3 min, t (major) = 6.8 min, 92% ee. $[\alpha]_D^{20}$ = -22.0 (c = 0.5, $CHCl_3$).

butyl (*E*)-3-(1-(2-(ethylthio)phenyl)naphthalen-2-yl)acrylate (2-39)



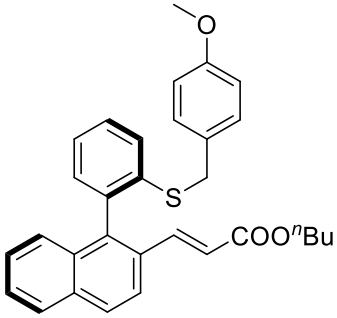
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(19.3 mg, 99%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 – 7.85 (m, 2H), 7.82 (d, *J* = 8.7 Hz, 1H), 7.54 – 7.42 (m, 4H), 7.40 – 7.32 (m, 2H), 7.32 – 7.27 (m, 1H), 7.15 (dt, *J* = 7.6, 1.0 Hz, 1H), 6.47 (d, *J* = 16.0 Hz, 1H), 4.11 (td, *J* = 6.6, 1.1 Hz, 2H), 2.86 – 2.69 (m, 2H), 1.64 – 1.58 (m, 2H), 1.40 – 1.29 (m, 2H), 1.16 (t, *J* = 7.3 Hz, 3H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.13, 143.09, 140.00, 137.72, 136.97, 134.18, 132.69, 131.39, 130.36, 128.79, 128.61, 128.16, 127.14, 127.10, 126.95, 126.80, 125.29, 122.75, 119.13, 64.29, 30.80, 26.57, 19.29, 13.99, 13.88. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_2S$ ($M+Na^+$): 413.1546, found: 413.1546. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 8.4 min, t (major) = 7.7 min, 93% ee. $[\alpha]_D^{20}$ = -106.9 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(1-(2-((2,2,2-trifluoroethyl)thio)phenyl)naphthalen-2-yl)acrylate (2-40)



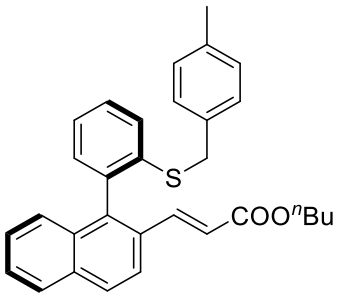
根据通用方法 C 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(14.2 mg, 64%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (d, *J* = 8.8 Hz, 1H), 7.90 – 7.86 (m, 1H), 7.83 (d, *J* = 8.8 Hz, 1H), 7.66 (d, *J* = 7.7 Hz, 1H), 7.55 – 7.48 (m, 2H), 7.46 – 7.36 (m, 3H), 7.30 – 7.26 (m, 1H), 7.23 (dd, *J* = 7.5, 1.6 Hz, 1H), 6.47 (d, *J* = 15.9 Hz, 1H), 4.17 – 4.05 (m, 2H), 3.15 (q, *J* = 9.7 Hz, 2H), 1.63 – 1.57 (m, 2H), 1.36 – 1.30 (m, 2H), 0.91 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.95, 142.53, 139.29, 139.27, 134.38, 134.16, 132.67, 131.84, 130.92, 130.52, 129.35, 128.94, 128.28, 127.85, 127.27, 127.09, 126.91, 125.17(q, J_{CF} = 276.7 Hz), 122.80, 119.75, 64.41, 36.37(q, J_{CF} = 33.3Hz), 30.79, 19.28, 13.85. ^{19}F NMR (376 MHz, $CDCl_3$) δ -65.88. HRMS (ESI-TOF) calcd for $C_{24}H_{23}F_3O_2S$ ($M+Na^+$): 467.1267, found: 467.1265. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 11.0 min, t (major) = 9.0 min, 90% ee. $[\alpha]_D^{20}$ = -13.9 (c = 0.6, $CHCl_3$).

butyl (*E*)-3-(1-(2-((4-methoxybenzyl)thio)phenyl)naphthalen-2-yl)acrylate (2-41)



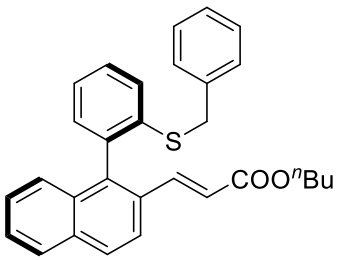
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(22.0 mg, 91%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 – 7.84 (m, 2H), 7.82 (d, *J* = 8.8 Hz, 1H), 7.53 – 7.46 (m, 2H), 7.45 – 7.38 (m, 2H), 7.38 – 7.33 (m, 1H), 7.33 – 7.28 (m, 2H), 7.16 (dd, *J* = 7.2, 1.2 Hz, 1H), 7.09 – 7.01 (m, 2H), 6.76 – 6.68 (m, 2H), 6.47 (d, *J* = 15.9 Hz, 1H), 4.13 (t, *J* = 6.5 Hz, 2H), 3.91 (s, 2H), 3.74 (s, 3H), 1.65 – 1.59 (m, 2H), 1.41 – 1.30 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.11, 158.77, 143.10, 139.92, 137.67, 137.29, 134.16, 132.71, 131.33, 130.46, 130.02, 128.78, 128.74, 128.62, 128.30, 128.12, 127.19, 127.07, 126.79, 125.81, 122.75, 119.14, 113.88, 64.32, 55.31, 37.26, 30.81, 19.30, 13.90. HRMS (ESI-TOF) calcd for $C_{31}H_{30}O_3S$ ($M+Na^+$): 505.1808, found: 505.1811. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 11.8 min, t (major) = 9.5 min, 90% ee. $[\alpha]_D^{20}$ = -92.4 (c = 1.3, $CHCl_3$).

butyl (*E*)-3-(1-(2-((4-methylbenzyl)thio)phenyl)naphthalen-2-yl)acrylate (2-42)



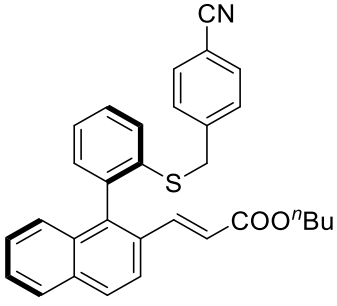
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(16.1 mg, 69%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 – 7.76 (m, 3H), 7.56 – 7.27 (m, 7H), 7.16 (d, *J* = 7.4 Hz, 1H), 7.10 – 6.92 (m, 4H), 6.47 (d, *J* = 16.0 Hz, 1H), 4.13 (t, *J* = 6.5 Hz, 2H), 3.92 (s, 2H), 2.27 (s, 3H), 1.60 (td, *J* = 12.1, 10.1, 4.9 Hz, 3H), 1.35 (h, *J* = 7.4 Hz, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.11, 143.12, 139.90, 137.81, 137.21, 136.84, 134.20, 133.73, 132.73, 131.34, 130.52, 129.19, 128.81, 128.63, 128.15, 128.13, 127.22, 127.07, 126.79, 125.77, 122.78, 119.19, 64.32, 37.53, 30.83, 21.18, 19.32, 13.89. HRMS (ESI-TOF) calcd for $C_{31}H_{30}O_2S$ ($M+Na^+$): 489.1859, found: 489.1856. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 8.4 min, t (major) = 7.3 min, 92% ee. $[\alpha]_D^{20}$ = -116.6 (c = 0.8, $CHCl_3$).

butyl (*E*)-3-(1-(2-(benzylthio)phenyl)naphthalen-2-yl)acrylate (2-43)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(15.6 mg, 69%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88 (t, *J* = 8.9 Hz, 2H), 7.82 (d, *J* = 8.8 Hz, 1H), 7.54 – 7.45 (m, 2H), 7.44 – 7.27 (m, 5H), 7.25 – 7.05 (m, 6H), 6.47 (d, *J* = 16.0 Hz, 1H), 4.12 (t, *J* = 6.5 Hz, 2H), 3.95 (s, 2H), 1.64 – 1.59 (m, 2H), 1.40 – 1.29 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.12, 143.05, 139.87, 137.54, 137.28, 136.84, 134.18, 132.71, 131.36, 130.49, 128.93, 128.81, 128.66, 128.50, 128.22, 128.14, 127.21, 127.18, 127.10, 126.83, 125.87, 122.76, 119.21, 64.33, 37.78, 30.81, 19.31, 13.90. HRMS (ESI-TOF) calcd for $C_{30}H_{28}O_2S$ ($M+Na^+$): 475.1702, found: 475.1706. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 11.0 min, t (major) = 9.5 min, 92% ee. $[\alpha]_D^{20}$ = -108.4 (c =1.3, $CHCl_3$).

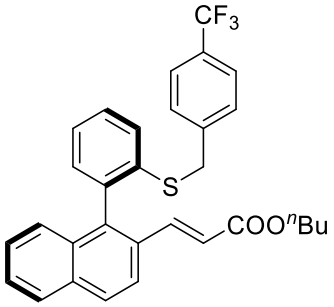
butyl (*E*)-3-(1-(2-((4-cyanobenzyl)thio)phenyl)naphthalen-2-yl)acrylate (2-44)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 4/1 为展开剂)(17.7 mg, 74%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (t, *J* = 9.0 Hz, 2H), 7.82 (d, *J* = 8.7 Hz, 1H), 7.51 (t, *J* = 7.5 Hz, 1H), 7.47 – 7.30 (m, 7H), 7.25 – 7.14 (m, 4H), 6.48 (d, *J* = 16.0 Hz, 1H), 4.14 (t, *J* = 6.6 Hz, 2H), 3.91 (s, 2H), 1.66 – 1.56 (m,

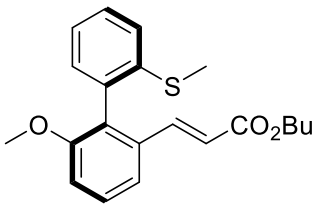
2H), 1.41 – 1.31 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.02, 142.89, 142.80, 139.62, 138.24, 135.86, 134.15, 132.69, 132.30, 131.69, 130.46, 129.53, 129.31, 128.96, 128.80, 128.23, 127.19, 126.95, 126.92, 126.76, 122.71, 119.36, 118.85, 111.04, 64.46, 37.76, 30.84, 19.31, 13.89. HRMS (ESI-TOF) calcd for $C_{31}H_{27}NO_2S$ ($M+Na^+$): 500.1655, found: 500.1654. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.5 mL·min^{-1}, λ = 254 nm, t (minor) = 11.0 min, t (major) = 9.9 min, 91% ee. $[\alpha]_D^{20}$ = -69.1 (c = 0.7, $CHCl_3$).

butyl (*E*)-3-(1-(2-((4-(trifluoromethyl)benzyl)thio)phenyl)naphthalen-2-yl)acrylate (2-45)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(21.3 mg, 82%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.89 (t, *J* = 9.3 Hz, 2H), 7.82 (d, *J* = 8.7 Hz, 1H), 7.56 – 7.37 (m, 6H), 7.37 – 7.30 (m, 2H), 7.26 – 7.20 (m, 3H), 7.18 (d, *J* = 7.4 Hz, 1H), 6.48 (d, *J* = 16.0 Hz, 1H), 4.13 (t, *J* = 6.6 Hz, 2H), 3.94 (s, 2H), 1.69 – 1.59 (m, 2H), 1.40 – 1.30 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.05, 142.89, 141.30, 139.69, 137.88, 136.50, 134.17, 132.68, 131.57, 130.52, 129.42 (d, J_{CF} = 32.4 Hz), 129.13, 128.94, 128.85, 128.77, 128.20, 127.16, 127.02, 126.89, 126.45, 125.44 (q, J_{CF} = 3.7 Hz), 124.23(q, J_{CF} = 273.0 Hz), 122.74, 119.34, 64.40, 37.47, 30.82, 19.30, 13.87. ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.50. HRMS (ESI-TOF) calcd for $C_{31}H_{27}F_3O_2S$ ($M+Na^+$): 543.1576, found: 543.1575. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 7.0 min, t (major) = 6.1 min, 93% ee. $[\alpha]_D^{20}$ = -54.5 (c = 1.3, $CHCl_3$).

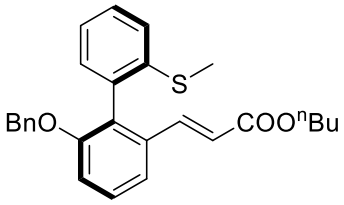
butyl (*E*)-3-(6-methoxy-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-46)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 4/1 为展开剂)(17.3 mg, 97%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.46 – 7.33 (m, 3H), 7.32 – 7.25 (m, 2H), 7.21 (td, *J* = 7.4, 1.3 Hz, 1H), 7.05 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.00 (dd, *J* = 7.6, 1.6 Hz, 1H), 6.32 (d, *J* = 16.0 Hz, 1H), 4.07 (*t*, *J* = 6.5 Hz, 2H), 3.74 (s, 3H), 2.34 (s, 3H), 1.57 – 1.44 (m, 1H), 1.44 – 1.17 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.01, 157.60, 142.81, 138.66, 134.78, 134.62, 130.79, 130.35, 129.23, 128.59, 125.36, 124.88, 119.53, 118.42, 112.40, 64.27, 56.19, 30.77, 19.26, 15.81, 13.85. HRMS (ESI-TOF) calcd for $C_{21}H_{24}O_3S$ ($M+Na^+$): 379.1338, found: 379.1338. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-

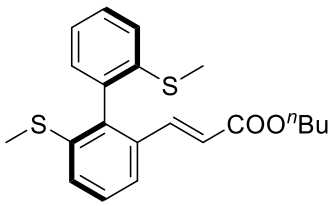
propanol = 95/5, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 8.2 min, t (major) = 8.7 min, 94% ee. $[\alpha]_D^{20}$ = -77.6 (c = 1.2, $CHCl_3$).

butyl (*E*)-3-(6-(benzyloxy)-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-47)



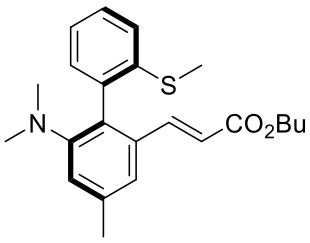
根据通用方法 C 经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.3 mg, 80%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.42 – 7.29 (m, 5H), 7.29 – 7.17 (m, 5H), 7.15 (d, *J* = 6.9 Hz, 2H), 7.09 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.01 (dd, *J* = 7.7, 1.5 Hz, 1H), 6.33 (d, *J* = 16.0 Hz, 1H), 5.04 (s, 2H), 4.08 (t, *J* = 6.5 Hz, 2H), 2.33 (s, 3H), 1.62 – 1.53 (m, 3H), 1.38 – 1.27 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.03, 156.59, 142.78, 138.72, 137.30, 134.92, 134.68, 131.21, 130.81, 129.16, 128.58, 128.42, 127.55, 126.59, 125.26, 124.86, 119.54, 118.85, 114.54, 70.57, 64.29, 30.77, 19.27, 15.80, 13.86. HRMS (ESI-TOF) calcd for $C_{27}H_{28}O_3S$ (M^+): 432.1754, found: 432.1754. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 6.4 min, t (major) = 7.8 min, 96% ee. $[\alpha]_D^{20}$ = -46.2 (c = 1.0, $CHCl_3$).

butyl (*E*)-3-(2',6-bis(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-48)



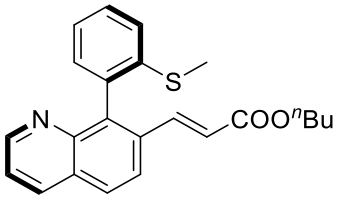
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(7.1 mg, 38%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (d, *J* = 7.5 Hz, 1H), 7.47 – 7.38 (m, 2H), 7.29 – 7.22 (m, 3H), 7.07 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.33 (d, *J* = 16.0 Hz, 1H), 4.08 (t, *J* = 6.5 Hz, 2H), 2.38 (s, 6H), 1.61 – 1.52 (m, 2H), 1.36 – 1.27 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.90, 142.51, 140.11, 138.65, 138.58, 135.52, 133.87, 130.51, 129.25, 128.83, 125.53, 125.04, 124.98, 122.18, 119.75, 64.30, 30.72, 19.24, 15.71, 15.52, 13.85. HRMS (ESI-TOF) calcd for $C_{21}H_{24}O_2S_2$ (M+Na^+): 395.1110, found: 395.1110. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 9.8 min, t (major) = 8.9 min, 98% ee. $[\alpha]_D^{20}$ = -48.8 (c = 0.7, $CHCl_3$).

butyl (*E*)-3-(6-(dimethylamino)-4-methyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-51)



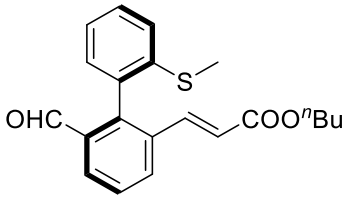
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(14.2 mg, 74%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 – 7.31 (m, 1H), 7.31 – 7.26 (m, 2H), 7.23 – 7.16 (m, 2H), 7.08 (d, *J* = 7.5 Hz, 1H), 6.95 (s, 1H), 6.28 (d, *J* = 15.9 Hz, 1H), 4.07 (t, *J* = 6.5 Hz, 2H), 2.49 (s, 6H), 2.39 (s, 3H), 2.36 (s, 3H), 1.60 – 1.53 (m, 2H), 1.38 – 1.28 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.24, 153.03, 144.12, 139.20, 138.50, 137.00, 134.38, 132.31, 131.60, 128.08, 125.38, 124.78, 121.43, 120.48, 118.69, 64.15, 43.83, 30.80, 21.76, 19.28, 15.93, 13.87. HRMS (EI-TOF) calcd for $C_{23}H_{29}NO_2S$ (M^+): 383.1914, found: 383.1912. 手性 HPLC 分离条件：a Daicel Chiralpak OD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) =10.5 min, t (major) = 6.0 min, 95% ee. $[\alpha]_D^{20}$ =-61.9 (c =1.0, $CHCl_3$).

butyl (*E*)-3-(8-(2-(methylthio)phenyl)quinolin-7-yl)acrylate (2-52)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯/二氯甲烷 = 9/1/1 为展开剂)(10.8 mg, 57%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.53 (dd, J = 7.9, 1.1 Hz, 1H), 7.42 (m, 7.8 Hz, 2H), 7.28 (m, 4H), 7.07 (dd, J = 7.5, 1.5 Hz, 1H), 6.33 (d, J = 16.0 Hz, 1H), 4.08 (t, J = 6.5 Hz, 2H), 2.38 (s, 6H), 1.60 – 1.52 (m, 2H), 1.36 – 1.27 (m, 2H), 0.90 (t, J = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.90, 142.51, 140.11, 138.65, 138.58, 135.52, 133.87, 130.51, 129.25, 128.83, 125.53, 125.04, 124.98, 122.18, 119.75, 64.30, 30.72, 19.24, 15.71, 15.52, 13.85. HRMS (ESI-TOF) calcd for $C_{23}H_{23}NO_2S$ ($M+Na^+$): 400.1342, found: 400.1343. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 80/20, v = 1.2 mL · min^{-1}, λ = 254 nm, t (minor) = 9.5 min, t (major) = 12.9 min, 91% ee. $[\alpha]_D^{20}$ = -93.7 (c = 1.3, $CHCl_3$).

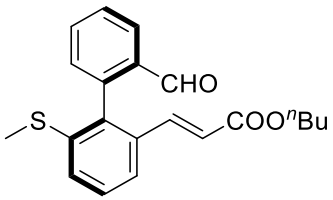
butyl (*E*)-3-(6-formyl-2'-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-55)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(7.3 mg, 41%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 9.59 (s, 1H), 8.05 (d, *J* = 7.7 Hz, 1H), 7.98 (d, *J* = 7.8 Hz, 1H), 7.57 (t, *J* = 7.8 Hz, 1H), 7.46 (t, *J* = 7.8 Hz, 1H), 7.36 – 7.26 (m, 3H), 7.11 (d, *J* = 7.5 Hz, 1H), 6.38 (d, *J* = 16.0 Hz, 1H), 4.10 (t, *J* = 6.5 Hz, 2H), 2.36 (s, 3H), 1.62 – 1.52 (m, 2H), 1.39 – 1.30 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.69,

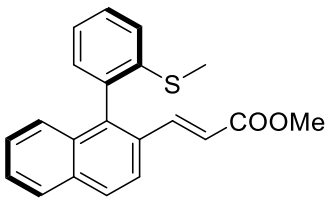
141.34, 137.09, 136.47, 134.17, 132.17, 132.10, 131.19, 130.37, 129.96, 129.17, 128.96, 128.46, 127.72, 127.67, 126.83, 126.32, 122.86, 120.88, 110.07, 64.60, 30.75, 19.30, 13.88. HRMS (ESI-TOF) calcd for $C_{21}H_{22}O_3S$ ($M+Na^+$): 377.1182, found: 377.1183. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 7.1 min, t (major) = 8.5 min, 97% ee. $[\alpha]_D^{20}$ = -87.3 (c = 1.2, $CHCl_3$).

butyl (*E*)-3-(2'-formyl-6-(methylthio)-[1,1'-biphenyl]-2-yl)acrylate (2-56)



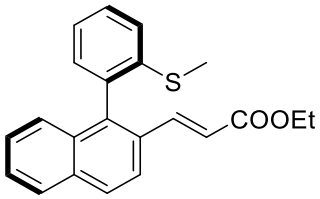
在干燥的 10 mL 密封管中依次加入底物(0.10 mmol)，丙烯酸正丁酯(0.3 mmol)，醋酸钯(2.2 mg, 0.010 mmol)，叔亮氨酸(3.9 mg, 0.03 mmol)，苯醌(1.1 mg, 0.01 mmol)和醋酸(1 mL)。将反应至于 50 ºC 下反应 72 小时，冷却后将混合物通过一小段硅藻土以淬灭反应，将滤液收集旋干后，经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(19.1 mg, 54%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 9.61 (s, 1H), 8.07 (d, *J* = 7.8 Hz, 1H), 7.70 (t, *J* = 7.5 Hz, 1H), 7.59 (t, *J* = 7.6 Hz, 1H), 7.53 (d, *J* = 7.8 Hz, 1H), 7.44 (t, *J* = 7.9 Hz, 1H), 7.29 – 7.16 (m, 3H), 6.30 (d, *J* = 15.9 Hz, 1H), 4.07 (t, *J* = 6.5 Hz, 2H), 1.55 (q, *J* = 7.1 Hz, 2H), 1.30 (m, 2H), 0.89 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 191.31, 166.36, 141.72, 140.78, 140.14, 136.11, 134.41, 134.36, 134.27, 131.51, 129.14, 129.09, 127.86, 125.08, 122.45, 120.62, 64.37, 30.59, 19.11, 15.53, 13.68. HRMS (ESI-TOF) calcd for $C_{21}H_{22}O_3S$ ($M+Na^+$): 377.1182, found: 377.1183. 手性 HPLC 分离条件：a Daicel Chiralpak IA, *n*-hexane/2-propanol = 85/15, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 6.9 min, t (major) = 8.0 min, 81% ee. $[\alpha]_D^{20}$ = +8.2 (c = 0.6, $CHCl_3$).

methyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-57)



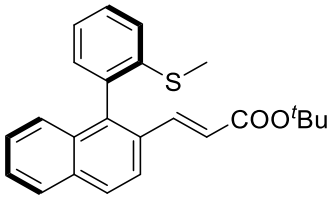
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(10.2 mg, 61%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 – 7.78 (m, 3H), 7.57 – 7.41 (m, 3H), 7.40 – 7.26 (m, 4H), 7.14 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.48 (d, *J* = 15.9 Hz, 1H), 3.71 (s, 3H), 2.30 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.53, 143.23, 139.68, 139.24, 135.73, 134.28, 132.62, 131.06, 130.52, 129.04, 128.78, 128.19, 127.21, 127.05, 126.91, 124.95, 124.87, 122.87, 118.92, 51.72, 15.57. HRMS (ESI-TOF) calcd for $C_{21}H_{18}O_2S$ ($M+Na^+$): 357.0920, found: 357.0920. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 9.6 min, t (major) = 7.8 min, 95% ee. $[\alpha]_D^{20}$ = -95.7 (c = 0.7, $CHCl_3$).

ethyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-58)



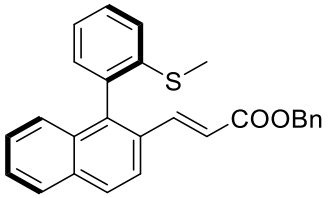
根据通用方法C经过制备级TLC分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.3 mg, 99%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 – 7.85 (m, 2H), 7.83 (d, *J* = 8.7 Hz, 1H), 7.54 – 7.44 (m, 3H), 7.42 – 7.32 (m, 3H), 7.30 (td, *J* = 7.4, 1.2 Hz, 1H), 7.15 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.49 (d, *J* = 16.0 Hz, 1H), 4.18 (q, *J* = 7.1 Hz, 2H), 2.30 (s, 3H), 1.26 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.11, 143.01, 139.63, 139.21, 135.68, 134.23, 132.59, 131.06, 130.54, 129.01, 128.75, 128.18, 127.17, 127.03, 126.88, 124.86, 124.82, 122.83, 119.26, 60.45, 15.53, 14.37. HRMS (ESI-TOF) calcd for $C_{22}H_{20}O_2S$ ($M+Na^+$): 371.1076, found: 371.1078. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 8.2 min, t (major) = 7.0 min, 96% ee. $[\alpha]_D^{20}$ = -92.0 (c = 0.9, $CHCl_3$).

***t*-butyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-59)**



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(16.9 mg, 90%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 – 7.79 (m, 3H), 7.53 – 7.44 (m, 2H), 7.43 – 7.26 (m, 5H), 7.14 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.43 (d, *J* = 15.9 Hz, 1H), 2.30 (s, 3H), 1.45 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.39, 141.93, 139.46, 139.21, 135.88, 134.17, 132.66, 131.12, 130.68, 128.97, 128.66, 128.17, 127.04, 127.03, 126.82, 124.97, 124.86, 122.85, 121.09, 80.33, 28.31, 15.61. HRMS (ESI-TOF) calcd for $C_{24}H_{24}O_2S$ ($M+Na^+$): 399.1389, found: 399.1390. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 98/2, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 8.0 min, t (major) = 7.2 min, 98% ee. $[\alpha]_D^{20}$ = -109.6 (c = 0.6, $CHCl_3$).

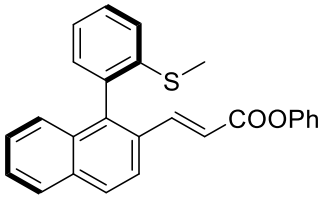
benzyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-60)



根据通用方法 C 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(10.5 mg, 51%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 – 7.79 (m, 3H), 7.61 – 7.46 (m, 3H), 7.42 – 7.27 (m, 9H), 7.15 (dt, *J* = 7.5, 1.7 Hz, 1H), 6.58 – 6.49 (m, 1H), 5.17 (s, 2H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.81, 143.66, 139.84, 139.29, 136.32, 135.71, 134.33, 132.61, 131.11, 130.44, 129.02, 128.80, 128.64, 128.21, 128.17, 127.99, 127.26, 127.08, 126.92, 124.90, 124.84, 122.75, 118.78, 66.17, 29.85. HRMS (ESI-TOF) calcd for $C_{27}H_{22}O_3S$ ($M+Na^+$): 433.1233, found: 433.1234. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-

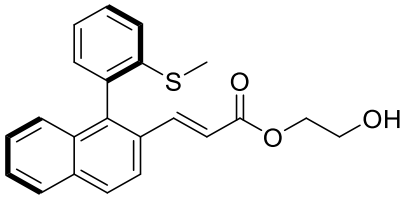
propanol = 95/5, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 14.7 min, t (major) = 12.2 min, 95% ee. $[\alpha]_D^{20}$ = -76.0 (c = 1.0, $CHCl_3$).

phenyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-61)



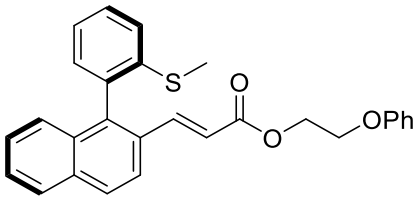
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(9.1 mg, 46%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98 – 7.86 (m, 3H), 7.66 (d, *J* = 15.9 Hz, 1H), 7.55 – 7.50 (m, 1H), 7.47 (td, *J* = 7.7, 1.5 Hz, 1H), 7.43 – 7.32 (m, 5H), 7.29 (td, *J* = 7.4, 1.2 Hz, 1H), 7.23 – 7.18 (m, 1H), 7.16 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.12 – 7.04 (m, 2H), 6.68 (d, *J* = 15.9 Hz, 1H), 2.31 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.56, 150.95, 145.01, 140.21, 139.20, 135.46, 134.46, 132.61, 131.06, 130.26, 129.44, 129.14, 128.90, 128.25, 127.45, 127.17, 127.01, 125.78, 124.83, 122.80, 121.75, 118.19, 15.52. HRMS (EI-TOF) calcd for $C_{26}H_{20}O_2S$ (M^+): 396.1179, found: 396.1180. 手性 HPLC 分离条件：a Daicel Chiralpak IB-N, *n*-hexane/2-propanol = 97.5/2.5, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 16.3 min, t (major) = 14.6 min, 97% ee. $[\alpha]_D^{20}$ = -92.3 (c = 1.0, $CHCl_3$).

2-hydroxyethyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-62)



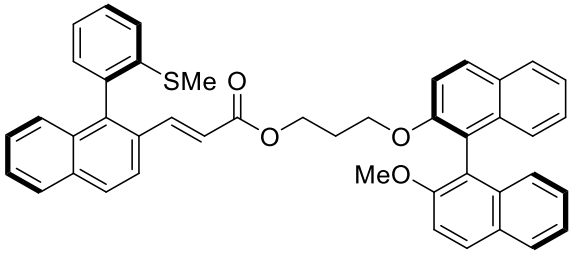
根据通用方法 C 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 =9/1 为展开剂)(15.3 mg, 84%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 – 7.85 (m, 2H), 7.82 (d, *J* = 8.7 Hz, 1H), 7.57 – 7.46 (m, 3H), 7.42 – 7.33 (m, 3H), 7.30 (td, *J* = 7.4, 1.2 Hz, 1H), 7.15 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.53 (d, *J* = 15.9 Hz, 1H), 4.32 – 4.21 (m, 2H), 3.87 – 3.76 (m, 2H), 2.31 (s, 3H), 2.07 (t, *J* = 6.0 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.30, 143.89, 139.86, 139.22, 135.53, 134.31, 132.52, 131.04, 130.30, 129.05, 128.81, 128.18, 127.29, 127.05, 126.93, 124.77, 124.75, 122.71, 118.43, 66.19, 61.48, 15.47. HRMS (ESI-TOF) calcd for $C_{22}H_{20}O_3S$ ($M+Na^+$): 387.1025, found: 387.1025. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 70/30, v = 1.5 mL · min^{-1}, λ = 254 nm, t (minor) = 5.7 min, t (major) = 4.9 min, 90% ee. $[\alpha]_D^{20}$ = -57.7 (c = 1.2, $CHCl_3$).

2-phenoxyethyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-63)



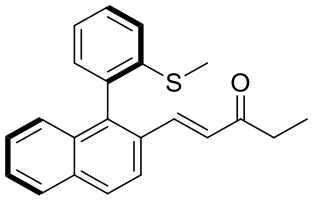
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =9/1 为展开剂)(19.6 mg, 89%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 – 7.85 (m, 2H), 7.83 (d, *J* = 8.7 Hz, 1H), 7.55 (d, *J* = 16.0 Hz, 1H), 7.53 – 7.48 (m, 1H), 7.46 (td, *J* = 7.7, 1.5 Hz, 1H), 7.41 – 7.27 (m, 6H), 7.15 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.99 (t, *J* = 7.4 Hz, 1H), 6.94 – 6.89 (m, 2H), 6.55 (d, *J* = 15.9 Hz, 1H), 4.51 – 4.44 (m, 2H), 4.18 (t, *J* = 4.8 Hz, 2H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.91, 158.61, 143.79, 139.84, 139.20, 135.63, 134.31, 132.58, 131.04, 130.41, 129.61, 129.56, 129.02, 128.77, 128.18, 127.23, 127.06, 126.88, 124.91, 124.81, 122.79, 121.25, 118.61, 114.77, 66.01, 62.83, 15.52. HRMS (ESI-TOF) calcd for $C_{28}H_{24}O_3S$ ($M+Na^+$): 463.1338, found: 463.1338. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 11.6 min, t (major) = 6.7 min, 95% ee. $[\alpha]_D^{20}$ = -87.7 (c = 1.1, $CHCl_3$).

3-(((S)-2'-methoxy-[1,1'-binaphthalen]-2-yl)oxy)propyl(*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-64)



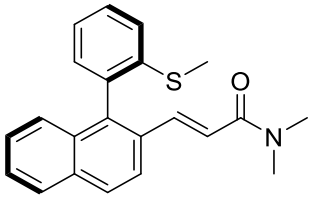
根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(31.1 mg, 94%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.05 – 7.94 (m, 2H), 7.93 – 7.83 (m, 4H), 7.80 (d, *J* = 8.8 Hz, 1H), 7.50 (t, *J* = 7.3 Hz, 1H), 7.46 – 7.42 (m, 2H), 7.40 – 7.32 (m, 4H), 7.31 – 7.21 (m, 5H), 7.20 – 7.09 (m, 3H), 7.06 (d, *J* = 8.5 Hz, 1H), 6.37 (d, *J* = 15.9 Hz, 1H), 4.09 – 3.99 (m, 1H), 3.99 – 3.89 (m, 1H), 3.85 – 3.67 (m, 4H), 3.63 – 3.52 (m, 1H), 2.22 (s, 3H), 1.80 – 1.65 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.60, 154.92, 154.15, 142.83, 139.58, 139.18, 135.52, 134.22, 134.16, 134.05, 132.52, 130.96, 130.46, 129.55, 129.42, 129.13, 128.99, 128.77, 128.19, 128.03, 127.20, 127.00, 126.89, 126.43, 125.54, 125.25, 124.69, 124.62, 123.85, 123.55, 122.73, 120.77, 119.27, 119.15, 115.90, 113.83, 66.03, 60.71, 56.74, 28.81, 15.34. HRMS (ESI-TOF) calcd for $C_{44}H_{36}O_4S$ ($M+Na^+$): 683.2227, found: 683.2230. 手性 HPLC 分离条件：a Daicel Chiralpak IA, *n*-hexane/2-propanol = 90/10, v = 1.3 mL·min^{-1}, λ = 254 nm, t (minor) = 10.6 min, t (major) = 9.5 min, 91% de. $[\alpha]_D^{20}$ = -97.5 (c = 1.0, $CHCl_3$).

(*E*)-1-(1-(2-(methylthio)phenyl)naphthalen-2-yl)pent-1-en-3-one (2-65)



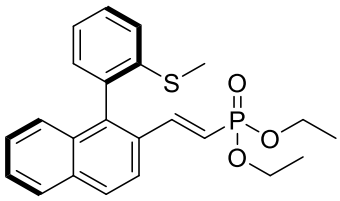
根据通用方法 C 以 40 ºC 反应 72 小时后经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(7.6 mg, 46%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.93 – 7.82 (m, 3H), 7.51 (t, *J* = 7.7 Hz, 2H), 7.41 – 7.28 (m, 5H), 7.15 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.75 (d, *J* = 16.3 Hz, 1H), 2.50 (q, *J* = 7.3 Hz, 2H), 2.31 (s, 3H), 1.06 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 201.27, 140.86, 139.92, 139.27, 135.67, 134.31, 132.57, 131.08, 130.69, 129.06, 128.82, 128.22, 127.28, 127.25, 126.98, 126.92, 124.77, 124.70, 122.71, 33.58, 15.49, 8.37. HRMS (ESI-TOF) calcd for $C_{22}H_{20}OS$ ($M+Na^+$): 355.1127, found: 355.1129. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 7.9 min, t (major) = 7.4 min, 93% ee. $[\alpha]_D^{20}$ = -110.1 (c = 1.0, $CHCl_3$).

(*E*)-N,N-dimethyl-2-(1-(2-(methylthio)phenyl)naphthalen-2-yl)ethen-1-amine (2-66)



根据通用方法 C 以 40 ºC 反应 72 小时后经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(10.1 mg, 58%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 – 7.83 (m, 2H), 7.81 (d, *J* = 8.7 Hz, 1H), 7.53 – 7.39 (m, 3H), 7.39 – 7.30 (m, 3H), 7.30 – 7.26 (m, 1H), 7.14 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.83 (d, *J* = 15.5 Hz, 1H), 3.09 (s, 3H), 2.99 (s, 3H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.88, 140.51, 139.15, 138.78, 136.12, 133.87, 132.74, 131.41, 130.99, 128.89, 128.53, 128.10, 126.89, 126.79, 126.76, 124.96, 124.94, 123.43, 119.12, 37.55, 35.89, 15.56. HRMS (EI-TOF) calcd for $C_{22}H_{21}NOS$ (M^+): 347.1344, found: 347.1345. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 70/30, v = 1.5 mL·min^{-1}, λ = 254 nm, t(minor) = 11.8 min, t (major) = 14.6 min, 87% ee. $[\alpha]_D^{20}$ = -86.0 (c = 1.1, $CHCl_3$).

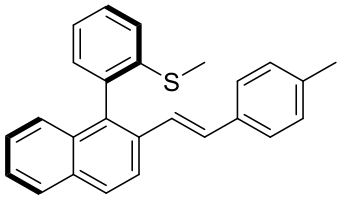
diethyl (*E*)-(2-(1-(2-(methylthio)phenyl)naphthalen-2-yl)vinyl)phosphonate (2-67)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(12.2 mg, 59%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, *J* = 8.7 Hz, 1H), 7.87 (d, *J* = 8.3 Hz, 1H), 7.79 (d, *J* = 8.8 Hz, 1H), 7.53 – 7.44 (m, 2H), 7.41 – 7.35 (m, 1H), 7.35 – 7.31 (m, 2H), 7.30 – 7.18 (m, 2H), 7.13 (dd, *J* = 7.5, 1.4 Hz, 1H), 6.35 – 6.23 (m, 1H), 4.07 – 3.94 (m, 4H), 2.28 (s, 3H), 1.23 (q, *J* = 6.7 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 146.33 (d, J_{CP} = 7.2 Hz), 139.34, 138.88, 135.73, 134.19, 132.52, 131.05, 131.03 (d, J_{CP} = 22.9 Hz), 129.01, 128.79, 128.20, 127.13, 126.94, 126.90, 124.83, 124.81, 122.63, 115.33 (d, J_{CP} = 191.1 Hz), 62.01 (d, J_{CP}

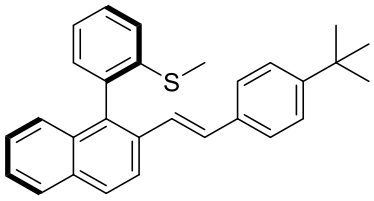
= 5.5 Hz), 16.42, 16.36, 15.44. ^{31}P NMR (162 MHz, $CDCl_3$) δ 19.16. HRMS (ESI-TOF) calcd for $C_{23}H_{25}O_3PS$ ($M+Na^+$): 435.1154, found: 435.1154. 手性 HPLC 分离条件：a Daicel Chiralpak AS, *n*-hexane/2-propanol = 75/25, v = 1.3 mL · min^{-1}, λ = 254 nm, t (minor) = 20.2 min, t (major) = 14.8 min, 97% ee. $[\alpha]_D^{20}$ = -31.3 (c = 0.9, $CHCl_3$).

(*E*)-methyl(2-(2-(4-methylstyryl)naphthalen-1-yl)phenyl)sulfane (2-68)



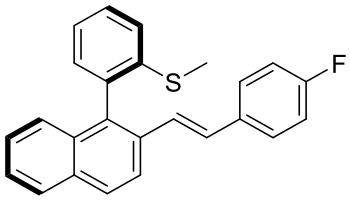
根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(16.1 mg, 88%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 – 7.85 (m, 2H), 7.83 (d, *J* = 8.0 Hz, 1H), 7.47 (td, *J* = 7.6, 1.5 Hz, 1H), 7.44 – 7.38 (m, 1H), 7.37 – 7.26 (m, 4H), 7.24 – 7.14 (m, 4H), 7.14 – 7.08 (m, 1H), 7.06 (d, *J* = 7.9 Hz, 2H), 6.81 (d, *J* = 16.3 Hz, 1H), 2.29 (s, 3H), 2.27 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.52, 137.53, 136.91, 136.12, 135.02, 133.29, 133.00, 132.81, 131.32, 129.74, 129.38, 128.54, 128.43, 128.11, 126.67, 126.50, 126.39, 126.26, 125.84, 124.76, 124.71, 122.73, 21.36, 15.53. HRMS (EI-TOF) calcd for $C_{26}H_{22}S$ (M^+): 366.1442, found: 366.1443. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 6.7 min, t (major) = 7.8 min, 94% ee. $[\alpha]_D^{20}$ = -257.1 (c = 0.87, $CHCl_3$).

(*E*)-(2-(2-(4-(tert-butyl)styryl)naphthalen-1-yl)phenyl)(methyl)sulfane (2-69)



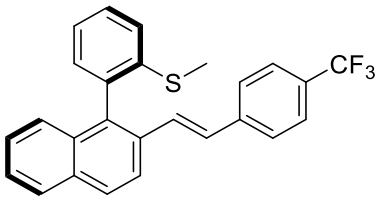
根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(19.2 mg, 94%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, *J* = 8.8 Hz, 1H), 7.88 (d, *J* = 8.8 Hz, 1H), 7.84 (d, *J* = 8.1 Hz, 1H), 7.48 (td, *J* = 7.6, 1.5 Hz, 1H), 7.44 – 7.39 (m, 1H), 7.39 – 7.29 (m, 4H), 7.29 – 7.27 (m, 2H), 7.25 – 7.21 (m, 2H), 7.20 – 7.11 (m, 2H), 6.84 (d, *J* = 16.3 Hz, 1H), 2.28 (s, 3H), 1.29 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 150.79, 139.53, 136.93, 136.15, 135.05, 133.33, 133.02, 132.82, 131.31, 129.56, 128.55, 128.43, 128.12, 126.54, 126.50, 126.40, 125.85, 125.61, 124.76, 124.71, 122.77, 34.72, 31.40, 15.54. HRMS (ESI-TOF) calcd for $C_{29}H_{28}S$ ($M+H^+$): 409.1984, found: 409.1983. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 6.7 min, t (major) = 7.7 min, 95% ee. $[\alpha]_D^{20}$ = -180.6 (c = 1.1, $CHCl_3$).

(*E*)-(2-(2-(4-fluorostyryl)naphthalen-1-yl)phenyl)(methyl)sulfane (2-70)



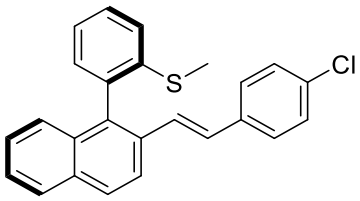
根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(15.7 mg, 85%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.92 (d, *J* = 8.7 Hz, 1H), 7.88 (d, *J* = 8.8 Hz, 1H), 7.84 (d, *J* = 8.1 Hz, 1H), 7.49 (td, *J* = 7.7, 1.5 Hz, 1H), 7.45 – 7.40 (m, 1H), 7.39 – 7.36 (m, 1H), 7.35 – 7.27 (m, 3H), 7.26 – 7.21 (m, 2H), 7.18 (dd, *J* = 7.4, 1.5 Hz, 1H), 7.12 (d, *J* = 16.3 Hz, 1H), 6.99 – 6.88 (m, 2H), 6.78 (d, *J* = 16.3 Hz, 1H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.38 (d, J_{CF} = 247.2 Hz), 139.51, 136.75, 136.36, 133.94 (d, J_{CF} = 3.3 Hz), 133.10, 132.94, 132.78, 131.29, 128.64, 128.52, 128.24, 128.17, 128.13, 126.92 (d, J_{CF} = 2.4 Hz), 126.59, 126.43, 126.01, 124.72 (d, J_{CF} = 10.7 Hz), 122.60, 115.61 (d, J_{CF} = 21.6 Hz), 15.49. ^{19}F NMR (376 MHz, $CDCl_3$) δ -114.24. HRMS (ESI-TOF) calcd for $C_{25}H_{19}FS$ ($M+H^+$): 371.1264, found: 371.1260. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 12.2 min, t (major) = 13.1 min, 94% ee. $[\alpha]_D^{20}$ = -192.8 (c = 0.9, $CHCl_3$).

(*E*)-methyl(2-(2-(4-(trifluoromethyl)styryl)naphthalen-1-yl)phenyl)sulfane (2-71)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(19.2 mg, 91%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.97 (d, *J* = 8.8 Hz, 1H), 7.93 (d, *J* = 8.8 Hz, 1H), 7.89 (d, *J* = 8.1 Hz, 1H), 7.57 – 7.45 (m, 4H), 7.43 – 7.30 (m, 6H), 7.25 – 7.16 (m, 2H), 6.98 (d, *J* = 16.3 Hz, 1H), 2.32 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.24 (q, J_{CF} = 1.2 Hz), 139.51, 137.12, 136.48, 133.38, 132.74, 132.47, 131.26, 129.71, 129.20 (q, J_{CF} = 32.5 Hz), 128.78, 128.64, 128.17, 128.16, 126.76, 126.71, 126.57, 126.34, 125.63 (q, J_{CF} = 4.0 Hz), 124.78, 124.67, 124.34 (q, J_{CF} = 272.9 Hz), 122.57, 15.47. ^{19}F NMR (376 MHz, $CDCl_3$) δ -62.43. HRMS (ESI-TOF) calcd for $C_{26}H_{19}F_3S$ ($M+H^+$): 421.1233, found: 421.1232. 手性 HPLC 分离条件：a Daicel Chiralpak AD, *n*-hexane/2-propanol = 90/10, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 5.6 min, t (major) = 6.3 min, 94% ee. $[\alpha]_D^{20}$ = -225.9 (c = 1.0, $CHCl_3$).

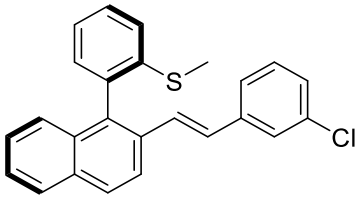
(*E*)-(2-(2-(4-chlorostyryl)naphthalen-1-yl)phenyl)(methyl)sulfane (2-72)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.4 mg, 90%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 (d, *J* = 8.8 Hz, 1H), 7.86 (d, *J* = 8.8 Hz, 1H), 7.82 (d, *J* = 8.0 Hz, 1H), 7.47 (td, *J* = 7.7, 1.5 Hz, 1H), 7.44 – 7.38 (m, 1H),

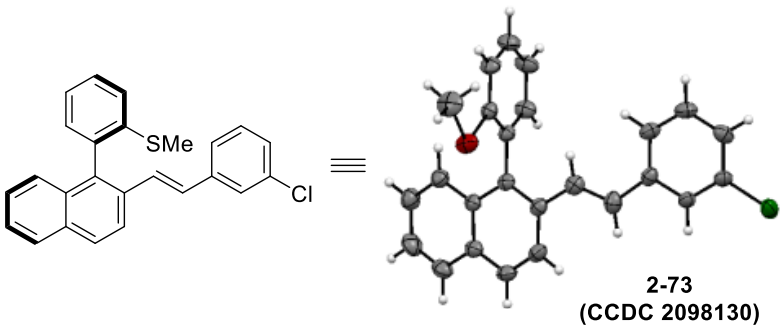
7.35 (dd, *J* = 8.0, 1.2 Hz, 1H), 7.34 – 7.24 (m, 3H), 7.23 – 7.14 (m, 5H), 7.08 (d, *J* = 16.3 Hz, 1H), 6.81 (d, *J* = 16.3 Hz, 1H), 2.27 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.50, 136.64, 136.59, 136.27, 133.19, 133.17, 132.78, 132.76, 131.28, 128.84, 128.68, 128.56, 128.44, 128.14, 127.87, 127.77, 126.63, 126.48, 126.11, 124.77, 124.67, 122.59, 15.49. HRMS (EI-TOF) calcd for $C_{25}H_{19}ClS$ (M^+): 386.0896, found: 386.0896. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 6.8 min, t (major) = 7.9 min, 90% ee. $[\alpha]_D^{20}$ = -230.4 (c = 1.0, $CHCl_3$).

(*E*)-(2-(2-(3-chlorostyryl)naphthalen-1-yl)phenyl)(methyl)sulfane (2-73)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(17.0 mg, 88%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.94 – 7.87 (m, 2H), 7.85 (d, *J* = 8.1 Hz, 1H), 7.50 (td, *J* = 7.7, 1.5 Hz, 1H), 7.47 – 7.41 (m, 1H), 7.40 – 7.26 (m, 5H), 7.21 – 7.13 (m, 4H), 7.08 (d, *J* = 16.3 Hz, 1H), 6.87 (d, *J* = 16.2 Hz, 1H), 2.30 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.67, 139.45, 136.80, 136.52, 134.57, 133.25, 132.74, 132.65, 131.23, 129.85, 128.74, 128.57, 128.39, 128.13, 127.47, 126.70, 126.63, 126.51, 126.18, 124.79, 124.76, 124.68, 122.66, 15.47. HRMS (EI-TOF) calcd for $C_{25}H_{19}ClS$ (M^+): 386.0896, found: 386.0895. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 12.3 min, t (major) = 9.0 min, 97% ee. $[\alpha]_D^{20}$ = -218.1 (c = 1.0, $CHCl_3$).

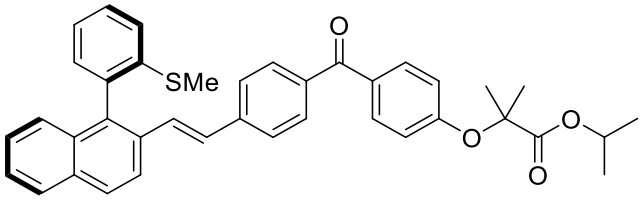
X-ray Data of 2-73



Empirical formula	$C_{25}H_{19}ClS$
Formula weight	386.91
Temperature/K	170.0
Crystal system	monoclinic

Space group	$P2_1$
a/Å	11.316(6)
b/Å	8.434(4)
c/Å	11.436(5)
α/°	90
β/°	114.617(17)
γ/°	90
Volume/Å^3	992.3(8)
Z	2
ρ_{calc}g/cm^3	1.295
μ/mm^{-1}	0.304
F(000)	404.0
Crystal size/mm^3	0.48 × 0.32 × 0.12
Radiation	MoKα (λ = 0.71073)
2Θ range for data collection/°	6.22 to 54.194
Index ranges	$-14 \le h \le 14$, $-10 \le k \le 10$, $-14 \le l \le 14$
Reflections collected	20060
Independent reflections	4348 [R_{int} = 0.0301, R_{sigma} = 0.0257]
Data/restraints/parameters	4348/79/309
Goodness-of-fit on F^2	1.090
Final R indexes [I>=2σ (I)]	R_1 = 0.0278, wR_2 = 0.0698
Final R indexes [all data]	R_1 = 0.0290, wR_2 = 0.0713
Largest diff. peak/hole / e Å^{-3}	0.16/-0.19
Flack parameter	0.006(17)

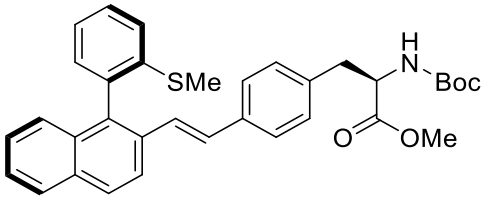
Isopropyl (*E*)-2-methyl-2-(4-(4-(2-(1-(2-(methylthio)phenyl)naphthalen-2-yl)vinyl)benzoyl)phenoxy)propanoate (2-74)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(28.5 mg, 95%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98 (d, *J* = 8.8 Hz, 1H), 7.92 (d, *J* = 8.8 Hz, 1H), 7.88 (d, *J* = 8.1 Hz, 1H), 7.78 – 7.72 (m, 2H), 7.69 (d, *J* = 8.3 Hz, 2H), 7.52 (td, *J*

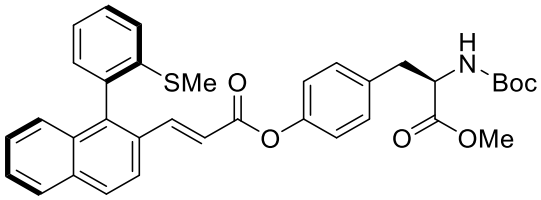
= 7.7, 1.6 Hz, 1H), 7.49 – 7.44 (m, 1H), 7.43 – 7.28 (m, 6H), 7.25 – 7.17 (m, 2H), 7.01 (d, *J* = 16.3 Hz, 1H), 6.91 – 6.80 (m, 2H), 5.10 (hept, *J* = 6.4 Hz, 1H), 2.32 (s, 3H), 1.67 (s, 6H), 1.22 (s, 3H), 1.20 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 194.96, 173.31, 159.49, 141.47, 139.44, 137.04, 136.76, 136.40, 133.30, 132.69, 132.57, 132.01, 131.24, 130.88, 130.46, 129.52, 128.74, 128.60, 128.14, 126.67, 126.53, 126.36, 126.29, 124.74, 124.55, 122.55, 117.25, 79.44, 69.42, 25.47, 21.64, 15.45. HRMS (ESI-TOF) calcd for $C_{39}H_{36}O_4S$ ($M+Na^+$): 623.2227, found: 623.2226. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 44.4 min, t (major) = 39.3 min, 94% ee. $[\alpha]_D^{20}$ = -174.4 (c = 1.2, $CHCl_3$).

Methyl (2*R*)-2-((tert-butoxycarbonyl)amino)-3-(4-((*E*)-2-(1-(2-(methylthio)phenyl)naphthalen-2-yl)vinyl)phenyl)propanoate (2-75)



根据通用方法 C 经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(21.7 mg, 78%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, *J* = 8.8 Hz, 1H), 7.90 (d, *J* = 8.8 Hz, 1H), 7.86 (d, *J* = 8.0 Hz, 1H), 7.51 (td, *J* = 7.7, 1.6 Hz, 1H), 7.47 – 7.42 (m, 1H), 7.41 – 7.28 (m, 4H), 7.24 (d, *J* = 8.1 Hz, 2H), 7.20 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.15 (d, *J* = 16.3 Hz, 1H), 7.03 (d, *J* = 7.8 Hz, 2H), 6.85 (d, *J* = 16.3 Hz, 1H), 4.96 (d, *J* = 8.5 Hz, 1H), 4.57 (q, *J* = 6.5 Hz, 1H), 3.71 (s, 3H), 3.16 – 2.87 (m, 2H), 2.31 (s, 3H), 1.41 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 172.46, 155.22, 139.48, 136.70, 136.55, 136.33, 135.43, 133.06, 133.06, 132.76, 131.28, 129.63, 129.31, 128.61, 128.48, 128.12, 126.98, 126.93, 126.56, 126.42, 125.98, 124.75, 124.60, 122.67, 80.11, 54.43, 52.40, 38.18, 28.42, 15.49. HRMS (ESI-TOF) calcd for $C_{34}H_{35}NO_4S$ ($M+Na^+$): 576.2179, found: 576.2182. 手性 HPLC 分离条件：a Daicel Chiralpak OD-H, *n*-hexane/2-propanol = 98/2, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 42.8 min, t (major) = 36.5 min, 93% de. $[\alpha]_D^{20}$ = -90.7 (c = 1.1, $CHCl_3$).

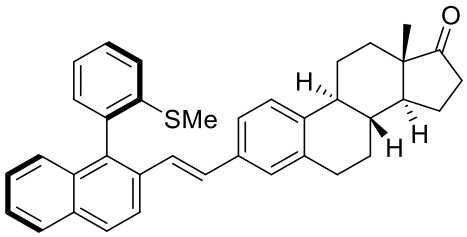
4-((*S*)-2-((tert-butoxycarbonyl)amino)-3-methoxy-3-oxopropyl)phenyl (*E*)-3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)acrylate (2-76)



根据通用方法 C 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(28.4 mg, 95%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.98 – 7.85 (m, 3H), 7.65 (d, *J* = 15.9 Hz, 1H), 7.56 – 7.45 (m, 2H), 7.43 – 7.33 (m, 3H), 7.29 (td, *J* = 7.4, 1.2 Hz, 1H), 7.16 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.12 (d, *J* = 8.4 Hz, 2H), 7.07 – 7.00 (m, 2H), 6.67 (d, *J* = 16.0 Hz, 1H), 5.06 – 4.70 (m, 1H), 4.62 – 4.30 (m, 1H),

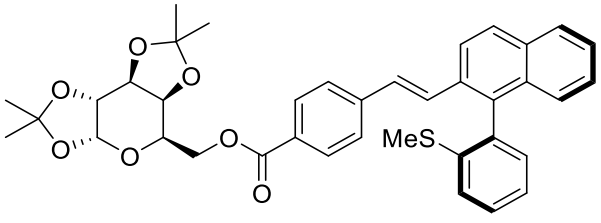
3.71 (s, 3H), 3.15 – 2.84 (m, 2H), 2.32 (s, 3H), 1.43 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 172.25, 165.39, 155.12, 149.89, 144.95, 140.13, 139.09, 135.31, 134.37, 133.41, 132.49, 130.94, 130.18, 130.11, 129.05, 128.81, 128.14, 127.37, 127.06, 126.92, 124.72, 124.70, 122.67, 121.71, 118.00, 80.05, 54.39, 52.33, 37.68, 28.34, 15.41. HRMS (ESI-TOF) calcd for $C_{35}H_{35}NO_6S$ ($M+Na^+$): 620.2077, found: 620.2077. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 36.6 min, t (major) = 29.3 min, 90% de. $[\alpha]_D^{20}$ = -129.7 (c = 1.0, $CHCl_3$).

(8*R*,9*S*,13*S*,14*S*)-13-methyl-3-((*E*)-2-(1-(2-(methylthio)phenyl)naphthalen-2-yl)vinyl)-6,7,8,9,11,12,13,14,15,16-decahydro-17H-cyclopenta[a]phenanthren-17-one (2-77)

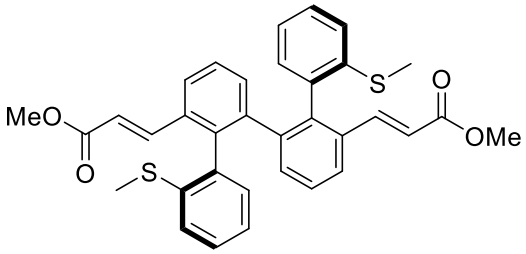


根据通用方法 C 经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(22.7 mg, 86%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, *J* = 8.8 Hz, 1H), 7.90 (d, *J* = 8.8 Hz, 1H), 7.86 (d, *J* = 8.0 Hz, 1H), 7.50 (td, *J* = 7.6, 1.5 Hz, 1H), 7.47 – 7.42 (m, 1H), 7.41 – 7.28 (m, 4H), 7.24 – 7.18 (m, 2H), 7.18 – 7.11 (m, 2H), 7.05 (s, 1H), 6.84 (d, *J* = 16.3 Hz, 1H), 2.88 (dd, *J* = 9.1, 4.2 Hz, 2H), 2.52 (dd, *J* = 18.8, 8.6 Hz, 1H), 2.44 – 2.36 (m, 1H), 2.33 – 2.23 (m, 4H), 2.22 – 1.95 (m, 4H), 1.67 – 1.45 (m, 6H), 0.91 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 220.99, 139.52, 139.46, 136.90, 136.71, 136.17, 135.47, 133.32, 133.02, 132.80, 131.29, 129.67, 128.54, 128.44, 128.11, 127.75, 126.77, 126.52, 126.40, 125.88, 125.70, 124.76, 124.74, 123.87, 122.81, 50.63, 48.11, 44.60, 38.29, 35.99, 31.72, 29.49, 26.60, 25.83, 21.72, 15.55, 13.97. HRMS (ESI-TOF) calcd for $C_{37}H_{36}OS$ ($M+Na^+$): 551.2379, found: 551.2375. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 24.5 min, t (major) = 32.6 min, 97% de. $[\alpha]_D^{20}$ = -28.8 (c = 1.2, $CHCl_3$).

((3a*R*,5*R*,5a*S*,8a*S*,8b*R*)-2,2,7,7-tetramethyltetrahydro-5H-bis([1,3]dioxolo)[4,5-b:4',5'-d]pyran-5-yl)methyl 4-((*E*)-2-((S)-1-(2-(methylthio)phenyl)naphthalen-2-yl)vinyl)benzoate (2-78)

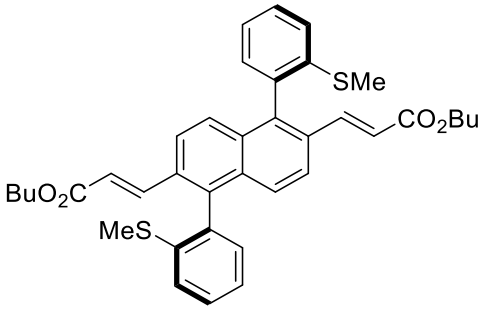


根据通用方法 C 经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(31.6 mg, 99%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.00 – 7.93 (m, 3H), 7.91 (d, *J* = 8.8 Hz, 1H), 7.86 (d, *J* = 8.1 Hz, 1H), 7.52 (td, *J* = 8.0, 1.3 Hz, 1H), 7.49 – 7.42 (m, 1H), 7.42 – 7.28 (m, 6H),



7.23 – 7.15 (m, 2H), 6.98 (d, *J* = 16.3 Hz, 1H), 5.57 (d, *J* = 4.9 Hz, 1H), 4.65 (dd, *J* = 7.9, 2.4 Hz, 1H), 4.57 – 4.47 (m, 1H), 4.44 – 4.27 (m, 3H), 4.20 – 4.13 (m, 1H), 2.31 (s, 3H), 1.51 (s, 3H), 1.47 (s, 3H), 1.35 (s, 3H), 1.33 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.27, 142.28, 139.42, 137.08, 136.33, 133.31, 132.69, 132.51, 131.22, 130.15, 129.65, 128.77, 128.69, 128.60, 128.57, 128.15, 126.67, 126.53, 126.50, 126.30, 124.74, 124.52, 122.53, 109.79, 108.92, 96.43, 71.22, 70.80, 70.59, 66.23, 63.86, 26.15, 26.09, 25.10, 24.61, 15.42. HRMS (ESI-TOF) calcd for $C_{38}H_{38}O_7S$ ($M+Na^+$): 661.2230, found: 661.2233. 手性 HPLC 分离条件：a Daicel Chiralpak IF, *n*-hexane/2-propanol = 70/30, v = 1.2 mL·min^{-1}, λ = 254 nm, t (minor) = 6.0 min, t (major) = 5.4 min, 94% d.e. $[\alpha]_D^{20}$ = -170.3 (c = 1.0, $CHCl_3$).

dibutyl 3,3'-(1,5-bis(2-(methylthio)phenyl)naphthalene-2,6-diyl)(2*E*,2'*E*)-diacrylate (2-79)



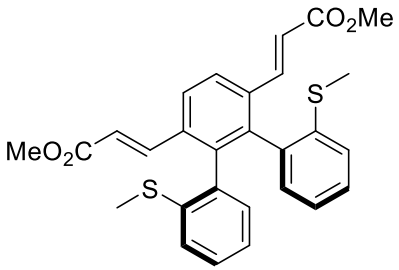
通过对标准反应条件进行微调:**2-1c** (0.05 mmol, 1.0 equiv)，**2-2a** (0.3 mmol)，$Pd(OAc)_2$ (1.7 mg, 15 mol%)，**2-L14** (30 mol%)，AgOAc (0.2 mmol)，Et_2O (0.5 ml)，60 ^{0}C 反应 72 小时然后经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(25.3 mg, 81%)。^{1}H NMR (400 MHz, $CDCl_3$) δ7.69 (d, *J* = 9.0 Hz, 1H), 7.51 (td, *J* = 7.7, 1.6 Hz, 1H), 7.48 – 7.35 (m, 3H), 7.35 – 7.27 (m, 1H), 7.18 (dd, *J* = 25.1, 7.4 Hz, 1H), 6.41 (d, *J* = 15.9 Hz, 1H), 4.09 (t, *J* = 6.5 Hz, 2H), 2.40 – 2.26 (m, 3H), 1.63 – 1.52 (m, 2H), 1.37 – 1.26 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.01, 142.60, 142.56, 139.55, 139.46, 135.43, 133.38, 131.50, 131.06, 129.11, 127.50, 124.83, 124.79, 123.56, 119.72, 64.38, 30.75, 19.27, 15.51, 13.87. HRMS (ESI-TOF) calcd for $C_{38}H_{40}O_4S_2$ ($M+Na^+$): 647.2252, found: 647.2258. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 85/15, v = 1.1 mL·min^{-1}, λ = 254 nm, t (minor) = 9.1 min, t (major) = 10.7 min, 97% ee, >20:1 *dr* $[\alpha]_D^{20}$ = -43.4 (c = 1.0, $CHCl_3$).

dimethyl 3,3'-(2,2'''-bis(methylthio)-[1,1':2',1'':2'',1'''-quaterphenyl]-3'',6'-diyl)(2E,2'E)-diacrylate (2-80)

通过对标准反应条件进行微调:**2-1d** (0.05 mmol, 1.0 equiv)，**2-2b** (0.3 mmol)，$Pd(OAc)_2$ (1.7

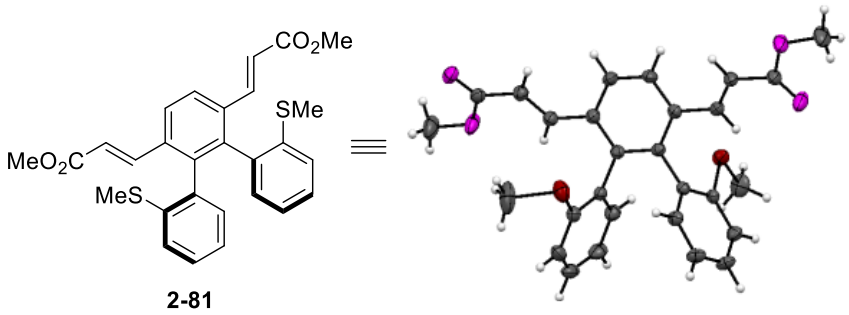
mg, 15 mol%)，**2-L14** (30 mol%)，AgOAc (0.2 mmol)，Et_2O (0.5 ml)，60 ºC 反应 48 小时然后经过制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(14.5 mg, 51%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.52 (t, *J* = 7.2 Hz, 2H), 7.35 (d, *J* = 7.6 Hz, 1H), 7.31 – 7.26 (m, 2H), 7.26 – 7.10 (m, 7H), 7.10 – 6.93 (m, 3H), 6.88 (d, 6H), 6.35 – 6.21 (m, 2H), 3.66 (d, *J* = 4.3 Hz, 6H), 2.49 – 2.21 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.48, 143.75, 140.28, 139.79, 139.26, 133.78, 132.36, 129.60, 128.45, 127.38, 125.02, 124.59, 124.08, 118.59, 51.64, 15.47. HRMS (EI-TOF) calcd for $C_{34}H_{30}O_4S_2$ (M^+): 566.1581, found: 566.1584. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 94/6, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 24.2 min, t (major) = 14.4 min, >99% ee. 91:9 *dr*, $[\alpha]_D^{20}$ = +509.7 (c = 1.0, $CHCl_3$).

dimethyl 3,3'-(2,2''-bis(methylthio)-[1,1':2',1''-terphenyl]-3',6'-diyl)(2*E*,2'*E*)-diacrylate (2-81)



通过对标准反应条件进行微调:**2-1e** (0.05 mmol, 1.0 equiv)，**2-2b** (0.3 mmol)，$Pd(OAc)_2$ (1.7 mg, 15 mol%)，**2-L14** (30 mol%)，AgOAc (0.2 mmol)，Et_2O (0.5 ml)，60 ºC 反应 48 小时然后经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 3/1 为展开剂)(20.9 mg, 85%)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.79 (s, 2H), 7.29 (s, 2H), 7.16 – 7.10 (m, 4H), 7.05 (dd, *J* = 8.4, 1.2 Hz, 2H), 6.88 (td, *J* = 7.4, 1.2 Hz, 2H), 6.41 (d, *J* = 16.0 Hz, 2H), 3.68 (s, 6H), 2.37 (s, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.15, 142.60, 141.24, 137.83, 136.09, 135.61, 128.58, 128.44, 125.83, 124.15, 123.97, 119.48, 51.62, 15.48. HRMS (EI-TOF) calcd for $C_{28}H_{26}O_4S_2$ (M^+): 490.1268, found: 490.1271. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 80/20, v = 1.0 mL·min^{-1}, λ = 254 nm, t (chiral, minor) = 9.1 min, t (chiral, major) = 6.6 min, t (meso) = 7.1 min, 95/5 dr, 98% ee. $[\alpha]_D^{20}$ = +56.0 (c = 1.0, $CHCl_3$).

X-Ray Data of 2-81

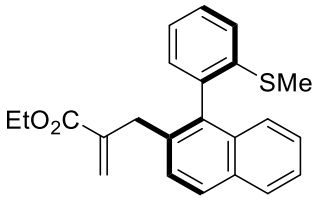


2-81

Empirical formula	$C_{28}H_{26}O_4S_2$
Formula weight	490.61
Temperature/K	170.0
Crystal system	monoclinic
Space group	$P2_1$
a/Å	8.286(3)
b/Å	16.234(7)
c/Å	9.476(4)
α/°	90
β/°	102.309(16)
γ/°	90
Volume/Å^3	1245.4(9)
Z	2
ρ_{calc}g/cm^3	1.308
μ/mm^{-1}	0.246
F(000)	516.0
Crystal size/mm^3	0.39 × 0.23 × 0.18
Radiation	MoKα (λ = 0.71073)
2Θ range for data collection/°	4.4 to 54.218
Index ranges	$-10 \leq h \leq 10$, $-20 \leq k \leq 20$, $-12 \leq l \leq 12$
Reflections collected	30870
Independent reflections	5469 [R_{int} = 0.0290, R_{sigma} = 0.0213]
Data/restraints/parameters	5469/1/311

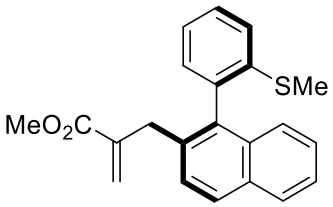
Goodness-of-fit on F^2	1.044
Final R indexes [I>=2σ (I)]	R_1 = 0.0269, wR_2 = 0.0686
Final R indexes [all data]	R_1 = 0.0280, wR_2 = 0.0696
Largest diff. peak/hole / e $Å^{-3}$	0.29/-0.30
Flack parameter	0.006(14)

ethyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-83)



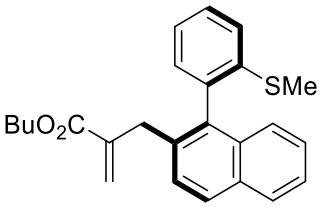
根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(15.0 mg, 83%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.91 – 7.79 (m, 2H), 7.48 – 7.37 (m, 3H), 7.36 – 7.29 (m, 2H), 7.27 – 7.18 (m, 2H), 7.12 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.16 (s, 1H), 5.19 (q, *J* = 1.6 Hz, 1H), 4.13 (q, *J* = 7.1 Hz, 2H), 3.61 (d, *J* = 16.5 Hz, 1H), 3.47 (dt, *J* = 16.4, 1.5 Hz, 1H), 2.30 (s, 3H), 1.23 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.13, 139.99, 139.17, 136.93, 136.71, 134.82, 132.67, 132.49, 130.79, 128.47, 128.24, 128.10, 128.08, 126.72, 126.23, 125.89, 125.51, 124.57, 124.49, 60.78, 35.76, 15.41, 14.31. HRMS (ESI-TOF) calcd for $C_{23}H_{22}O_2S$ ($M+Na^+$): 385.1233, found: 385.1236. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 8.2 min, t (major) = 4.8 min, 90% ee. $[\alpha]_D^{20}$ = +34.0 (c = 1.2, $CHCl_3$).

methyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-84)



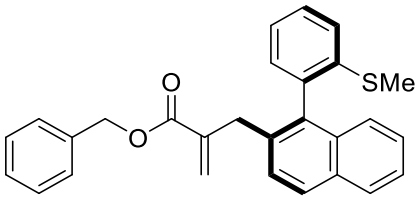
根据通用方法 D 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(14.5 mg, 83%)。 ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.15 (d, *J* = 7.6 Hz, 1H), 8.11 (t, *J* = 3.6 Hz, 2H), 8.09 – 8.02 (m, 2H), 7.98 – 7.90 (m, 2H), 7.52 (d, *J* = 9.3 Hz, 1H), 7.51 – 7.45 (m, 1H), 7.36 (d, *J* = 7.8 Hz, 1H), 7.29 (td, *J* = 7.4, 1.2 Hz, 1H), 7.22 (dd, *J* = 7.4, 1.6 Hz, 1H), 5.25 (q, *J* = 1.6 Hz, 1H), 3.87 (d, *J* = 16.4 Hz, 1H), 3.75 (d, *J* = 16.3 Hz, 1H), 3.67 (s, 3H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.56, 139.89, 139.48, 137.16, 135.31, 135.20, 131.28, 131.16, 130.87, 130.00, 128.62, 127.75, 127.72, 127.42, 127.38, 126.20, 125.92, 125.43, 125.26, 125.17, 124.80, 124.57, 124.44, 123.77, 51.98, 36.23, 15.37. HRMS (ESI-TOF) calcd for $C_{22}H_{20}O_2S$ ($M+Na^+$): 348.1179, found: 348.1178. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 92/8, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 8.0 min, t (major) = 4.3 min, 90% ee. $[\alpha]_D^{20}$ =+31.8 (c = 1.0, $CHCl_3$).

butyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-85)



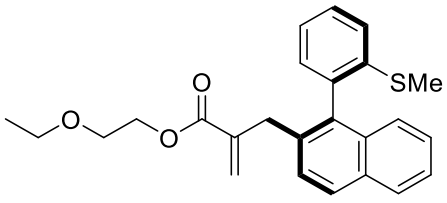
根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(16.0 mg, 82%)。 ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, *J* = 8.5 Hz, 2H), 7.47 – 7.40 (m, 3H), 7.37 – 7.30 (m, 2H), 7.28 – 7.22 (m, 2H), 7.12 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.17 (s, 1H), 5.19 (q, *J* = 1.6 Hz, 1H), 4.08 (t, *J* = 6.6 Hz, 2H), 3.62 (d, *J* = 16.5 Hz, 1H), 3.48 (d, *J* = 16.5 Hz, 1H), 2.30 (s, 3H), 1.64 – 1.58 (m, 2H), 1.36 – 1.28 (m, 2H), 0.89 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.21, 140.00, 139.23, 136.90, 136.71, 134.81, 132.68, 132.49, 130.76, 128.44, 128.23, 128.07, 128.03, 126.70, 126.22, 125.96, 125.49, 124.52, 124.43, 64.71, 35.77, 30.75, 19.29, 15.35, 13.84. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_2S$ ($M+Na^+$): 413.1546, found: 413.1548. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 0.8 mL·min^{-1}, λ = 254 nm, t (minor) = 6.9 min, t (major) = 6.1 min, 93% ee. $[\alpha]_D^{20}$ = +33.2 (c = 1.0, $CHCl_3$).

benzyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-86)



根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(15.1 mg, 71%)。 ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (t, *J* = 7.8 Hz, 2H), 7.45 – 7.38 (m, 3H), 7.36 – 7.29 (m, 2H), 7.29 – 7.24 (m, 4H), 7.22 – 7.15 (m, 3H), 7.01 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.23 (s, 1H), 5.25 (q, *J* = 1.6 Hz, 1H), 5.15 – 5.06 (m, 2H), 3.63 (d, *J* = 16.5 Hz, 1H), 3.51 (d, *J* = 16.5 Hz, 1H), 2.27 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.89, 139.63, 139.24, 136.84, 136.70, 136.08, 134.69, 132.70, 132.50, 130.73, 128.56, 128.43, 128.27, 128.18, 128.09, 128.07, 127.88, 127.43, 126.23, 125.98, 125.51, 124.51, 124.38, 66.52, 35.84, 15.31. HRMS (ESI-TOF) calcd for $C_{28}H_{24}O_2S$ ($M+Na^+$): 447.1389, found: 447.1391. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 5.8 min, t (major) = 6.5 min, 96% ee. $[\alpha]_D^{20}$ = +41.3 (c = 1.1, $CHCl_3$).

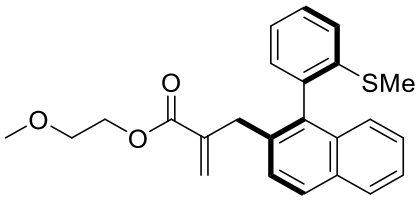
2-ethoxyethyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-87)



根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(14.0 mg, 69%)。 ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, *J* = 8.4 Hz, 2H), 7.49 –

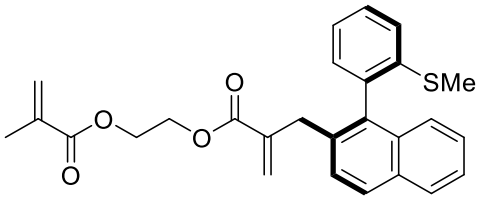
7.40 (m, 3H), 7.39 – 7.30 (m, 2H), 7.29 – 7.26 (m, 1H), 7.25 – 7.19 (m, 1H), 7.13 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.21 (d, *J* = 1.3 Hz, 1H), 5.22 (q, *J* = 1.6 Hz, 1H), 4.28 – 4.18 (m, 2H), 3.67 – 3.57 (m, 3H), 3.54 – 3.42 (m, 3H), 2.30 (s, 3H), 1.17 (t, *J* = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.06, 139.60, 139.23, 136.86, 136.75, 134.68, 132.67, 132.48, 130.78, 128.44, 128.22, 128.07, 128.05, 127.24, 126.21, 125.96, 125.50, 124.52, 124.41, 68.41, 66.72, 64.14, 35.76, 15.33, 15.24. HRMS (ESI-TOF) calcd for $C_{25}H_{26}O_3S$ ($M+Na^+$): 429.1495, found: 429.1493. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 1.1 mL·min^{-1}, λ = 254 nm, t (minor) = 6.0 min, t (major) = 5.6 min, 91% ee. $[\alpha]_D^{20}$ = +28.3 (c = 1.2, $CHCl_3$).

2-methoxyethyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-88)



根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(13.0 mg, 66%)。 ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, *J* = 8.3 Hz, 2H), 7.46 – 7.39 (m, 3H), 7.36 – 7.28 (m, 2H), 7.28 – 7.25 (m, 1H), 7.24 – 7.19 (m, 1H), 7.12 (dd, *J* = 7.5, 1.6 Hz, 1H), 6.21 (d, *J* = 1.2 Hz, 1H), 5.22 (q, *J* = 1.6 Hz, 1H), 4.27 – 4.21 (m, 2H), 3.65 – 3.45 (m, 4H), 3.33 (s, 3H), 2.30 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.05, 139.56, 139.24, 136.87, 136.77, 134.67, 132.68, 132.49, 130.78, 128.45, 128.24, 128.07, 127.31, 126.22, 125.98, 125.51, 124.53, 124.42, 70.56, 63.94, 59.10, 35.76, 15.34. HRMS (ESI-TOF) calcd for $C_{24}H_{24}O_3S$ ($M+Na^+$): 415.1338, found: 415.1340. 手性 HPLC 分离条件：a Daicel Chiralpak ID, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 8.4 min, t (major) = 10.0 min, 94% ee. $[\alpha]_D^{20}$ = +21.8 (c = 1.1, $CHCl_3$).

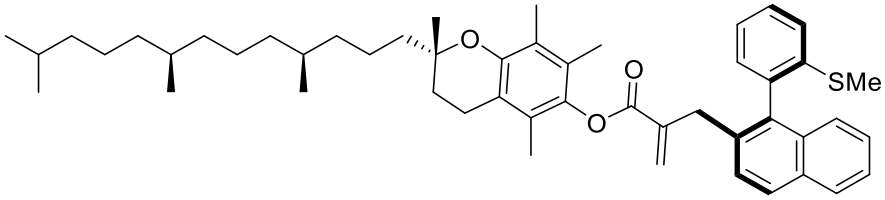
2-(methacryloyloxy)ethyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-89)



根据通用方法 D 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(16.1 mg, 72%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88 – 7.81 (m, 2H), 7.46 – 7.39 (m, 3H), 7.38 – 7.30 (m, 2H), 7.28 – 7.26 (m, 1H), 7.25 – 7.19 (m, 1H), 7.11 (dd, *J* = 7.5, 1.5 Hz, 1H), 6.19 (d, *J* = 1.2 Hz, 1H), 6.04 (t, *J* = 1.3 Hz, 1H), 5.55 – 5.48 (m, 1H), 5.23 (q, *J* = 1.6 Hz, 1H), 4.33 (s, 4H), 3.62 (d, *J* = 16.3 Hz, 1H), 3.49 (d, *J* = 16.4 Hz, 1H), 2.30 (s, 3H), 1.89 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.21, 166.77, 139.32, 139.25, 136.83, 136.75, 135.98, 134.52, 132.67, 132.51, 130.75, 128.47, 128.26, 128.07, 127.94, 127.58, 126.25, 126.14, 125.95, 125.54, 124.51, 124.42, 62.45, 62.43, 35.79, 18.34, 15.31.

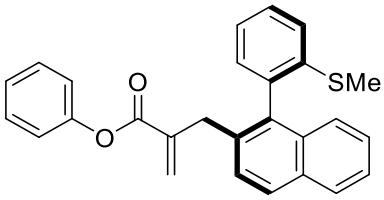
HRMS (ESI-TOF) calcd for $C_{27}H_{26}O_4S$ ($M+Na^+$): 469.1444, found: 469.1448. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.1 mL·min^{-1}, λ = 254 nm, t (minor) = 5.6 min, t (major) = 6.2 min, 90% ee. $[\alpha]_D^{20}$ = +34.0 (c = 0.9, $CHCl_3$).

(*S*)-2,5,7,8-tetramethyl-2-((4*S*,8*S*)-4,8,12-trimethyltridecyl)chroman-6-yl 2-((1-((*R*)-2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-90)



根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(10.1 mg, 27%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (t, *J* = 7.7 Hz, 2H), 7.79 (d, *J* = 8.8 Hz, 1H), 7.56 – 7.45 (m, 2H), 7.43 – 7.31 (m, 4H), 7.29 – 7.26 (m, 1H), 7.25 – 7.16 (m, 6H), 6.43 (d, *J* = 15.9 Hz, 1H), 4.13 (t, *J* = 6.5 Hz, 2H), 1.66 – 1.60 (m, 2H), 1.42 – 1.29 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.63, 149.43, 140.59, 139.32, 139.26, 136.86, 136.82, 134.51, 132.75, 132.57, 130.89, 128.46, 128.26, 128.10, 128.00, 126.88, 126.24, 126.00, 125.52, 125.09, 124.51, 124.37, 123.07, 117.45, 75.13, 39.52, 37.59, 37.43, 36.15, 32.93, 32.85, 28.12, 24.94, 24.58, 22.87, 22.78, 21.16, 20.70, 19.90, 19.79, 15.30, 11.92. HRMS (ESI-TOF) calcd for $C_{50}H_{66}O_3S$ ($M+Na^+$): 769.4625, found: 769.4625. 手性 HPLC 分离条件：a Daicel Chiralpak IA, *n*-hexane/2-propanol = 80/20, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 13.7 min, t (major) = 17.4 min, 97% de. $[\alpha]_D^{20}$ = +34.3 (c = 1.0, $CHCl_3$).

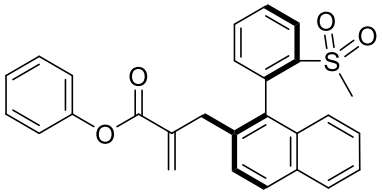
phenyl (*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylate (2-91)



根据通用方法 D 经过制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(10.9 mg, 53%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.87 (dd, 2H), 7.50 (d, *J* = 8.5 Hz, 1H), 7.47 – 7.41 (m, 2H), 7.38 – 7.28 (m, 5H), 7.28 – 7.15 (m, 3H), 7.14 (dd, *J* = 7.5, 1.6 Hz, 1H), 7.03 – 6.94 (m, 2H), 6.38 (s, 1H), 5.37 (d, *J* = 1.6 Hz, 1H), 3.81 – 3.57 (m, 2H), 2.29 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.57, 150.95, 139.35, 139.25, 136.88, 136.81, 134.42, 132.72, 132.57, 130.82, 129.47, 128.66, 128.53, 128.35, 128.11, 128.05, 126.29, 125.99, 125.82, 125.60, 124.56, 124.44, 121.72, 35.99, 15.31. HRMS (ESI-TOF) calcd for $C_{27}H_{22}O_2S$ ($M+Na^+$): 433.1233, found: 433.1235. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1. mL·min^{-1}, λ = 254 nm, t (minor) = 5.9 min, t (major) = 6.3 min,

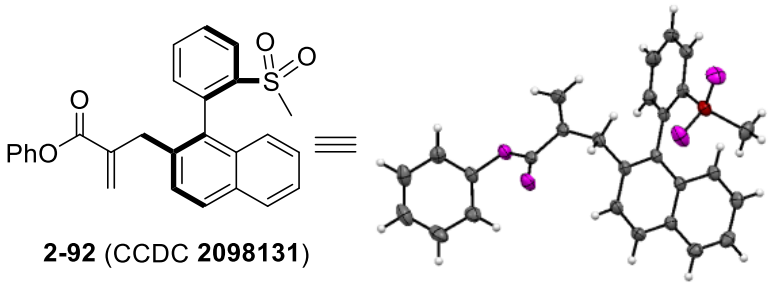
88% ee. $[\alpha]_D^{20}$ =+39.8 (c = 0.49, THF).

phenyl (*R*)-2-((1-(2-(methylsulfonyl)phenyl)naphthalen-2-yl)methyl)acrylate (2-92)



通过如下反应制备:室温下，**2-91** (0.1 mmol)和 *m*-CPBA (0.22 mol)在二氯甲烷(1 ml)中反应过夜。反应完全后，过滤旋干经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 9/1 为展开剂)(44.3 mg, 99%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.37 – 8.31 (m, 1H), 7.93 (d, *J* = 8.6 Hz, 1H), 7.89 (d, *J* = 8.1 Hz, 1H), 7.73 – 7.65 (m, 2H), 7.53 (d, *J* = 8.5 Hz, 1H), 7.44 (t, *J* = 7.2 Hz, 1H), 7.40 – 7.28 (m, 4H), 7.19 (t, *J* = 7.3 Hz, 1H), 7.07 (d, *J* = 8.5 Hz, 1H), 7.00 – 6.88 (m, 2H), 6.45 (s, 1H), 5.55 (s, 1H), 3.82 (d, *J* = 16.5 Hz, 1H), 3.56 (d, *J* = 16.4 Hz, 1H), 2.40 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 165.34, 150.84, 140.30, 139.22, 138.58, 136.31, 134.01, 133.62, 133.58, 132.85, 132.24, 129.52, 129.21, 129.07, 128.93, 128.55, 127.33, 126.66, 125.92, 125.65, 125.61, 121.68, 43.85, 37.11. HRMS (ESI-TOF) calcd for $C_{27}H_{22}O_4S$(M+Na^+): 465.1131, found: 465.1134. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 18.5 min, t (major) = 28.1 min, 89% ee. $[\alpha]_D^{20}$ = +114.1 (c = 0.5, THF).

X-ray Data of 92

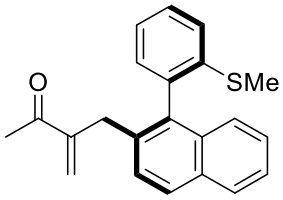


2-92 (CCDC **2098131**)

Empirical formula	$C_{27}H_{22}O_4S$
Formula weight	442.50
Temperature/K	170.0
Crystal system	orthorhombic
Space group	$P2_12_12_1$
a/Å	8.8344(3)
b/Å	14.4678(5)
c/Å	17.0334(6)
α/°	90
β/°	90
γ/°	90
Volume/Å^3	2177.11(13)
Z	4
ρ_{calc}g/cm^3	1.350
μ/mm^{-1}	0.181
F(000)	928.0
Crystal size/mm^3	0.46 × 0.34 × 0.3
Radiation	MoKα (λ = 0.71073)
2Θ range for data collection/°	4.782 to 54.238
Index ranges	$-11 \le h \le 11$, $-18 \le k \le 17$, $-21 \le l \le 21$
Reflections collected	35887
Independent reflections	4817 [R_{int} = 0.0271, R_{sigma} = 0.0211]
Data/restraints/parameters	4817/0/290
Goodness-of-fit on F^2	1.072

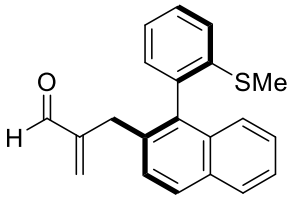
Final R indexes [I>=2σ (I)]	R_1 = 0.0251, wR_2 = 0.0671
Final R indexes [all data]	R_1 = 0.0256, wR_2 = 0.0675
Largest diff. peak/hole / e Å^{-3}	0.18/-0.27
Flack parameter	-0.009(12)

(*R*)-3-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)but-3-en-2-one (2-93)



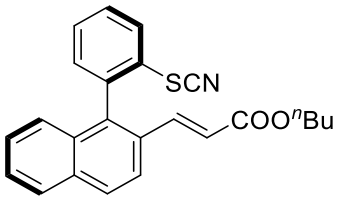
根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(10.5 mg, 63%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (dd, *J* = 8.2, 3.0 Hz, 2H), 7.46 – 7.40 (m, 2H), 7.39 – 7.29 (m, 3H), 7.28 – 7.26 (m, 1H), 7.22 (td, *J* = 7.4, 1.2 Hz, 1H), 7.11 (dd, *J* = 7.4, 1.5 Hz, 1H), 6.02 (s, 1H), 5.41 (t, *J* = 1.7 Hz, 1H), 3.63 – 3.38 (m, 2H), 2.30 (s, 3H), 2.27 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 199.38, 148.39, 139.26, 136.91, 136.76, 135.21, 132.67, 132.44, 130.75, 128.47, 128.27, 128.07, 127.05, 126.23, 125.95, 125.49, 124.46, 34.51, 25.99, 15.34. HRMS (ESI-TOF) calcd for $C_{22}H_{20}OS$ ($M+Na^+$): 355.1127, found: 355.1129. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 7.4 min, t (major) = 5.9 min, 92% ee. $[\alpha]_D^{20}$ = +50.5 (c = 0.9, $CHCl_3$).

(*R*)-2-((1-(2-(methylthio)phenyl)naphthalen-2-yl)methyl)acrylaldehyde (2-94)



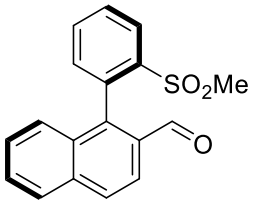
根据通用方法 D 经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(9.1 mg, 57%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 9.50 (s, 1H), 7.85 (dd, *J* = 8.3, 1.9 Hz, 2H), 7.47 – 7.40 (m, 2H), 7.39 – 7.29 (m, 3H), 7.28 – 7.25 (m, 1H), 7.21 (td, *J* = 7.4, 1.2 Hz, 1H), 7.09 (dd, *J* = 7.5, 1.5 Hz, 1H), 5.98 (s, 1H), 5.89 (s, 1H), 3.62 – 3.31 (m, 2H), 2.30 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 194.04, 149.49, 139.23, 136.86, 136.73, 135.84, 134.21, 132.68, 132.52, 130.73, 128.56, 128.39, 128.18, 128.10, 126.34, 125.99, 125.62, 124.52, 124.47, 32.09, 15.31. HRMS (ESI-TOF) calcd for $C_{21}H_{18}OS$ ($M+Na^+$): 341.0971, found: 341.0973. 手性 HPLC 分离条件：two Daicel Chiralpak AD-Hs, *n*-hexane/2-propanol = 92/8, v = 0.8 mL · min^{-1}, λ = 254 nm, t (minor) = 14.8 min, t (major) = 15.4 min, 86% ee. $[\alpha]_D^{20}$ = +30.7 (c = 0.9, $CHCl_3$).

butyl (*E*)-3-(1-(2-thiocyanatophenyl)naphthalen-2-yl)acrylate (2-95)



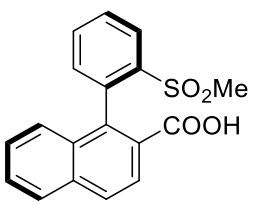
无色液体(33.7 mg, 87%, 97% ee)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, *J* = 8.8 Hz, 1H), 7.90 (t, *J* = 8.4 Hz, 2H), 7.82 (d, *J* = 8.7 Hz, 1H), 7.63 (td, *J* = 7.8, 1.6 Hz, 1H), 7.56 (t, *J* = 7.5 Hz, 2H), 7.44 (t, *J* = 7.6 Hz, 1H), 7.38 – 7.30 (m, 2H), 7.26 – 7.22 (m, 1H), 6.50 (d, *J* = 15.9 Hz, 1H), 4.13 (t, *J* = 6.6 Hz, 2H), 1.66 – 1.59 (m, 2H), 1.40 – 1.30 (m, 2H), 0.92 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.69, 141.34, 137.09, 136.47, 134.17, 132.17, 132.10, 131.19, 130.37, 129.96, 129.17, 128.96, 128.46, 127.72, 127.67, 126.83, 126.32, 122.86, 120.88, 110.07, 64.60, 30.75, 19.30, 13.88. HRMS (ESI-TOF) calcd for $C_{24}H_{21}O_2NS$ ($M+Na^+$): 410.1185, found: 410.1186. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 80/20, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 7.9 min, t (major) = 8.6 min, 97% ee. $[\alpha]_D^{20}$ = -52.5 (c = 1.0, $CHCl_3$).

1-(2-(methylsulfonyl)phenyl)-2-naphthaldehyde (2-96)



在 10 mL 密封管中依次加入 **2-4** (0.1 mmol)，OsO_4 (36 μl, 0.005 mmol)，$NaIO_4$ (107.0 mg, 0.5 mmol)，THF/H_2O (2/1, 3 mL)。反应混合物在 40 °C 下反应过夜。反应完全后加入饱和亚硫酸钠水溶液淬灭并使用乙酸乙酯萃取。收集有机相，经无水硫酸钠干燥后旋干浓缩经制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(27.9 mg, 90%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 9.82 (s, 1H), 8.36 (d, *J* = 7.2 Hz, 1H), 8.12 (d, *J* = 8.6 Hz, 1H), 8.04 (d, *J* = 8.6 Hz, 1H), 7.97 (d, *J* = 8.2 Hz, 1H), 7.86 – 7.74 (m, 2H), 7.62 (t, *J* = 7.5 Hz, 1H), 7.51 – 7.41 (m, 2H), 7.29 (d, *J* = 8.5 Hz, 1H), 2.46 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 191.40, 140.51, 140.43, 135.94, 135.55, 133.53, 133.43, 132.45, 132.21, 129.74, 129.46, 128.98, 128.84, 127.59, 126.83, 122.72, 43.91. HRMS (ESI-TOF) calcd for $C_{18}H_{14}O_3S$ ($M+Na^+$): 333.0556, found: 333.0558. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 70/30, v = 1.3 mL · min^{-1}, λ = 254 nm, t (minor) = 10.6 min, t (major) = 8.2 min, 95% ee. $[\alpha]_D^{20}$ = +21.9 (c = 1.0, $CHCl_3$).

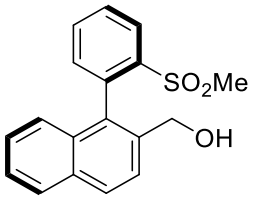
1-(2-(methylsulfonyl)phenyl)-2-naphthoic acid (2-97)



无色液体(31.0 mg, 95%)。^{1}H NMR (400 MHz, CD_3OD) δ 8.19 (d, *J* = 7.6 Hz, 1H), 8.12 (d, *J* = 8.6 Hz, 1H), 8.02 (d, *J* = 8.7 Hz, 1H), 7.96 (d, *J* = 8.2 Hz, 1H), 7.81 – 7.66 (m, 2H), 7.57 (t, *J* = 7.5 Hz, 1H), 7.44 – 7.35 (m, 1H), 7.28 (d, *J* = 7.2 Hz, 1H), 7.19 (d, *J* = 8.6 Hz, 1H), 2.71 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.04, 141.11, 140.32, 140.21, 136.23, 134.46, 134.35, 133.30, 130.29,

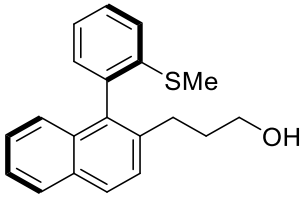
129.60, 129.50, 129.04, 128.80, 128.75, 127.83, 127.08, 44.43. HRMS (ESI-TOF) calcd for $C_{18}H_{14}O_4S$ ($M+Na^+$): 349.0505, found: 349.0506. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 70/30, v = 1.3 mL · min^{-1}, λ = 254 nm, t (minor) = 6.9 min, t (major) = 8.6 min, 95% ee. $[\alpha]_D^{20}$ = +24.1 (c = 1.1, $CHCl_3$).

(1-(2-(methylthio)phenyl)naphthalen-2-yl)methanol (2-98)



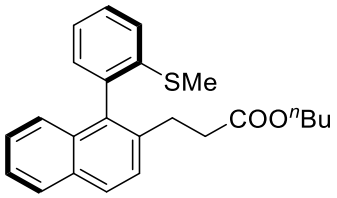
经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(22.5 mg, 72%, 96% ee)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.35 (dd, *J* = 7.8, 1.5 Hz, 1H), 7.99 (d, *J* = 8.6 Hz, 1H), 7.91 (d, *J* = 8.2 Hz, 1H), 7.82 (d, *J* = 8.5 Hz, 1H), 7.76 (td, *J* = 7.5, 1.6 Hz, 1H), 7.70 (td, *J* = 7.7, 1.5 Hz, 1H), 7.51 – 7.43 (m, 1H), 7.40 – 7.31 (m, 2H), 7.06 (d, *J* = 8.4 Hz, 1H), 4.54 – 4.31 (m, 2H), 3.19 (d, *J* = 6.7 Hz, 1H), 2.35 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.69, 138.71, 138.05, 133.80, 133.69, 132.76, 132.18, 132.14, 129.54, 129.41, 128.94, 128.67, 127.27, 126.90, 126.05, 125.62, 63.10, 43.73. HRMS (ESI-TOF) calcd for $C_{18}H_{16}O_3S$ ($M+Na^+$): 312.0820, found: 312.0817. 手性 HPLC 分离条件：a Daicel Chiralpak IA, *n*-hexane/2-propanol = 80/20, v = 1.1 mL · min^{-1}, λ = 254 nm, t (minor) = 14.3 min, t (major) = 12.9 min, 96% ee. $[\alpha]_D^{20}$ = +37.8 (c = 1.0, $CHCl_3$).

3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)propan-1-ol (2-99)



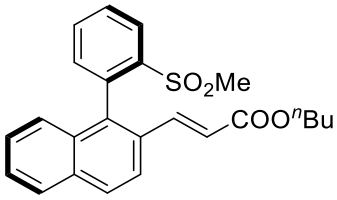
经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 2/1 为展开剂)(21.3 mg, 69%, 93% ee)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90–7.78 (m, 2H), 7.52–7.38 (m, 3H), 7.36 – 7.29 (m, 2H), 7.28–7.20 (m, 2H), 7.15 (dd, *J* = 7.5, 1.6 Hz, 1H), 3.53 (t, *J* = 6.4 Hz, 2H), 2.71–2.59 (m, 1H), 2.58–2.47 (m, 1H), 2.30 (s, 3H), 1.94–1.74 (m, 2H), 1.37 (s, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 139.10, 137.65, 137.13, 135.75, 132.56, 132.16, 130.82, 128.40, 128.33, 128.04, 127.35, 126.22, 125.83, 125.26, 124.56, 124.13, 62.37, 33.62, 29.72, 15.12. HRMS (ESI-TOF) calcd for $C_{20}H_{20}OS$ ($M+Na^+$): 331.1127, found: 331.1128. 手性 HPLC 分离条件：a Daicel Chiralpak IA, *n*-hexane/2-propanol = 90/10, v = 1.2 mL · min^{-1}, λ = 254 nm, t (minor) = 7.3 min, t (major) = 6.5 min, 93% ee. $[\alpha]_D^{20}$ =-12.6 (c = 0.6, $CHCl_3$).

butyl 3-(1-(2-(methylthio)phenyl)naphthalen-2-yl)propanoate (2-100)



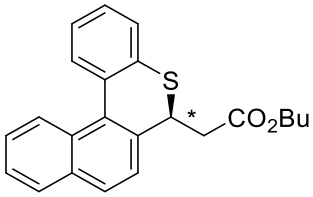
经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(32.2 mg, 85% yield, 97% ee)。^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88–7.79 (m, 2H), 7.49–7.38 (m, 3H), 7.35–7.29 (m, 2H), 7.28–7.20 (m, 2H), 7.15 (d, *J* = 7.4 Hz, 1H), 4.00 (t, *J* = 6.7 Hz, 2H), 2.95–2.84 (m, 1H), 2.83–2.72 (m, 1H), 2.62 –2.46 (m, 2H), 2.30 (s, 3H), 1.57–1.49 (m, 2H), 1.39–1.27 (m, 2H), 0.88 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 173.26, 139.18, 136.90, 136.55, 136.06, 132.64, 132.37, 130.75, 128.47, 128.46, 128.05, 127.29, 126.27, 125.88, 125.41, 124.63, 124.35, 64.38, 35.43, 30.72, 29.17, 19.22, 15.19, 13.82. HRMS (ESI-TOF) calcd for $C_{24}H_{26}O_2S$ ($M+Na^+$): 401.1546, found: 401.1547. 手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 4.8 min, t (major) = 6.3 min, 97% ee. $[\alpha]_D^{20}$ =-12.5 (c = 0.8, $CHCl_3$).

butyl (*E*)-3-(1-(2-(methylsulfonyl)phenyl)naphthalen-2-yl)acrylate (2-101)



经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(31.4 mg, 77%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.34 (dd, *J* = 7.6, 1.8 Hz, 1H), 7.94 (d, *J* = 8.7 Hz, 1H), 7.88 (d, *J* = 8.1 Hz, 1H), 7.84 (d, *J* = 8.8 Hz, 1H), 7.80 – 7.70 (m, 2H), 7.54 – 7.45 (m, 1H), 7.42 – 7.30 (m, 3H), 7.17 (d, *J* = 8.5 Hz, 1H), 6.49 (d, *J* = 15.9 Hz, 1H), 4.10 (t, *J* = 6.5 Hz, 2H), 2.58 (s, 3H), 1.65 – 1.57 (m, 2H), 1.39 – 1.29 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 166.74, 142.36, 140.41, 137.59, 137.31, 133.82, 133.77, 133.32, 133.10, 130.75, 129.84, 129.47, 129.43, 128.27, 127.33, 127.31, 127.07, 122.45, 119.77, 64.50, 44.05, 30.70, 19.26, 13.86. HRMS (ESI-TOF) calcd for $C_{24}H_{24}O_4S$ ($M+Na^+$): 431.1288, found: 431.1290. 手性 HPLC 分离条件：a Daicel Chiralpak IA, *n*-hexane/2-propanol = 80/20, v = 1.0 mL·min^{-1}, λ = 254 nm, t (minor) = 13.7 min, t (major) = 17.4 min, 93% ee. $[\alpha]_D^{20}$ = -31.3 (c = 1.1, $CHCl_3$).

butyl (*R*)-2-(6H-naphtho[2,1-c]thiochromen-6-yl)acetate (2-102)



经过制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 9/1 为展开剂)(25.4 mg, 70%)。^{1}H NMR (400 MHz, $CDCl_3$) δ 8.43 – 8.32 (m, 1H), 7.95 – 7.83 (m, 2H), 7.79 (d, *J* = 8.3 Hz, 1H), 7.60 (dd, *J* = 7.5, 1.6 Hz, 1H), 7.52 – 7.40 (m, 3H), 7.40 – 7.26 (m, 2H), 4.43 (t, *J* = 7.6 Hz, 1H), 4.15 – 3.98 (m, 2H), 2.72 – 2.55 (m, 2H), 1.58 – 1.49 (m, 2H), 1.34 – 1.26 (m, 2H), 0.89 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.99, 136.82, 134.32, 133.05, 132.63, 131.25,

130.94, 130.72, 130.42, 128.64, 128.56, 127.70, 126.60, 126.03, 125.78, 125.03, 64.76, 41.85, 38.80, 30.69, 19.19, 13.78. HRMS (EI-TOF) calcd for $C_{23}H_{22}O_2S$ (M^+): 362.1336, found: 362.1334. 手性 HPLC 分离条件：a Daicel Chiralpak AS-H, *n*-hexane/2-propanol = 94/6, v = 1.0 mL · min^{-1}, λ = 254 nm, t (minor) = 6.3 min, t (major) = 7.2 min, 87% ee. $[\alpha]_D^{20}$ = -236.5 (c = 0.8, $CHCl_3$).

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第三章 钯催化不对称芳烃碳氢键官能团化构建轴手性烯基芳烃

3.1 研究背景

轴手性化合物广泛存在于药物分子和天然产物中[1,2]，也是不对称合成中广泛应用的优势骨架[3-8]。相比近期得到迅猛发展的联芳基轴手性化合物[9–14]，一类最早被 Adams[15]发现并研究的手性轴介于烯烃和芳烃之间的轴手性烯基芳烃化合物却鲜有被研究报道[16]。阻碍这一类轴手性化合物发展的主要原因是其拥有一个灵活易动的骨架，导致翻转能垒要比联芳轴手性化合物低很多。因此，不对称合成轴手性烯基芳烃是极具挑战性的(**图 3.1**)。

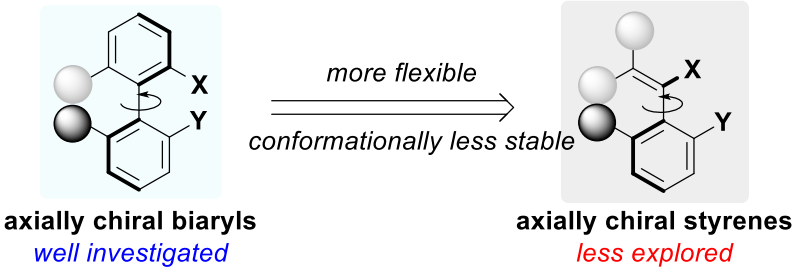


图 3.1 含非环状烯烃结构轴手性烯基芳烃的合成挑战

另一方面，手性烯烃不仅可以作为全合成中的合成子[17]，还可以作为手性催化剂或手性配体应用于不对称反应中[18–20]。所以，研究和发展高效的方法对烯基芳烃轴手性骨架进行不对称合成是非常有意义的。

早期的研究主要集中于使用化学当量的手性分子作为反应前体，通过点到轴的手性传递方法来实现不对称合成轴手性烯基芳烃。比如 1996 年，Baker 课题组[21]利用手性亚砜作为手性辅基，通过 1,3-氢迁移的方法合成轴手性烯基芳烃。之后在 2001 年，Miyano 和 Hattori 等人[22]报道了通过 α-取代的手性环酮和格式试剂发生加成反应后在三氟乙酸酐的作用下立体专一性地脱除水分子生成烯基芳烃轴手性化合物。而在 2009 年，Suzuki 课题组[17]将手性亚砜辅助非对映体选择性地合成轴手性烯基芳烃的策略成功应用到了抗生素 **TAN-1085** 的全合成中。

然而，催化不对称合成烯基芳烃轴手性化合物的方法直到近期才得以实现。2016 年，顾振华课题组[23]通过钯催化芳基卤代物与卡宾前体腙类化合物的交叉偶联反应首次实现轴手性烯基芳烃的催化不对称合成(**图 3.2**)。

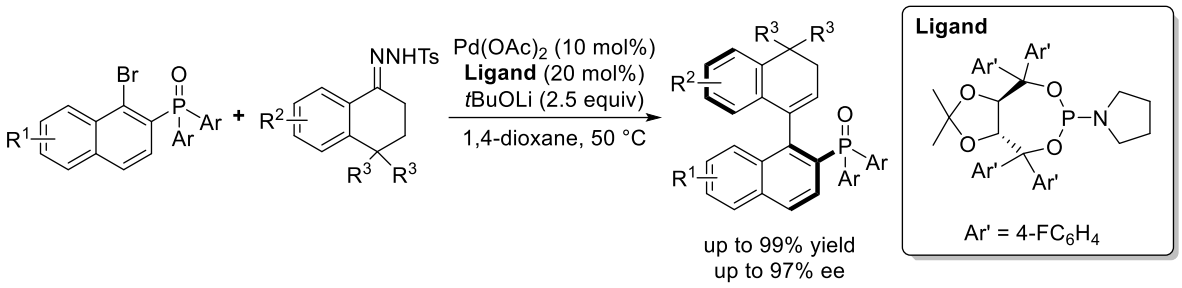


图 3.2 钯催化芳基卤代物与卡宾前体不对称偶联反应构建轴手性烯基芳烃

Smith 课题组[24]则在 2017 年报道了利用手性相转移催化的不对称 *O*-烷基化反应来实现轴手性烯基芳烃的合成(**图 3.3**)。

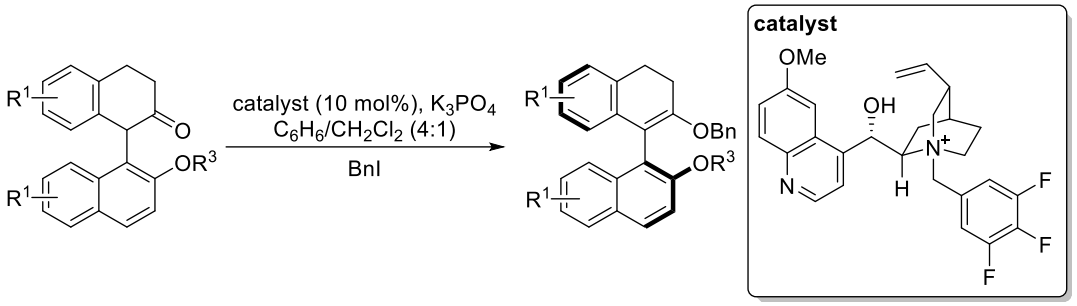


图 3.3 不对称相转移催化烷基化反应

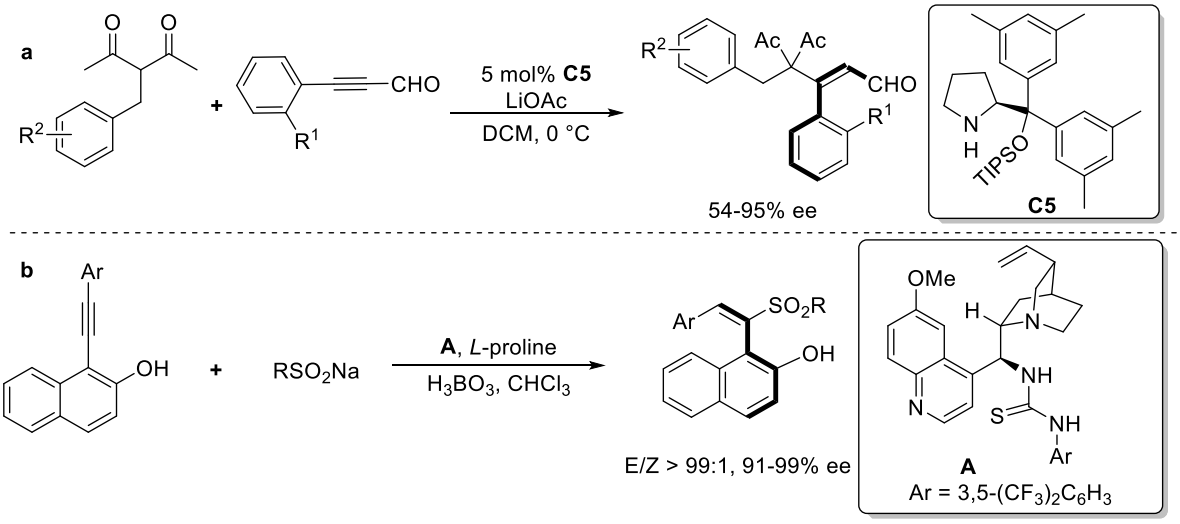


图 3.4 不对称亲核加成反应构建轴手性烯基芳烃

2017 年，谭斌课题组[25]首次报道了有机小分子催化策略来合成轴手性烯基芳烃(**图 3.4a**)。反应使用芳基炔丙醛为底物，在手性吡咯分子的催化下，完成了亲核试剂对炔烃的不对称加成反应，得到轴手性烯基芳烃产物。几乎在同期，闫海龙课题组[26]也利用有机小分子催化策略，使用奎宁衍生的手性硫脲为催化剂，通过一个活性的四取代联烯基醌

(VQMs)中间体，催化不对称合成了烯基芳烃轴手性砜类化合物(**图 3.4b**)。

3.2 课题设计思路

通过对研究背景的梳理，我们发现虽然近年来已经涌现出不少催化不对称合成轴手性烯基芳烃的方法，但是这些方法都存在着一定的局限性。比如顾振华和 Smith 课题组对轴手性烯基芳烃化合物的早期催化不对称合成尝试中产物都是带有一个比较刚性的环烯烃结构，从而提高了轴手性烯基芳烃化合物的稳定性。但是对于一个转动能力更强的开链式烯烃骨架的轴手性烯基芳烃的合成却没有被报道。至此仅有谭斌和闫海龙等人发展的有机小分子催化策略来构建含开链式烯烃结构的轴手性烯基芳烃。因此，急需发展一种简单高效的方法来实现含开链式烯烃结构的轴手性烯基芳烃的催化不对称构建。

不对称碳氢键活化策略作为一种强有力的手段可以用于快速构建联芳轴手性骨架[11, 14, 27–41]，我们设想可以利用导向不对称碳氢键活化策略[14, 43–46]在产物对映体中引入一个大体积的取代基来阻碍其手性轴的转动，从而实现含开链式烯烃结构的轴手性烯基芳烃的快速构建(**图 3.5**)。实现这一合成策略的难点在于：1）反应需要在比较温和的条件下进行以保证轴手性烯基芳烃的稳定性，这与一般比较苛刻的碳氢键活化条件相矛盾；2）需要找寻到一个合适的手性配体和导向基团，平衡反应的活性和手性控制。基于我们课题组前期一系列钯催化不对称碳氢键活化构建轴手性联芳化合物的研究[36–41]，我们发展了以吡啶为导向基团，*L*-焦谷氨酸为手性配体，钯催化不对称碳氢键烯基化和炔基化反应来构建含开链式烯烃结构的轴手性烯基芳烃化合物。

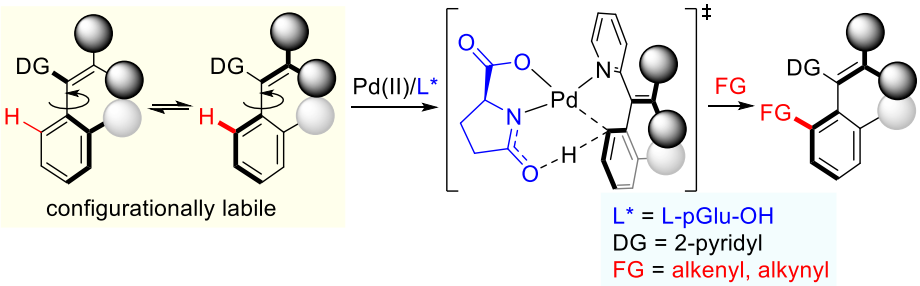
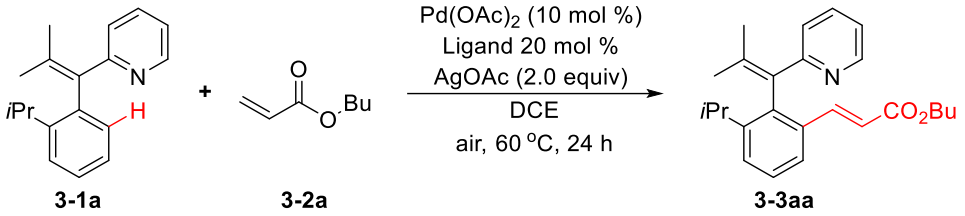


图 3.5 我们的策略：不对称碳氢键官能团化

3.3 反应条件优化

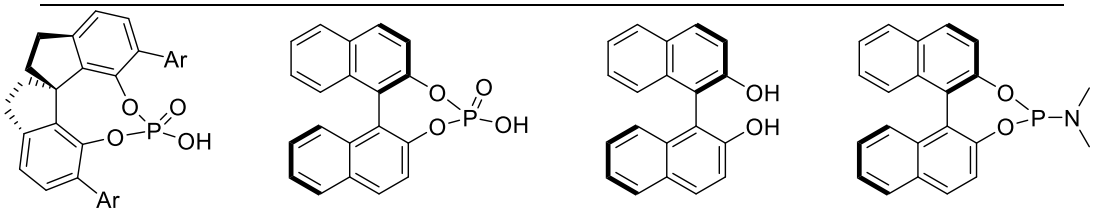
3.3.1 烯基化反应条件优化

表 3.1 手性配体筛选 [a]



3-1a **3-2a** **3-3aa**

entry	Ligand	yield [b] %	ee [c] %
1	**3-L1**	65	43
2	**3-L2**	52	13
3	**3-L3**	61	-24
4	**3-L4**	53	-19
5	**3-L5**	39	-10
6	**3-L6**	72	-15
7	**3-L7**	48	-14
8	**3-L8**	55	-10
9	**3-L9**	44	-3
10	**3-L10**	47	-8
11	**3-L11**	89	3
12	**3-L12**	90	6
13	**3-L13**	93	4
14	**3-L14**	52	0

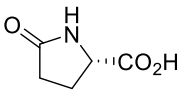


3-L11:(*R*)-STRIP
Ar = 2,4,6-*i*Pr$_3$C$_6$H$_2$

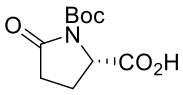
3-L12

3-L13

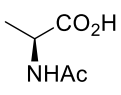
3-L14



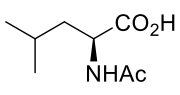
3-L1



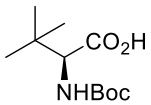
3-L2



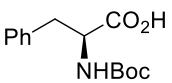
3-L3



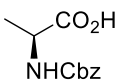
3-L4



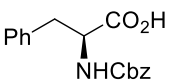
3-L5



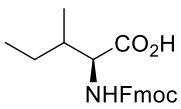
3-L6



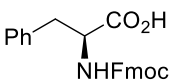
3-L7



3-L8



3-L9



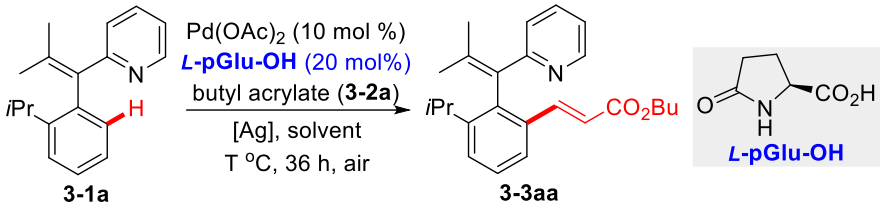
3-L10

[a] 反应条件:**3-1a** (0.1 mmol), **3-2a** (2.0 equiv), $Pd(OAc)_2$ (10 mol %), Ag_3PO_4 (2.0 equiv), Ligand (20 mol %), in DCE (1.0 mL) at 60 °C for 24 h under air. [b] 产率由 CH_2Br_2 作为内标物的 ^1H NMR 测定。[c]ee 值由手性 HPLC 分离测定。

在反应初期，我们选择一个带有吡啶基团的取代苯乙烯 **3-1a** 为我们的模板底物，丙烯酸正丁酯 **3-2a** 为烯基化试剂，$Pd(OAc)_2$ 为催化剂，对反应的手性配体，溶剂，氧化剂等条件进行了筛选。

2008 年，余金权课题组[46]已经证明了单保护氨基酸是一类有效的手性配体被应用于钯催化不对称碳氢键官能团化反应中[47–51]。因此我们首先筛选了各种保护基的单保护氨基酸，令我们高兴的是，当使用 *L*-焦谷氨酸[52]作为手性配体时，反应可以以 65%的产率和 43%的 ee 值得到目标的烯基化产物 **3-3aa**(**表 3.1**，**entry 1**)。

表 3.2 氧化剂、溶剂和反应温度的筛选 [a]



entry	[Ag]	solvent	T/ °C	yield [b] %	ee [c] %
1	AgOAc	DCE	60	65	43
2	AgOAc	MeCN	60	90	79
3	AgOAc	1,4-dioxane	60	56	40
4	AgOAc	Toluene	60	85	25
5	AgOAc	DMF	60	96	70
6	AgOAc	MeOH	60	60	69
7	AgOAc	HFIP	60	85	-21
8	AgOAc	MeCN/MeOH(1:1)	60	80	85
9	AgOAc	MeCN/^{t}BuOH(1:1)	60	93	89
10	AgOAc	MeCN/^{t}BuOH(1:1)	50	96	89
11	AgOAc	MeCN/^{t}BuOH(1:1)	40	95	88
12	AgOAc	MeCN/^{t}BuOH(1:1)	30	44	84
13	AgOAc	MeCN/^{t}BuOH(4:1)	50	93	90
14	Ag_2SO_4	MeCN/^{t}BuOH(4:1)	50	94	93
15	Ag_3PO_4	MeCN/^{t}BuOH(4:1)	50	93	94
16 [d]	Ag_3PO_4	MeCN/^{t}BuOH(4:1)	50	92 (85) [e]	95

[a] 反应条件:**3-1a** (0.1 mmol), **3-2a** (2.0 equiv), $Pd(OAc)_2$ (10 mol %), [Ag] (2.0 equiv), *L*-pGlu-OH (20 mol %) 在溶剂(2.0 mL)中于相应的温度下空气氛围反应 36 小时。[b] 产率由 CH_2Br_2 作为内标物的 ^{1}H NMR 测定。[c]ee 值由手性 HPLC 分离测定。[d]MeCN/*t*BuOH(4:1, 4.0 mL)。[e] 分离产率。

当使用其余的单保护氨基酸为配体时，虽然可以顺利的得到想要的目标烯基化产物，

但是其 ee 值均有不同程度的下降(**entry 3–10**)。同时，使用 *N*-叔丁氧羰基保护的焦谷氨酸作为配体时，其产物的 ee 值会产生明显的下降(**entry 2**)。这表明 *L*-焦谷氨酸中的 N-H 在反应中有重要的作用。另外我们也对其他类型常用的手性配体进行了筛选，比如螺环磷酸、基于 BINOL 骨架的手性磷酸和手性亚膦酰胺以及 BINOL 配体(**entry 11–14**)。令人失望的是，这些手性骨架的配体虽然可以以很好的产率得到烯基化产物，但是都几乎不能诱导出烯基化产物的手性。

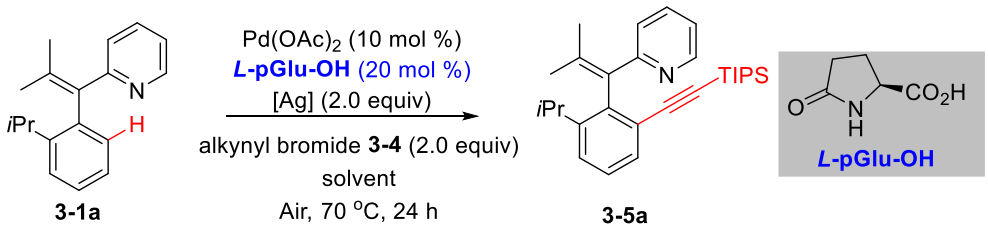
在确定好最优配体后，我们对反应的其他条件也进行了系统的筛选(**表 3.2**)。在对溶剂的筛选中我们发现，乙腈和甲醇均可以对反应产率和手性控制起到促进作用(**entry 2, 6**)。受这个结果的鼓舞，我们继续细致地筛选了溶剂的混合效果，发现溶剂是 MeCN/*t*BuOH (1:1, 0.05 M)时，可以以 93%的核磁产率和 89%的 ee 值得到目标烯基化产物 **3-3aa**(**entry 9**)。接着我们对反应温度进行了筛选，发现 50 ºC 是反应的最优温度(**entry 10**)。然后我们对反应的氧化剂进行了筛选，发现磷酸银是反应的最佳氧化剂，可以将产物的 ee 值上升到 94%，核磁产率保持在 93%(**entry 15**)。最后，将反应的浓度稀释到 0.025M 时，产物的 ee 值可以进一步提升到 95%，而产物的分离产率可以达到 85%(**entry 16**)。

3.3.2 炔基化反应条件优化

在成功实现了通过不对称碳氢键烯基化反应构建轴手性烯基芳烃化合物后，我们又尝试着将这一策略应用于其他的碳氢键官能团化中。我们选取了带有 TIPS-保护的炔基溴 **3-4** 作为反应的炔基化试剂，**3-1a** 为模板底物，$Pd(OAc)_2$ 为催化剂，*L*-焦谷氨酸为手性配体，对炔基化反应条件进行了系统的筛选。

在对反应条件的初步筛选中我们发现，使用碳酸银为添加剂，甲醇为反应溶剂，70 ºC 反应时，目标炔基化产物可以以 39%的分离产率和 93%的 ee 值得到(**entry 5**)。之后对反应的温度和反应时间进行控制，发现在降低温度的同时延长反应时间至 48 小时，可以在保持 ee 值的同时将产率上升到 59%(**entry 9**)。最后经过对溶剂的混合和浓度调整，选用 MeOH/DMSO(1:1, 0.025 M)为溶剂时，在 60 ºC 下反应 24 小时，就可以以最优 86%的产率和 99%的 ee 值得到目标炔基化产物(**entry 18**)。

表 3.3 不对称碳氢键炔基化反应条件筛选 [a]



3-1a **3-5a**

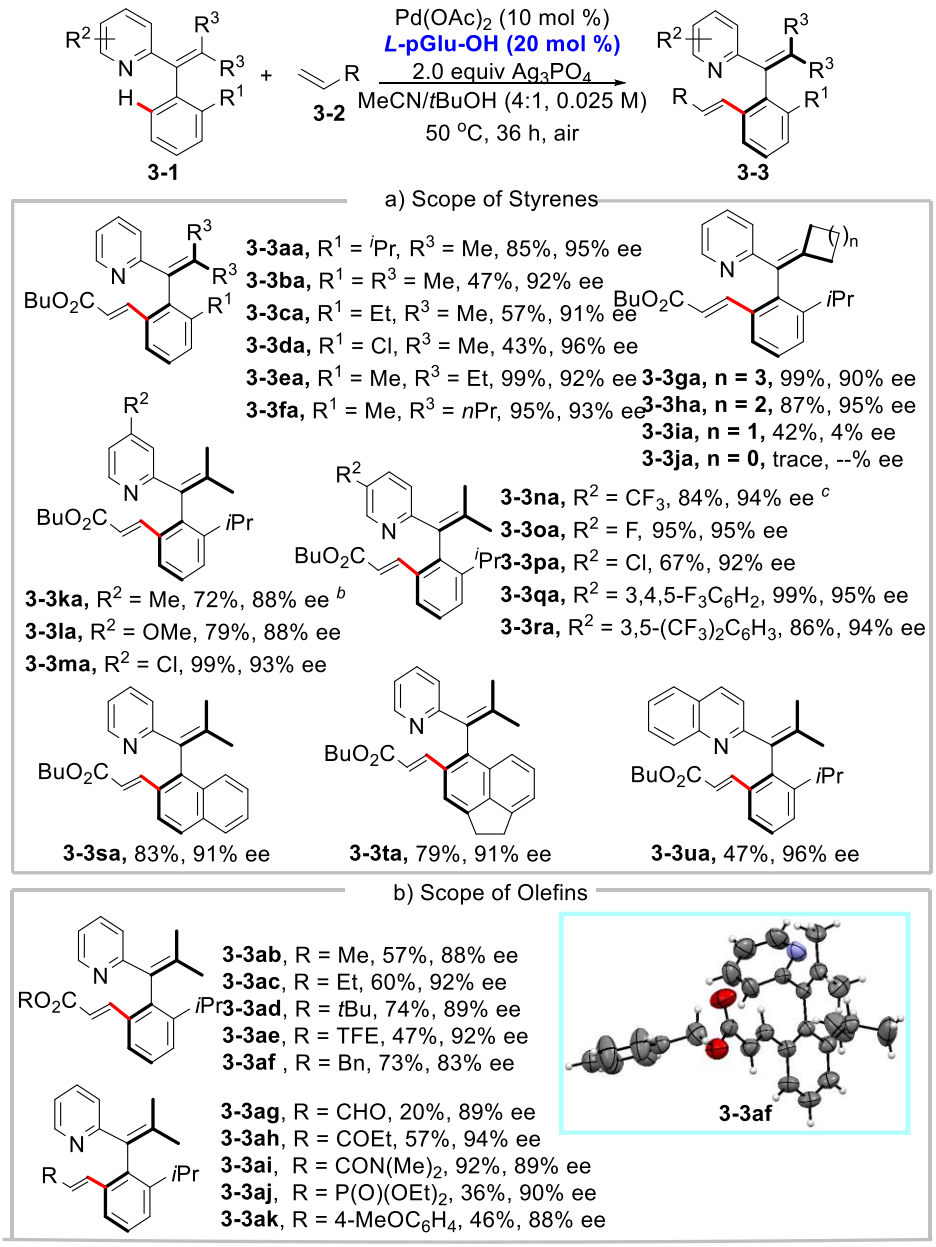
entry	[Ag]	solvent	yield (%) [b]	ee (%) [c]
1	Ag_2CO_3	DCE	9	61
2	Ag_2CO_3	MeCN	47	88
3	Ag_2CO_3	THF	40	88
4	Ag_2CO_3	Toluene	29	80
5	Ag_2CO_3	MeOH	39	93
6	Ag_2CO_3	Acetone	34	88
7	Ag_2CO_3	TFE	14	63
8	Ag_2CO_3	DMF	25	88
9 [d]	Ag_2CO_3	MeOH	59	93
10 [e]	Ag_2CO_3	MeOH	53	93
11 [d]	Ag_2CO_3	MeOH/MeCN (1:1)	56	96
12 [d]	Ag_2CO_3	MeOH/THF (1:1)	44	86
13 [d]	Ag_2CO_3	MeOH/DMF (1:1)	58	95
14 [d]	Ag_2CO_3	MeOH/DME (1:1)	26	86
15 [d]	Ag_2CO_3	MeOH/DMSO (1:1)	78	99
16 [f]	Ag_2CO_3	MeOH/DMSO (1:1, 0.5 mL)	73	99
17 [f]	Ag_2CO_3	MeOH/DMSO (1:1, 1.5 mL)	84	99
18 [f]	Ag_2CO_3	MeOH/DMSO (1:1, 3.0 mL)	86	99

[a]**3-1a** (0.05 mmol), **3-4** (2.0 equiv), $Pd(OAc)_2$ (10 mol %), [Ag] (2.0 equiv), *L*-pGlu-OH (20 mol %)在溶剂(1.0 mL)中于相应的温度下空气氛围反应 24 小时。[b] 产率由 CH_2Br_2 作为内标物的 ^{1}H NMR 测定。[c]ee 值由手性 HPLC 分离测定。[d]60 ºC 反应 48 小时。[e]50 ºC 反应 48 小时。[f]60 ºC 反应 24 小时。

3.4 反应底物的拓展

在得到了上述最优的烯基化反应条件后，我们开始对反应的普适性进行探究(**表 3.4**)。

表 3.4 钯催化不对称烯基化反应底物扩展 [a]

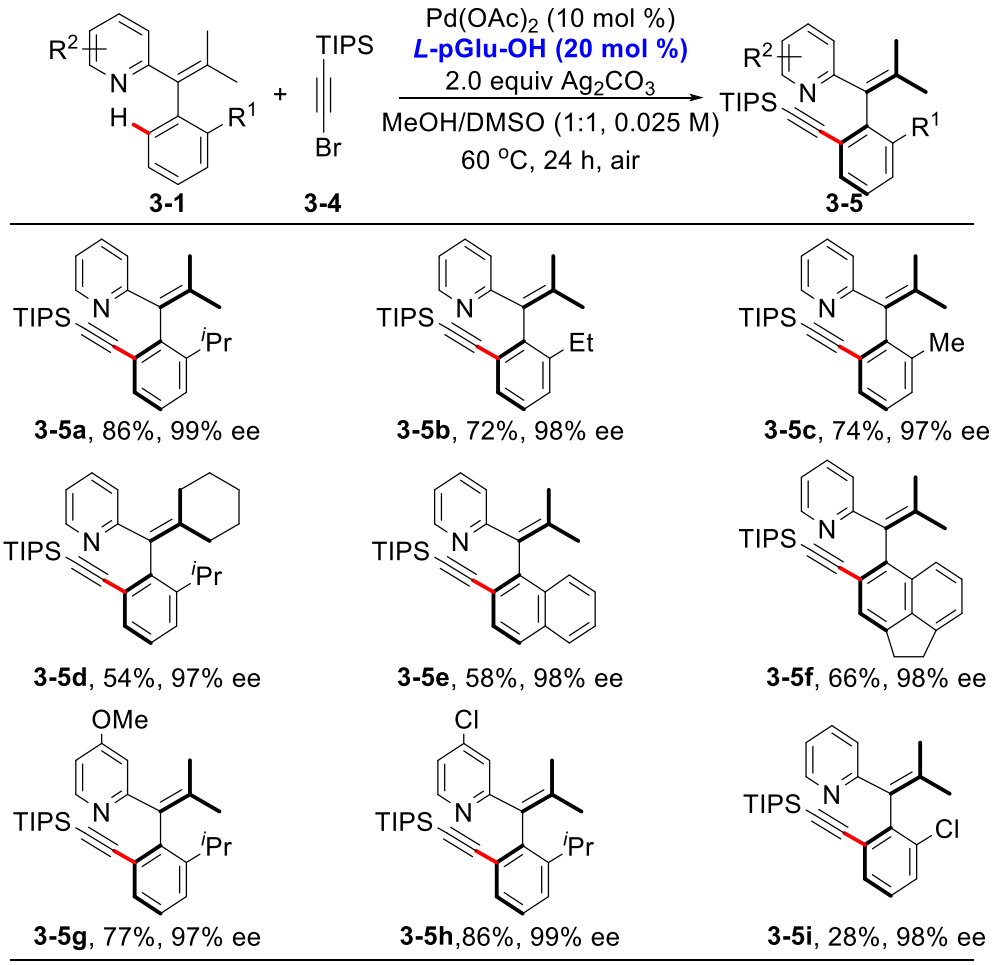


[a] **3-1** (0.1 mmol), **3-2** (2.0 equiv), $Pd(OAc)_2$ (10 mol%), Ag_3PO_4 (2.0 equiv)和 *L*-pGlu-OH (20 mol%)在 MeCN:*t*BuOH(4:1, 0.025 M)于 50 °C 空气氛围反应 36 小时。[b]Ag_2SO_4 (2.0 equiv)。[c]AgOAc (2.0 equiv)。

我们首先对苯环邻位的取代基进行替换，以此来探究其位阻对反应的影响。甲基(**3-1b**)、乙基(**3-1c**)、异丙基(**3-1a**)和氯原子(**3-1d**)都可以得到很好的容忍，实现优秀的对映体选择性(**3-3aa**–**3-3da**, 91–96% ee)。之后烯烃上的取代基也被进行了替换。我们用乙基和正丙基对烯烃上取代的甲基进行替换，均可以得到高产率和高对映体选择性的目标产物(**3-3ea,** 99%, 92% ee; **3-3fa**, 95%, 93% ee)。同样的反应效果也可以实现在用环己烷和环戊烷取代的烯烃产物中(**3-3ga**, 99%, 91% ee; **3-3ha**, 87%, 95%)。然而当用更小的环丁烷和环丙烷作为

烯烃部分的取代基时，反应活性产生了断崖式地下降(**3-3ia**, 42%, 4% ee; **3-3ja**, trace)。这可能是由于小环的环张力影响了钯催化剂与芳环邻位碳氢键的接触与活化过程。之后我们研究了不同类型的取代基对吡啶导向基的影响。我们发现，不管在导向基上安装供电子基团(**3-1k**, **3-1l**)，卤素原子(**3-1m**, **3-1p**, **3-1o**)，还是吸电子类型的基团(**3-1n, 3-1q, 3-1r**)，反应都可以顺利地进行，得到优秀的对映体选择性控制(88–95% ee)。萘环和苊环结构的底物也可以被反应兼容(**3-3sa**, 83%, 91% ee; **3-3ta**, 79%, 91% ee)。而当喹啉作为反应的导向基团时，反应则以中等的产率(47%)，优异的对映体选择性(96%)进行。

表 3.5 钯催化不对称炔基化反应底物扩展 [a]



[a]**3-1** (0.10 mmol), **3-4** (2.0 equiv), $Pd(OAc)_2$ (10 mol %), Ag_2CO_3 (3.0 equiv), *L*-pGlu-OH (20 mol %)在 MeOH:DMSO(1:1, 0.025 M)中于 60 °C 空气氛围反应 24 小时。

接下来我们对不同的烯基化试剂进行了研究和拓展(**表 3.4b**)。许多不同取代基的丙烯酸酯均可以被反应容忍，以中等到良好的产率和优秀的对映体选择性得到相应的目标产物(**3-3aa**–**3-3af**)。另外，丙烯醛、乙烯基酮、丙烯酰胺、烯基磷酸酯和 4-甲氧基苯乙烯也可

以作为烯基化试剂，以中等到良好的产率和优秀的对映体选择性得到相应的轴手性烯基芳烃化合物(**3-3ag**–**3-3ak**)。其中产物 **3-3af** 通过单晶衍射得到其绝对构型为 *R* 型，其他轴手性烯基芳烃产物的绝对构型通过类比来确定。

在优化得到了钯催化不对称碳氢键炔基化的反应条件后，我们使用 TIPS-保护的炔基溴 **3-4** 作为我们的炔基化试剂，对反应的底物进行了拓展(**表 3.5**)。含有不同位阻取代基和导向基效应的芳烃底物均可以在最优反应条件下以中等到优秀的产率和优异的对映体选择性得到相应的炔基化产物(**3-5a**–**3-5i**, 97–99% ee)。而且炔基化反应得到的产物的对映体比率均要比烯基化反应的产物好。

3.5 合成应用

为了使该反应具有更好的实用性，我们对烯基化和炔基化反应均进行了规模放大试验。烯基化和炔基化反应均可以在不损耗活性和对映体选择性的情况下得到克级规模地放大(**图 3.7a**, **3-3aa**, 886.0 mg, 78%, 94% ee; **图 3.7b**, **3-5a**, 1.1 g, 85%, 99% ee)。

反应得到的烯基化产物 **3-3aa** 可以被 *m*-CPBA 选择性地氧化吡啶导向基成为吡啶氮氧化合物(**3-6**)。当把氧化剂 *m*-CPBA 的用量增加到产物的五倍当量时，产物结构中的四取代烯烃可以被进一步氧化成手性环氧化合物(**3-7**)。这也实现了从轴到点的手性传递。烯基化产物中的丙烯酸酯部分也可以被高碘酸钠选择性的氧化切断成醛基，再经过亚氯酸钠的氧化，得到一类基于烯基芳烃轴手性骨架的手性酸(**3-9**)。同样的，产物 **3-9** 的绝对构型也由单晶衍射实验确定为 *R* 构型。

与此同时，炔基化产物(**3-5a**)可以在四丁基氟化铵的作用下顺利脱除硅基保护基得到活泼的端炔化合物(**3-10**)。该端炔化合物可以以中等的产率进行 Sonogashira 偶联反应和 Click 反应分别得到内炔烃化合物(**3-11**)和三氮唑化合物(**3-12**)。

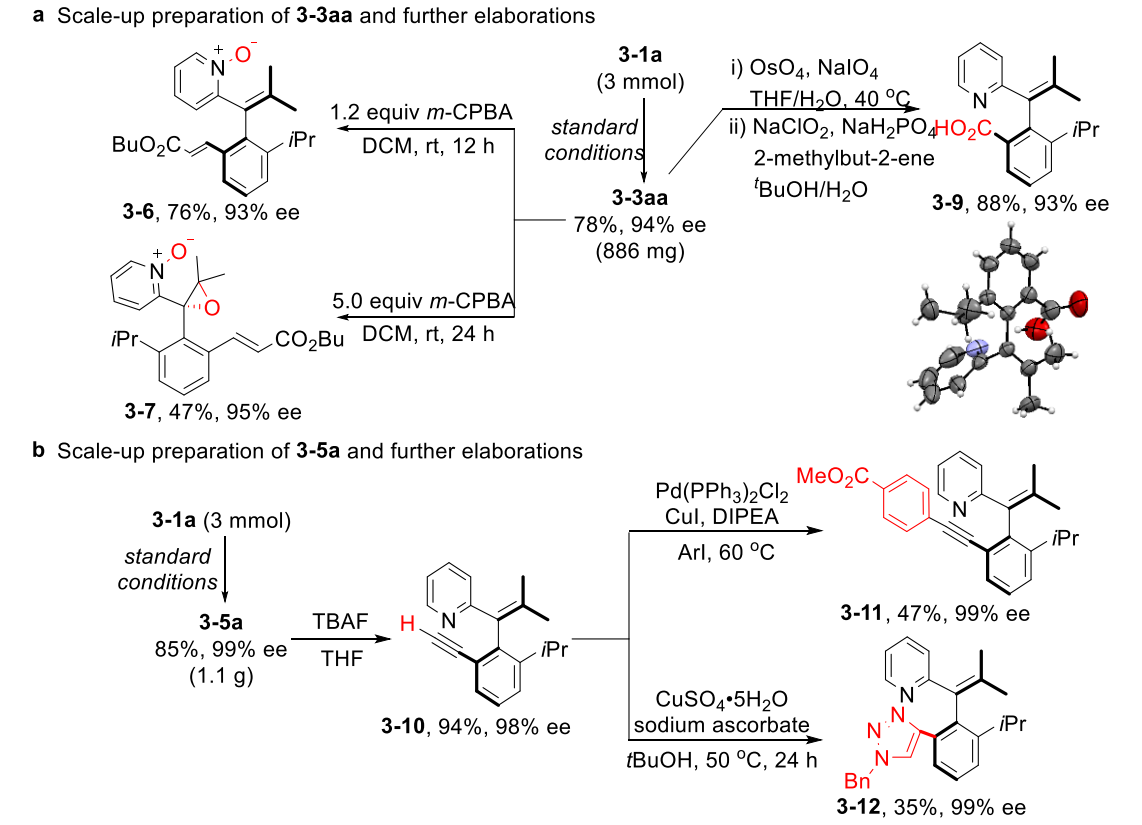


图 3.7 规模扩大反应、衍生化和应用

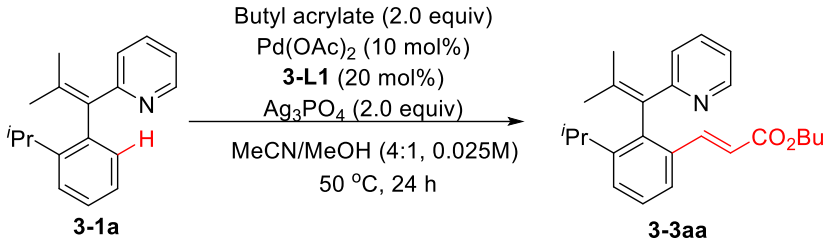
为了探寻轴手性烯基芳烃骨架在不对称合成中的潜在应用，我们将产物衍生化后得到的手性羧酸**(3-9)**作为手性配体，应用于三价钴催化的不对称二茂铁碳氢键酰胺化反应中[53]**(图 3.7c)**。经过初步的尝试和调整，我们发现使用含 4-甲氧基吡啶取代的烯基芳烃轴手性骨架的羧酸**(3-9b)**为反应的手性配体时，可以以 75%的产率，78.8/21.2 的 er 值得到目标

酰胺化产物(**3-19**)。这一结果要优于原文中使用*D*-Bz-Hpg-OH(**3-16**)所取得的结果(73.5/27.5 er)。同时，作为对比，一些基于联芳基轴手性骨架的羧酸(**3-13, 3-14, 3-15**)也被进行了测试。令人失望的是，这些基于联芳基轴手性骨架的手性酸在该酰胺化反应中几乎都不能诱导出手性。综上结果证明了我们发展得到的这类含有开链式烯烃结构的轴手性烯基芳烃化合物在不对称反应中可能存在着优于联芳基轴手性骨架的应用前景。

3.6 反应机理探究

为了进一步了解钯催化不对称芳烃碳氢键烯基化反应的机理，我们做了一系列的机理探究性实验。

3.6.1 动力学实验



3-1a **3-3aa**

entry	ee% (**3-L1**)	ee% (product)
1	0	0
2	33.3	45.3
3	50	59.1
4	60	67
5	66.7	77
6	71.4	79.8
7	75	83.5
8	99	95

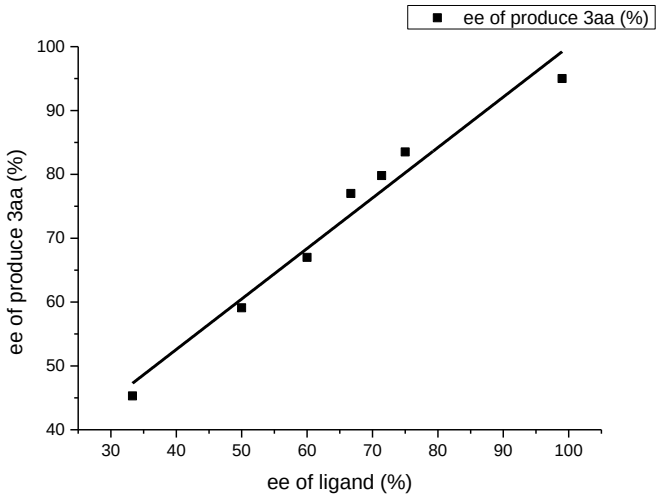


图 3.8　3-L1 和(*R*)3-3aa 的线性相关效应

首先我们进行了产物(**3-3aa**)ee 值与手性配体(*L*-pGlu-OH)ee 值的数学关系测定实验(**图 3.8**)。实验证明手性配体的 ee 值与产物的 ee 值是呈线性相关关系的。这也预示着手性配体是以单一分子的形式参与到反应立体选择性的决定步骤中。

之后，我们分别进行了底物在配体存在与否情况下的动力学效应实验(**图 3.9a**)。实验测定的 KIE 的数值分别是 1.3(without ligand)和 1.2(with ligand)。这表明碳氢键活化过程可能不是反应的决速步骤。同时，对于有无配体存在下的动力学速率研究，我们可以发现反应中存在着一个非常规的配体减速效应(LDE)(**图 3.9b**)。

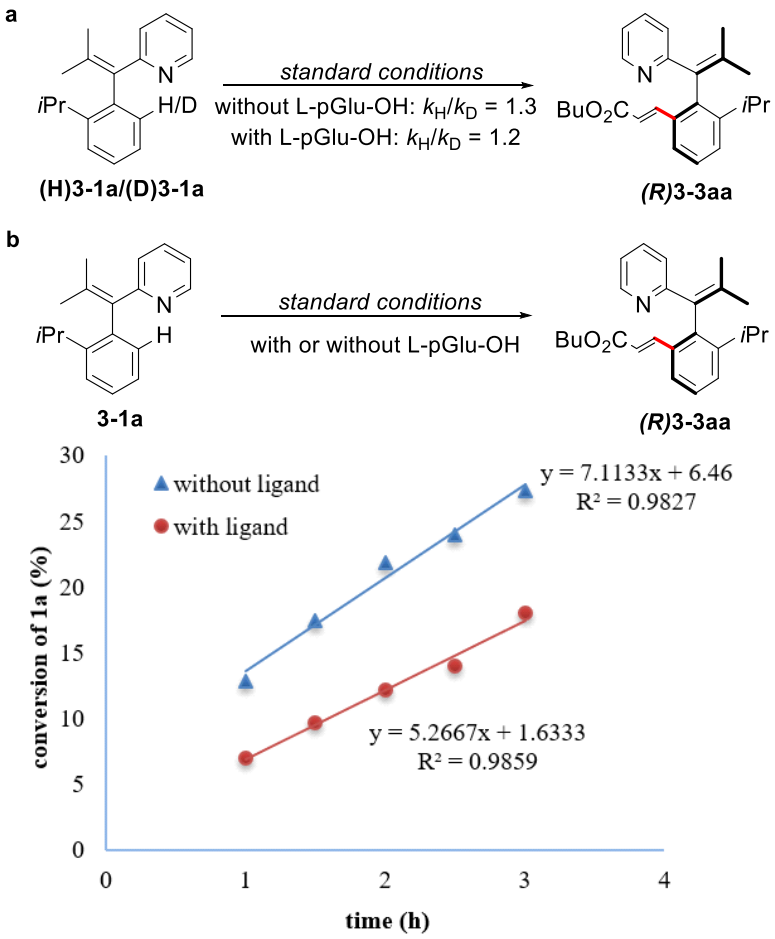


图 3.9 KIE 研究和配体减速效应

3.6.2 产物 3-3ab 和 3-5a 翻转能垒和半衰期的测定

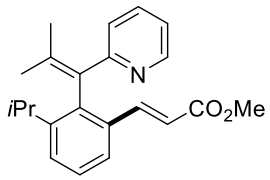
翻转能垒是根据对映体的外消旋动力学实验获得的。一阶动力学曲线的斜率给出了外消旋常数($k_{racemisation}$ =2 * $k_{enantiomerisation}$)，根据 Eyring 方程，代入对映异构常数($k_{enantiomerisation}$)，可以求出翻转能垒($\Delta G^{\ddagger}_{enaniomerization}$)，其中 R(气体常数) = 8.31451 $J.K^{-1}.mol^{-1}$, h(普朗克常数)

= 6.62608 x 10-34 J*s 和 k_B(玻尔兹曼常数) = 1.38066 x 10-23 J*K^{-1}。

$$\Delta G^{\ddagger}_{enaniomerization} = RT_1*\ln(k_BT_1/hk_{enantiomerization})$$

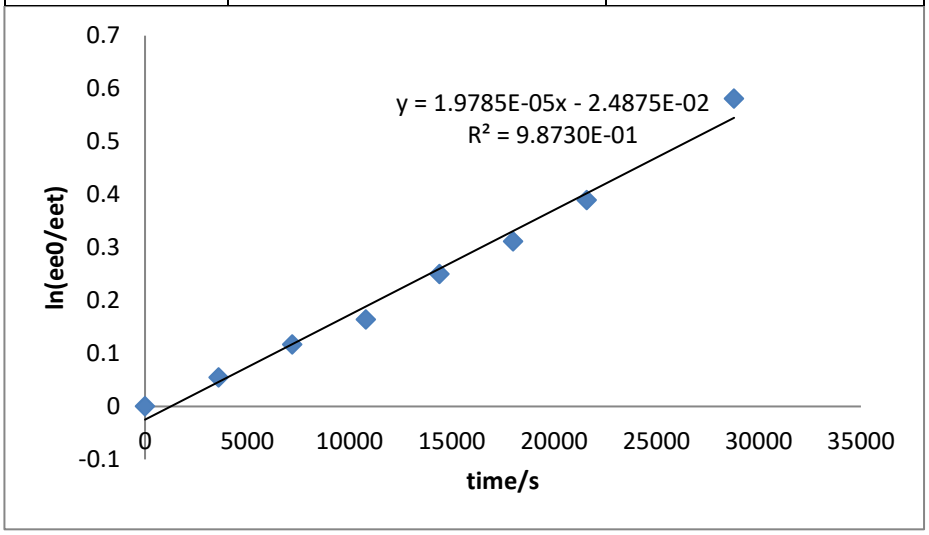
$$t_{1/2}(T_1) = 0.5*\ln2/k_{enantiomerization}$$

为了验证烯基化产物和炔基化产物的构象稳定性，我们以 **3-3ab** 和 **3-5a** 为模板底物，分别测试了其在一定温度下的翻转能垒，并且计算出相应温度下的半衰期。



3-3ab

time (second)	enantiomeric excess (ee)	first order racemization $\ln(ee_0/ee_t)$
0	95.628	0
3600	90.564	0.0544
7200	85.074	0.1169
10800	81.16	0.164
14400	74.508	0.2496
18000	70.03	0.3115
21600	64.785	0.3894
28800	53.5	0.5808



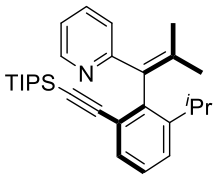
$k_{racemization}$ (170 °C) = 1.9785x10^{-5} s^{-}

$k_{enantiomerization}$ (170 °C) = 0.9893x10^{-5} s^{-}

$\Delta G^{\ddagger}$ $_{enaniomerization}$ = 153.4588 KJ/mol = 36.42 kcal/mol

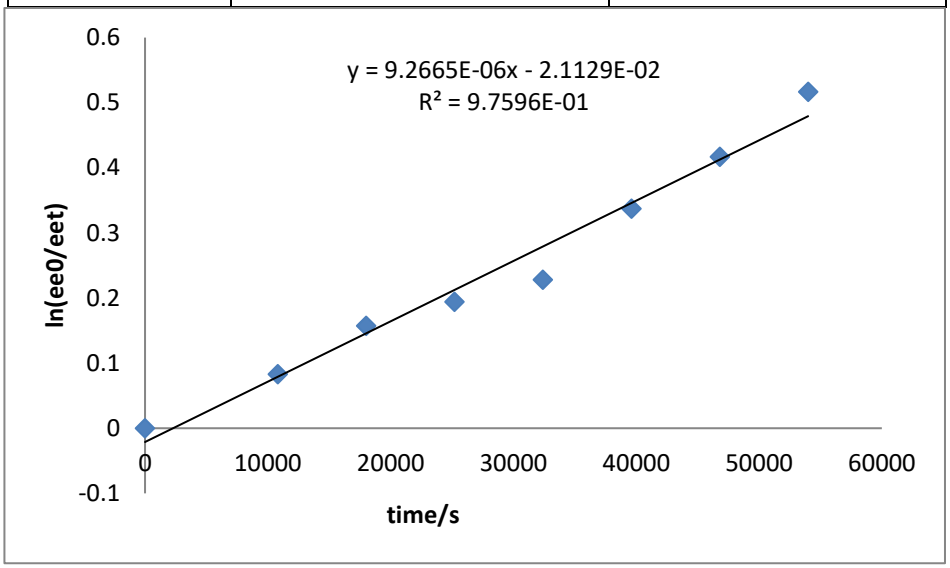
$t_{1/2}$ (170 °C) = 9.45 hours

图 3.10 化合物 **3-3ab** 在 170 °C 异丙醇中的消旋化反应



3-5a

time (second)	enantiomeric excess (ee)	first order racemization $\ln(ee_0/ee_t)$
0	99.652	0
10800	91.734	0.0828
18000	85.156	0.1572
25200	83.064	0.1942
32400	79.336	0.228
39600	71.142	0.337
46800	65.674	0.417
54000	59.458	0.5164



$k_{racemization}$ (180 °C) = 9.2665x10^{-6} s^{-}

$k_{enantiomerization}$ (180 °C) = 4.6333x10^{-6} s^{-}

$\Delta G^{‡}_{\ enaniomerization}$ = 158.8412 KJ/mol = 37.95 kcal/mol

$t_{1/2}$ (180 °C) = 21.31 hours

图 3.11 化合物 **3-5a** 在 180 °C 异丙醇中的消旋化反应

通过对以上测量数据的分析和计算，我们可以分别得到烯基化产物 **3-3ab** 的翻转能垒大约是 36.42 kcal/mol，在 170 °C，其半衰期为 9.45 小时(**图 3.10**)。而炔基化产物 **3-5a** 的翻转能垒更高，达到了 37.95 kcal/mol，在 180 °C，其半衰期为 21.31 小时(**图 3.11**)。这里也揭示了炔基化反应的手性控制普遍优于烯基化反应的原因。

3.6.3 理论计算

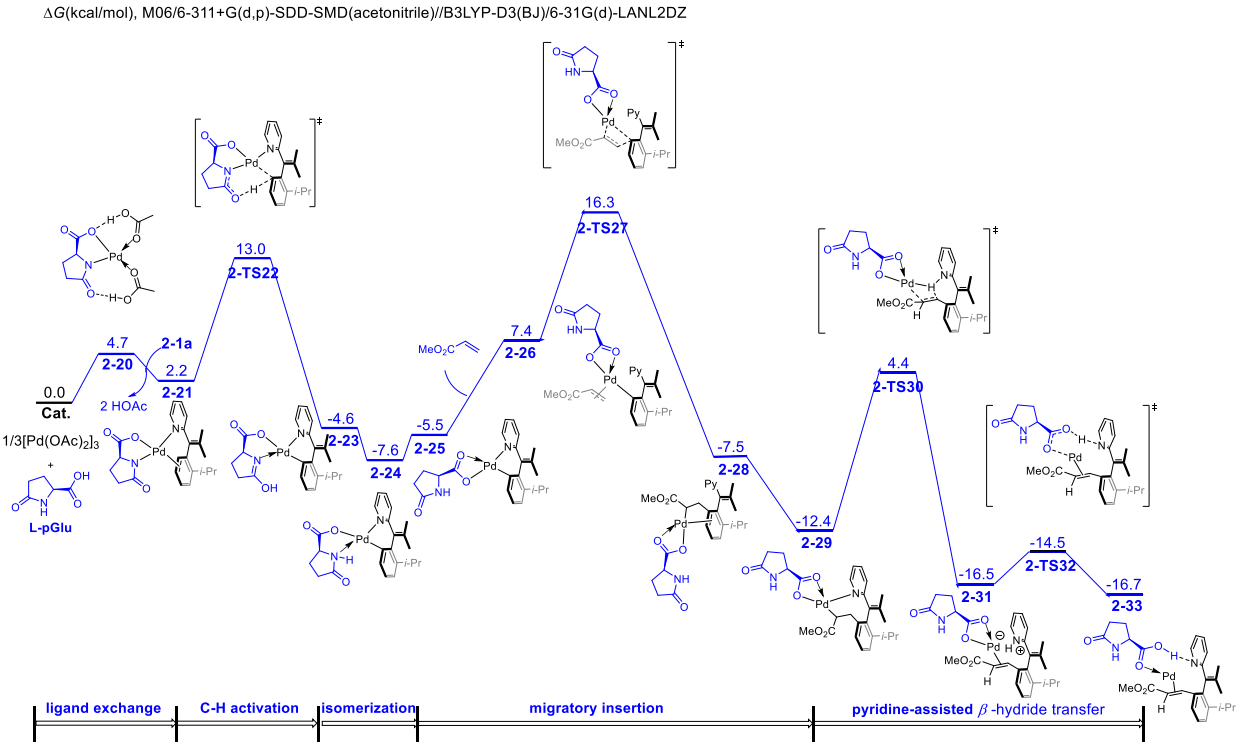


图 3.12 DFT 计算的最优化钯催化不对称碳氢键活化反应过程

为了进一步了解钯催化不对称芳烃碳氢键烯基化反应的机理，我们通过跟洪鑫老师课题组进行合作，在谢培培博士的帮助下，对烯基化反应的过程进行了详细的理论计算。我们选择苯乙烯底物 **3-1a** 和丙烯酸甲酯作为模型底物，经过详细的密度泛函理论计算(DFT)，得到了一条能量最优的 Pd(II)/*L*-pGlu-OH 催化的不对称碳氢键烯基化反应路径(**图 3.12**)。反应大致经历了以下过程：首先处于三聚体状态的醋酸钯催化剂在配体 *L*-焦谷氨酸的作用下进行催化剂解聚和配体交换，生成活性催化剂 **3-20**。之后活性的催化剂与底物 **3-1a** 进行结合成为中间体 **3-21**，再经过金属协同拔氢过渡态物种 **3-TS22** 之后得到碳氢键活化之后的芳基环钯物种 **3-23**。该物种接着进行异构化反应，生成更加稳定的物种 **3-25**。然后物种 **3-25** 跟烯烃进行反应，经过过渡态物种 **3-TS27**，发生烯烃的插入反应，生成烷基钯物种 **3-28**。物种 **3-28** 经异构成更加稳定的物种 **3-29** 后，在吡啶的作用下，经过过渡态物种 **3-TS30**，发生 *β*-氢消除反应后得到物种 **3-31**。物种 **3-31** 最后经过氢质子的交换得到目标产物 **3-33**。

通过分析计算所得的各个反应中间物种的静态自由能，我们发现整个反应中的决速步骤是芳基钯物种 **3-24** 经过过渡态物种 **3-TS27** 与烯烃发生的插入反应。这一过程需要克服约 23.9 kcal/mol 的反应能垒，要明显高于物种 **3-21** 发生碳氢键活化生成芳基环钯物种 **3-**

23 所需要翻越的反应能垒。这一结果与动力学实验所测得的结果相一致。

3.7 本章小节

我们成功发展了 Pd(II)/*L*-pGlu-OH 催化不对称芳烃碳氢键烯基化和炔基化反应来构建具有开链式烯烃骨架的轴手性烯基芳烃化合物。该合成策略为催化不对称构建轴手性烯基芳烃提供了一条高效便利的途径。机理实验和理论计算证实了烯基化反应经过碳氢键活化，烯烃插入和吡啶协助的 β-氢消除过程。同时，*L*-焦谷氨酸作为一种商业易得、廉价高效的手性配体，可以为之后不对称碳氢键活化策略的合成应用提供许多潜在的机会。

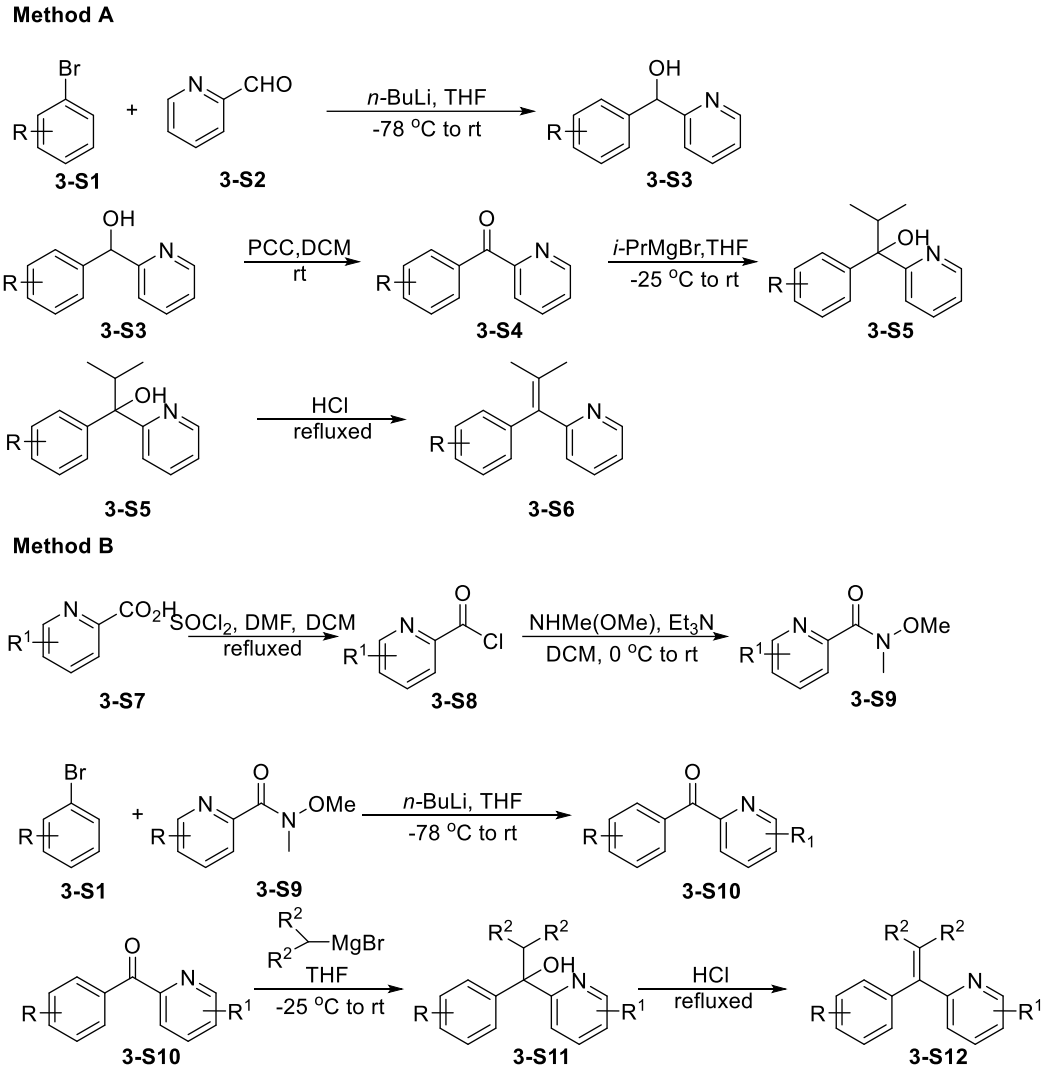
3.8 实验部分

3.8.1 仪器与试剂

测试仪器：Bruker Avance 400 M 核磁共振仪用于样品的 ^{1}H NMR、^{13}C NMR 和 ^{19}F NMR 检测。Waters TOF-MS GCT Premier 质谱仪用于高分辨质谱(EI)的测试，Bruker Apex 111 傅里叶变换离子回旋共振质谱仪用于高分辨质谱(ESI)的测试。Shimadzu HPLC LC-20A 液相色谱仪用于手性样品对映体比率的测定。有机反应用薄层层析法(TLC)跟踪，紫外灯，高锰酸钾显色剂和磷钼酸显色剂进行显色检测。

原料和试剂：一般原料试剂均由商业采购之后未经过纯化直接使用，所用无水溶剂由商业购买或者根据《Purification of Laboratory Chemicals, 6th Ed》做后处理之后再进行使用。醋酸钯从小辣椒公司购买。

3.8.2 苯乙烯类底物的合成



方法 A：在干燥的 250 mL 带有密封塞的三颈烧瓶中加入相应的芳基溴代物(**3-S1**, 25 mmol)和 100 mL 无水四氢呋喃，用干燥的氮气充换烧瓶三次，使其充满氮气。将烧瓶置于-78 ºC 下，缓慢往里滴加正丁基锂(26 mmol)。滴加完毕之后，将反应物在-78 ºC 下继续搅拌约一小时。然后往反应物中缓慢加入溶有相应 3-醛基吡啶化合物(**3-S2**, 25 mmol)的无水四氢呋喃溶液，加完之后继续保持-78 ºC，搅拌一小时。接着将反应物放于室温搅拌一小时。等原料反应完全后，用饱和氯化铵溶液小心淬灭反应。然后减压旋去四氢呋喃溶液，剩余水相物质用二氯甲烷溶液萃取两次(2 × 30 mL)，有机相经过饱和食盐水洗涤后用无水硫酸钠干燥，再经过减压浓缩后得到粗产物二级芳基醇(**3-S3**)。得到的粗产物醇(**3-S3**)用氯铬酸吡啶进行氧化反应，得到相对应的酮化合物(**3-S4**)。得到的酮化合物经过一步柱层析纯化后溶解在无水四氢呋喃(50 mL)中，加入到一个充满氮气的 250 mL 带密封塞的三颈烧

瓶中，然后冷却到-30 ºC。接着缓慢向反应物中滴加 *i*PrMgBr (1.5 equiv)。等滴加完成后，将反应物恢复到室温反应一个小时。混合物用饱和氯化铵溶液淬灭，旋去四氢呋喃，使用二氯甲烷萃取后，将得到的有机相用无水硫酸钠干燥。经过减压浓缩后，使用柱层析纯化得到对应的三级醇化合物(**3-S5**)。最后，将得到的三级醇溶解在浓盐酸(10 mL)中，加热回流 48 小时。结束后，将反应物冷却到室温，小心的用氢氧化钠溶液中和到 pH 值等于 9 左右。混合物用乙酸乙酯萃取三次(3 × 30 mL)，用饱和食盐水洗涤后，用无水硫酸钠干燥。最后经减压浓缩后用柱层析方法进行纯化，得到目标的苯乙烯类底物(**3-S6**)。

方法 B：室温下，在 250 mL 圆底烧瓶中依次加入相应的吡啶甲酸(**3-S7**, 25 mmol)，氯化亚砜(20 mL)和几滴 DMF。之后将反应加热到 50 °C 下回流三小时。反应完后将溶剂和多余的氯化亚砜用旋转蒸发仪减压去除后经油泵抽气干燥，得到相对应的粗产物酰氯(**3-S8**)。接着将得到的酰氯溶解在二氯甲烷(40 mL)中，缓慢滴加到溶有 *N,O*-二甲基羟胺(50 mmol)和三乙胺(3.0 equiv)的二氯甲烷溶液中。滴加完成后，将反应物置于室温搅拌过夜。反应完全后，混合物旋去二氯甲烷，用柱层析方式进行纯化，得到相应的酰胺化合物(**3-S9**)。

在干燥的 250 mL 带有密封塞的三颈烧瓶中加入相应的芳基溴代物(**3-S1**, 25 mmol)和无水四氢呋喃(100 mL)，用干燥的氮气充换烧瓶三次，使其充满氮气。将烧瓶置于-78 ºC 下，缓慢往里滴加正丁基锂(26 mmol)。滴加完毕之后，将反应物在-78 ºC 下继续搅拌约一小时。然后往反应物中缓慢加入溶有相应酰胺化合物(**3-S9**)的无水四氢呋喃溶液，加完之后继续保持-78 ºC 搅拌一小时。接着将反应物取置室温搅拌一小时。等原料反应完全后，用饱和氯化铵溶液小心淬灭。然后旋去四氢呋喃溶液，剩余水相物质用二氯甲烷溶液萃取两次(2 × 30 mL)，有机相经过饱和食盐水洗涤后用无水硫酸钠干燥，再减压浓缩经柱层析分离得到相对应的酮化合物(**3-S10**)。将得到的酮溶解在无水四氢呋喃(50 mL)中，加入到一个充满氮气的 250 mL 带密封塞的三颈烧瓶中，然后冷却到-30 ºC。接着缓慢向反应物中滴加 *i*PrMgBr (1.5 equiv)。等滴加完成后，将反应物恢复到室温反应一个小时。混合物用饱和氯化铵溶液淬灭，旋去四氢呋喃，使用二氯甲烷萃取后，将得到的有机相用无水硫酸钠干燥。经过减压浓缩后，使用柱层析纯化得到对应的三级醇化合物(**3-S11**)。最后，将得到的三级醇溶解在浓盐酸(10 mL)中，加热回流 48 小时。结束后，将反应物冷却到室温，小心的用氢氧化钠溶液中和到 pH 值等于 9 左右。混合物用乙酸乙酯萃取三次(3 × 30 mL)，用饱和食盐水洗涤后，用无水硫酸钠干燥。最后经减压浓缩后用柱层析分离纯化，得到目标的苯乙烯类底物(**3-S12**)。

3.8.3 钯催化不对称芳烃碳氢键烯基化构建烯基芳烃轴手性化合物

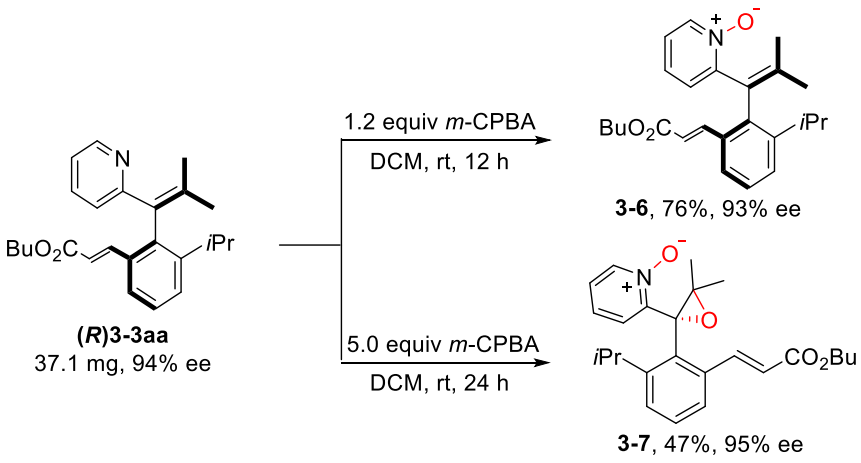
在 50 mL Schlenk 反应管中依次加入醋酸钯(3.3 mg, 0.01 mmol)，*L*-焦谷氨酸(3.6 mg，0.02 mmol)，苯乙烯类底物(0.1 mmol)，烯基化试剂(0.2 mmol)，磷酸银(83.6 mg, 0.2 mmol)，最后加入 MeCN/*t*BuOH(4:1, 0.025 M)。于空气氛围下，在 50 °C 中反应 36 小时。冷却到室温后，用乙酸乙酯稀释反应体系，通过硅藻土过滤，减压浓缩后用制备硅胶板分离得到相对应的烯基化产物。

3.8.4 钯催化不对称芳烃碳氢键炔基化构建烯基芳烃轴手性化合物

在 50 mL Schlenk 反应管中依次加入醋酸钯(3.3 mg, 0.01 mmol)，*L*-焦谷氨酸(3.6 mg, 0.02 mmol)，苯乙烯类底物(0.1 mmol)，炔基化试剂(0.2 mmol)，碳酸银(55.1 mg, 0.2 mmol)，最后加入 MeOH/DMSO(1:1, 0.025 M)。于空气氛围下，在 60 °C 中反应 24 小时。冷却到室温后，用乙酸乙酯稀释反应体系，通过硅藻土过滤，减压浓缩后用制备硅胶板分离得到相对应的炔基化产物。

3.8.5 产物衍生化

3.8.5.1 化合物 **3-6** 和 **3-7** 的合成

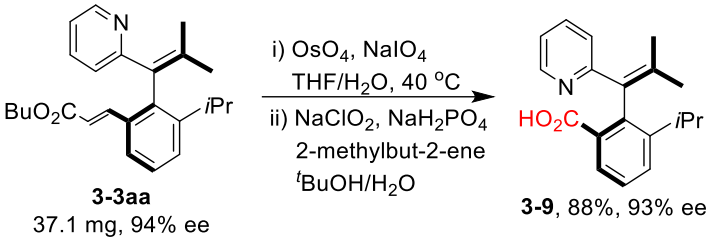


在 25 mL 圆底烧瓶中依次加入**(*R*)3-3aa**(37.1 mg, 0.1 mmol)，*m*-CPBA(24.4 mg, 1.2 equiv)和二氯甲烷(2.0 mL)。将反应置于室温反应 12 小时，用饱和亚硫酸钠溶液淬灭。之后用二

氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **3-6**(30 mg, 76% yield, 93% ee)。对映体比率由手性 HPLC 测定。

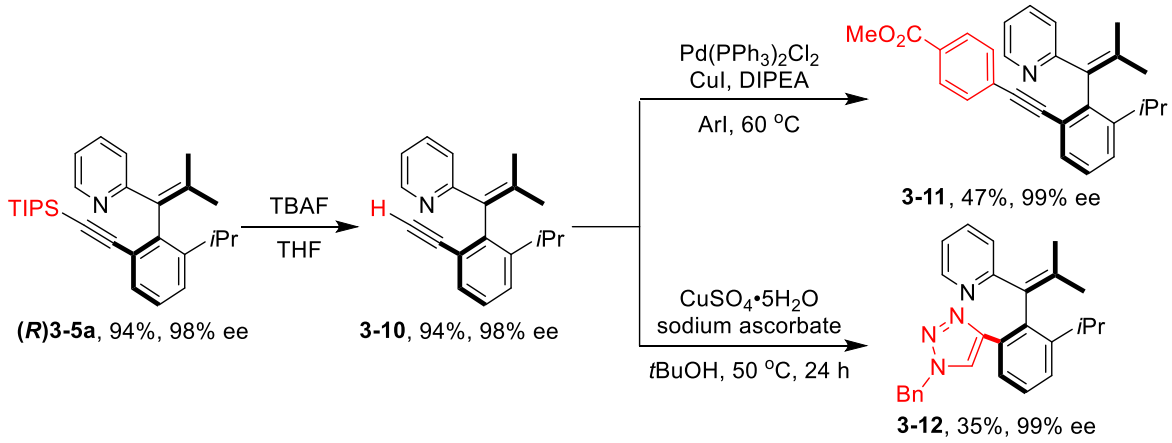
在 25 mL 圆底烧瓶中依次加入**(*R*)3-3aa**(37.1 mg, 0.1 mmol)，*m*-CPBA(101.5 mg, 5.0 equiv)和二氯甲烷(2.0 mL)。将反应置于室温反应 24 小时，用饱和亚硫酸钠溶液淬灭。之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **3-7**(20.6 mg, 47% yield, 95% ee)。对映体比率由手性 HPLC 测定。

3.8.5.2 手性酸 **3-9** 的合成



在 25 mL 圆底烧瓶中依次加入**(*R*)-3-3aa**(37.1 mg, 0.1 mmol)，高碘酸钠(108.0 mg, 5.0 equiv)，四氧化锇(64 μL, 5 mol%, 2%的水溶液)，THF/H_2O(2:1, 2.0 mL)。将反应置于 40 °C 反应过夜。用饱和亚硫酸钠溶液淬灭，之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后得到粗产物手性醛化合物 **3-8**。将得到的粗产物手性醛加入到 25 mL 圆底烧瓶中，再依次加入 3-甲基-3-丁烯(138 μL, 13.0 equiv)，叔丁醇(3.0 mL)。之后将溶有次氯酸钠(41.6 mg, 3.7 equiv)和磷酸二氢钠(60.0 mg, 5.0 equiv)饱和水溶液滴加到反应混合物中。然后让反应物在室温下搅拌 2 小时。完全反应后，用饱和亚硫酸钠溶液淬灭。之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到手性酸 **3-9**(26.0 mg, 88% yield 两步, 93% ee)。对映体比率由手性 HPLC 测定。手性酸 **3-9a** 至 **3-9c** 由以上方法经过细微调整合成。

3.8.5.3 化合物 **3-10**、**3-11** 和 **3-12** 的合成



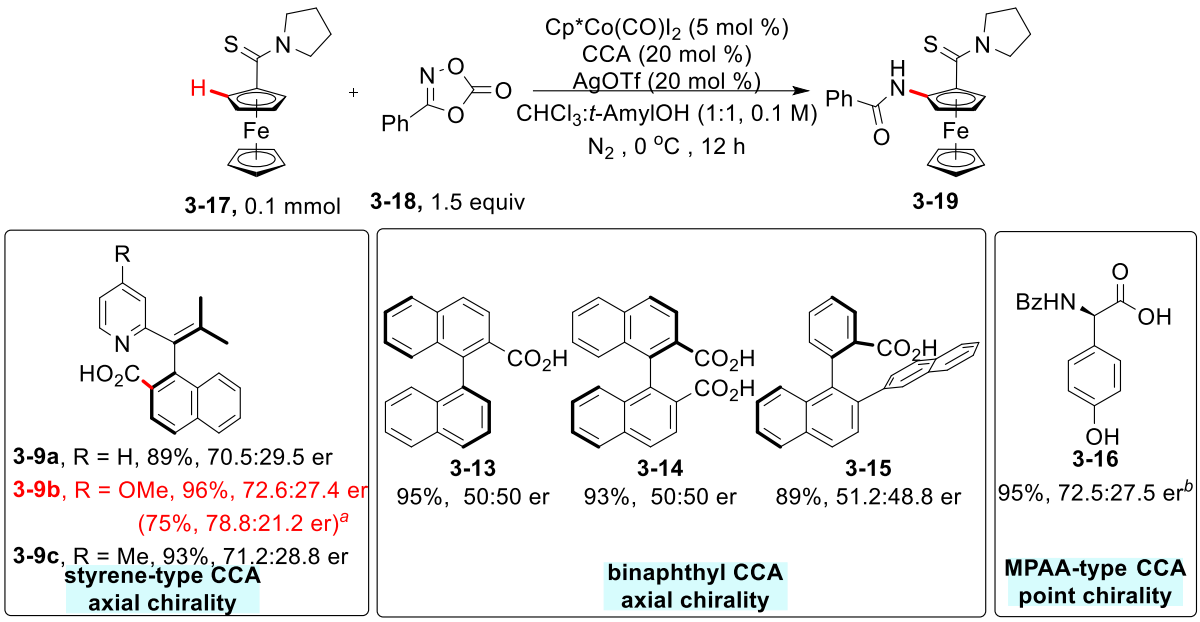
(***R***)**3-5a**, 94%, 98% ee　　**3-10**, 94%, 98% ee　　**3-11**, 47%, 99% ee　　**3-12**, 35%, 99% ee

在 25 mL 圆底烧瓶中依次加入(***R***)**3-5a**(43.1 mg, 0.1 mmol)，四丁基氟化铵(0.15 mL, 1.5 equiv, 1.0 M 四氢呋喃溶液)，四氢呋喃(2.0 mL)。将反应置于室温下反应 2 小时。用饱和碳酸氢钠溶液淬灭，之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **3-10**(25.8 mg, 94% yield, 98% ee)。对映体比率由手性 HPLC 测定。

将得到的端炔化合物 **3-10**(27.5 mg, 0.1 mmol)，碘化亚铜(1.0 mg, 6 mol%)，$Pd(PPh_3)_2Cl_2$ (3.1 mg, 3 mol%)，碘苯(39.3 mg, 1.5 equiv)和 *N,N*-二异丙基乙胺(1.0 mL)加入到充满氮气的 25 mL Schlenk 管中。接着将反应置于 60 ºC 搅拌 12 小时。反应完全之后，用饱和氯化铵溶液淬灭反应。二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **3-11**(19.3 mg, 47% yield, 99% ee)。对映体比率由手性 HPLC 测定。

在 25 mL 圆底烧瓶中依次加入端炔化合物 **3-10**(27.5 mg, 0.1 mmol)，苯基叠氮(20.0 mg, 1.5 equiv)，叔丁醇(3.0 mL)和水(240 μL)。紧接着在反应混合物中滴加五水合硫酸铜溶液(0.1 M 水溶液, 100 μL, 0.01 mmol)和 *L*-维生素 C 钠溶液(0.1 M 水溶液, 200 μL, 0.02 mmol)。然后将反应置于 45 ºC 反应 5 小时。冷却到室温后，用饱和的氨水溶液洗涤去除铜盐，之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **3-12**(15 mg, 94% yield, 98% ee)。对映体比率由手性 HPLC 测定。

3.8.6 手性酸的应用

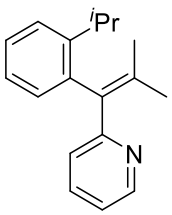


氮气氛围下，在 25 mL 圆底烧瓶中依次加入二茂铁底物 **3-17**(30.0 mg, 0.1 mmol)，[Cp*Co(CO)I_2] (3.5 mg, 5 mol %)，三氟甲磺酸银(5.2 mg，20 mol %)，酰胺化试剂 **3-18**(25.0 mg，0.15 mmol)，手性酸 **3-9**(20 mol %)和溶剂 $CHCl_3$/*t*-AmylOH(1:1, 0.1 M)。将反应管置于 0 ºC 反应 24 小时，用二氯甲烷稀释反应混合物。减压浓缩后经柱层析分离提纯得到酰胺化产物 **3-19**。

3.9 结构表征

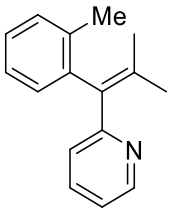
3.9.1 底物结构表征

(±)2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine(3-1a)



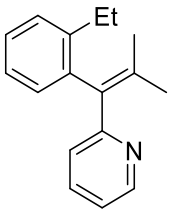
方法 A。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.58 (ddd, *J* = 4.8, 1.8, 1.0 Hz, 1H), 7.51 (td, *J* = 7.7, 1.9 Hz, 1H), 7.27 (d, *J* = 3.6 Hz, 2H), 7.18 (dd, *J* = 5.0, 3.7 Hz, 1H), 7.03 (ddd, *J* = 7.8, 5.7, 1.1 Hz, 2H), 3.11 (hept, *J* = 6.9 Hz, 1H), 1.99 (s, 3H), 1.67 (s, 3H), 1.16 (d, *J* = 6.9 Hz, 3H), 0.76 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.92, 148.74, 147.58, 136.04, 135.75, 135.49, 127.52, 125.91, 125.49, 124.71, 120.75, 30.07, 24.19, 23.83, 23.41, 21.73. HRMS (ESI-TOF) calcd for $C_{18}H_{22}N^{+}$ ($[M+H]^{+}$): 253.1747, found: 253.1748.

(±)2-(2-methyl-1-(o-tolyl)prop-1-en-1-yl)pyridine(3-1b)



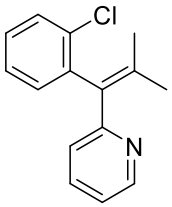
方法 A。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.60 (d, *J* = 5.0 Hz, 1H), 7.55 (td, *J* = 7.7, 1.9 Hz, 1H), 7.25 – 7.13 (m, 4H), 7.10 – 7.00 (m, 2H), 2.17 (s, 3H), 1.97 (s, 3H), 1.66 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.30, 148.57, 141.70, 136.75, 136.16, 135.69, 135.46, 130.44, 130.16, 127.03, 125.77, 124.68, 120.95, 22.86, 21.70, 19.96. HRMS (ESI-TOF) calcd for $C_{16}H_{18}N^{+}$ ($[M+H]^{+}$): 224.1434, found: 224.1433.

(±)2-(1-(2-ethylphenyl)-2-methylprop-1-en-1-yl)pyridine(3-1c):



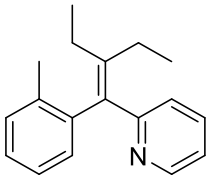
方法 A。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (dd, *J* = 5.6, 1.8 Hz, 1H), 7.51 (td, *J* = 7.7, 1.9 Hz, 1H), 7.25 – 7.16 (m, 4H), 7.04 (ddd, *J* = 7.7, 3.9, 1.4 Hz, 2H), 2.50 (qq, *J* = 14.7, 7.5 Hz, 2H), 1.98 (s, 3H), 1.66 (s, 3H), 0.99 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.70, 148.79, 142.70, 135.76, 135.48, 130.83, 128.46, 127.27, 125.67, 124.68, 120.80, 26.01, 23.25, 21.73, 14.86. HRMS (ESI-TOF) calcd for $C_{17}H_{20}N^{+}$ ($[M+H]^{+}$): 238.1590, found: 238.1591.

(±)2-(1-(2-chlorophenyl)-2-methylprop-1-en-1-yl)pyridine(3-1d):



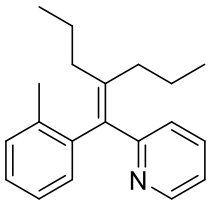
方法 A。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.58 (dd, *J* = 5.1, 1.8 Hz, 1H), 7.57 (td, *J* = 7.7, 1.9 Hz, 1H), 7.38 (dd, *J* = 7.8, 1.5 Hz, 1H), 7.33 (dd, *J* = 7.4, 1.9 Hz, 1H), 7.24 – 7.11 (m, 3H), 7.10 – 7.01 (m, 1H), 1.95 (s, 3H), 1.69 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.83, 149.05, 140.91, 136.92, 135.88, 134.03, 133.87, 133.15, 129.62, 128.31, 126.81, 124.91, 121.16, 22.78, 21.69. HRMS (ESI-TOF) calcd for $C_{15}H_{15}ClN^{+}$ ([M+H]$^{+}$): 244.0888, found: 244.0886.

(±) 2-(2-ethyl-1-(o-tolyl)but-1-en-1-yl)pyridine(3-1e):



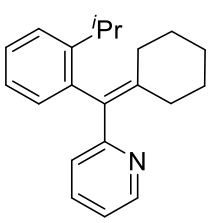
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.62 – 8.55 (m, 1H), 7.53 (td, *J* = 7.7, 1.8 Hz, 1H), 7.26 – 7.22 (m, 1H), 7.20 – 7.14 (m, 3H), 7.11 – 7.06 (m, 1H), 7.04 (ddd, *J* = 7.2, 4.9, 1.2 Hz, 1H), 2.35 (q, *J* = 7.5 Hz, 2H), 2.22 (s, 3H), 2.00 (ddt, *J* = 31.5, 13.5, 6.8 Hz, 2H), 1.03 (t, *J* = 7.5 Hz, 3H), 0.95 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.69, 149.09, 145.44, 141.75, 136.51, 135.80, 135.39, 130.36, 130.10, 126.91, 125.69, 124.36, 120.89, 25.32, 23.89, 20.03, 13.35, 13.73. HRMS (ESI-TOF) calcd for $C_{18}H_{21}N^{+}$ ([M+H]$^{+}$): 253.1747, found: 253.1745.

(±) 2-(2-propyl-1-(o-tolyl)pent-1-en-1-yl)pyridine(3-1f):



方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.63 – 8.53 (m, 1H), 7.52 (td, *J* = 7.7, 1.8 Hz, 1H), 7.24 – 7.18 (m, 1H), 7.18 – 7.12 (m, 3H), 7.05 (dd, 2H), 2.30 (t, 2H), 2.22 (s, 3H), 2.06 – 1.96 (m, 1H), 1.95 – 1.84 (m, 1H), 1.50 – 1.38 (m, 4H), 0.83 (t, *J* = 7.3 Hz, 3H), 0.78 (t, *J* = 7.3 Hz, 3H).^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.93, 149.08, 142.54, 141.92, 136.65, 136.51, 135.75, 130.50, 130.08, 126.86, 125.64, 124.55, 120.85, 34.70, 33.09, 21.82, 21.29, 20.15, 14.51, 14.34. HRMS (ESI-TOF) calcd for $C_{20}H_{26}N^{+}$ ([M+H]$^{+}$): 280.2060, found: 280.2061.

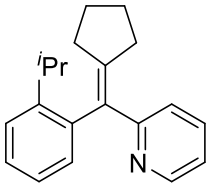
(±)2-(cyclohexylidene(2-isopropylphenyl)methyl)pyridine(3-1g):



方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 4.9, 1.8 Hz, 1H), 7.52 (td, *J* = 7.7, 1.9 Hz, 1H), 7.25 (d, *J* = 3.5 Hz, 3H), 7.21 – 7.15 (m, 1H), 7.07 (d, *J* = 7.9 Hz, 1H), 7.03 (dd, *J* = 7.5, 5.0 Hz, 1H), 3.16 (p, *J* = 6.9 Hz, 1H), 2.58 – 2.30 (m, 2H), 2.17 – 1.94 (m, 2H), 1.57 (dddd, *J* = 17.6, 13.7, 8.8, 4.8 Hz, 6H), 1.15 (d, *J* = 6.9 Hz, 3H), 0.76 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 148.92, 147.58, 143.84, 140.28, 135.71, 130.68, 127.45, 125.79, 125.52, 124.92, 120.74, 33.13, 31.54, 30.05, 28.55, 28.37, 26.80, 24.26, 23.75. HRMS (ESI-TOF) calcd for $C_{21}H_{26}N^{+}$

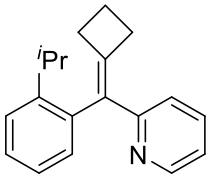
([M+H]$^+$): 292.2060, found: 292.2059.

(±)2-(cyclopentylidene(2-isopropylphenyl)methyl)pyridine(3-1h):



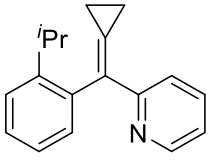
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.60 (ddd, *J* = 4.8, 3.0, 1.0 Hz, 1H), 7.46 (td, *J* = 7.7, 1.9 Hz, 1H), 7.36 – 7.27 (m, 2H), 7.24 – 7.16 (m, 2H), 7.01 (ddd, *J* = 7.6, 4.8, 1.1 Hz, 1H), 6.88 (dt, *J* = 8.0, 1.1 Hz, 1H), 2.98 (p, *J* = 6.9 Hz, 2H), 2.79 – 2.61 (m, 1H), 2.34 – 2.20 (m, 1H), 2.10 – 1.96 (m, 1H), 1.92 – 1.76 (m, 1H), 1.74 – 1.60 (m, 3H), 1.15 (d, *J* = 6.9 Hz, 3H), 0.82 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.48, 149.38, 148.65, 147.23, 140.81, 135.62, 131.80, 130.57, 127.50, 126.02, 125.96, 123.31, 120.41, 34.74, 33.26, 30.05, 27.52, 26.09, 24.34. HRMS (ESI-TOF) calcd for $C_{20}H_{24}N^+$ ([M+H]$^+$): 278.1903, found: 278.1903.

(±)2-(cyclobutylidene(2-isopropylphenyl)methyl)pyridine(3-1i):



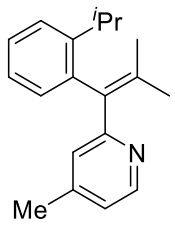
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (d, 1H), 7.47 (td, *J* = 7.8, 1.9 Hz, 1H), 7.37 – 7.27 (m, 2H), 7.21 (td, *J* = 7.2, 1.7 Hz, 1H), 7.15 (dd, *J* = 7.6, 1.5 Hz, 1H), 7.00 (ddd, *J* = 7.6, 4.8, 1.1 Hz, 1H), 6.81 (d, *J* = 8.0 Hz, 1H), 3.33 (td, *J* = 7.8, 3.6 Hz, 2H), 2.92 (p, *J* = 6.8 Hz, 1H), 2.60 (td, *J* = 7.9, 3.5 Hz, 2H), 2.07 (p, *J* = 7.8 Hz, 2H), 1.05 (d, *J* = 6.8 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.05, 149.05, 148.34, 147.80, 137.38, 135.84, 132.04, 130.76, 127.71, 125.91, 125.82, 121.90, 120.38, 34.09, 32.17, 30.21, 24.22, 17.84, 17.84. HRMS (ESI-TOF) calcd for $C_{19}H_{22}N^+$ ([M+H]$^+$): 264.1747, found: 264.1747.

(±)2-(cyclopropylidene(2-isopropylphenyl)methyl)pyridine(3-1j):



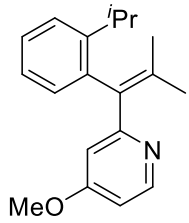
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.62 (d, *J* = 4.6 Hz, 1H), 7.49 (tt, *J* = 7.8, 1.6 Hz, 1H), 7.42 – 7.33 (m, 2H), 7.28 – 7.21 (m, 1H), 7.11 (t, 3H), 6.73 (dd, *J* = 7.9, 1.2 Hz, 1H), 3.60 (td, *J* = 7.1, 1.3 Hz, 2H), 2.88 – 2.76 (m, 1H), 2.55 – 2.41 (m, 2H), 1.12 (dd, *J* = 6.9, 1.3 Hz, 3H), 0.96 (dd, *J* = 7.0, 1.2 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 157.42, 149.40, 147.62, 142.48, 136.51, 136.25, 130.24, 128.68, 128.41, 126.15, 126.10, 122.14, 121.86, 43.81, 33.38, 30.22, 24.56, 23.77.
HRMS (ESI-TOF) calcd for $C_{18}H_{20}N^+$ ([M+H]$^+$): 250.159, found: 250.1588.

(±)2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)-4-methylpyridine(3-1k):



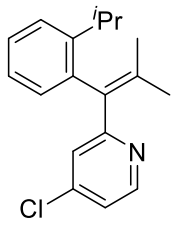
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.42 (d, *J* = 5.0 Hz, 1H), 7.25 (s, 2H), 7.23 – 7.14 (m, 2H), 6.88 – 6.79 (m, 2H), 3.13 (hept, *J* = 6.9 Hz, 1H), 2.21 (s, 3H), 1.94 (s, 3H), 1.64 (s, 3H), 1.15 (d, *J* = 6.9 Hz, 3H), 0.77 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.71, 148.49, 147.60, 146.66, 140.68, 136.09, 135.17, 130.66, 127.43, 125.86, 125.56, 125.37, 121.87, 30.02, 24.15, 23.88, 23.27, 21.71, 21.14. HRMS (ESI-TOF) calcd for $C_{19}H_{24}N^{+}$ ([M+H]$^{+}$): 266.1903, found: 266.1903.

(±)2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)-4-methoxypyridine (3-1l):



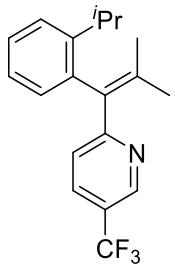
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.41 (d, *J* = 5.7 Hz, 1H), 7.25 (d, *J* = 5.5 Hz, 2H), 7.22 – 7.14 (m, 2H), 6.59 (dd, *J* = 5.7, 3.5 Hz, 1H), 6.56 (d, *J* = 3.5 Hz, 1H), 3.73 (s, 3H), 3.15 (hept, *J* = 6.9 Hz, 1H), 1.96 (s, 3H), 1.65 (s, 3H), 1.16 (d, *J* = 6.9 Hz, 3H), 0.83 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 165.49, 149.96, 147.45, 140.47, 135.90, 135.29, 130.50, 127.43, 125.82, 125.58, 110.72, 106.94, 54.99, 30.01, 24.13, 23.96, 23.25, 21.71. HRMS (ESI-TOF) calcd for $C_{19}H_{24}NO^{+}$ ([M+H]$^{+}$): 282.1852, found: 282.1853.

(±)4-chloro-2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine (3-1m):



方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.48 (d, *J* = 5.4 Hz, 1H), 7.29 (dd, *J* = 3.8, 1.7 Hz, 2H), 7.23 – 7.16 (m, 2H), 7.07 (dd, *J* = 5.3, 3.0 Hz, 1H), 7.04 (d, *J* = 1.9 Hz, 1H), 3.06 (hept, *J* = 6.9 Hz, 1H), 1.98 (s, 3H), 1.67 (s, 3H), 1.16 (d, *J* = 6.9 Hz, 3H), 0.81 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 162.39, 149.60, 147.56, 143.70, 139.85, 137.03, 130.67, 127.83, 126.05, 125.82, 124.82, 121.18, 30.13, 24.19, 23.88, 23.52, 21.81. HRMS (ESI-TOF) calcd for $C_{18}H_{21}ClN^{+}$ ([M+H]$^{+}$): 286.1357, found: 286.1361.

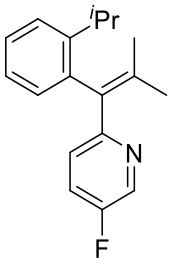
(±)2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)-5-(trifluoromethyl)pyridine (3-1n):



方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.88 – 8.81 (m, 1H), 7.74 (dd, *J* = 8.3, 3.3 Hz, 1H), 7.33 – 7.27 (m, 2H), 7.23 – 7.17 (m, 2H), 7.14 (d, *J* = 8.3 Hz, 1H), 2.03 (hept, *J* = 6.9 Hz, 1H), 3.03 (s, 3H), 1.70 (s, 3H), 1.16 (d, *J* = 6.9 Hz, 3H), 0.81 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 164.36 (q, J_{CF} = 2.02 Hz), 147.61, 145.66 (q, J_{CF} = 4.04 Hz), 139.80, 138.06, 135.09, 132.85 (q, J_{CF} = 3.03 Hz), 130.73, 127.95, 126.12, 125.86, 124.23, 123.91 (q, J_{CF} = 274.72 Hz), 123.45

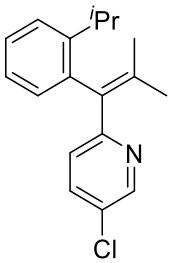
(q, J_{CF} = 33.33 Hz), 30.17, 24.22, 23.84, 23.76, 21.89. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -63.23. HRMS (ESI-TOF) calcd for $C_{19}H_{21}F_3N^+$ ([M+H]$^+$): 320.1621, found: 320.1619.

(±)5-fluoro-2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine (3-1o):



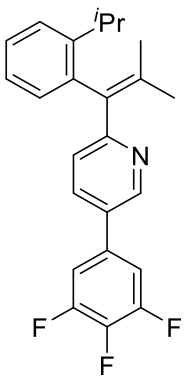
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.43 (d, *J* = 2.9 Hz, 1H), 7.27 (d, *J* = 2.6 Hz, 1H), 7.25 (dd, *J* = 4.6, 2.7 Hz, 1H), 7.21 (dd, *J* = 8.5, 3.0 Hz, 1H), 7.21 – 7.15 (m, 2H), 7.01 (dd, *J* = 8.7, 4.5 Hz, 1H), 3.04 (hept, *J* = 6.9 Hz, 1H), 1.96 (s, 3H), 1.66 (s, 3H), 1.14 (d, *J* = 6.9 Hz, 3H), 0.77 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 157.49 (d, J_{CF} = 256.54 Hz), 157.08 (d, J_{CF} = 4.04 Hz), 147.51, 140.42, 136.69 (d, J_{CF} = 22.22 Hz), 135.81, 135.02, 130.61, 127.66, 126.00, 125.71, 125.50 (d, J_{CF} = 3.03 Hz), 122.62 (d, J_{CF} = 18.18 Hz), 30.08, 24.18, 23.85, 23.43, 21.71. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -130.93. HRMS (ESI-TOF) calcd for $C_{18}H_{21}FN^+$ ([M+H]$^+$): 270.1653, found: 270.1655.

(±) 5-chloro-2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine (3-1p):



方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.54 (d, *J* = 2.5 Hz, 1H), 7.48 (dd, *J* = 8.5, 2.6 Hz, 1H), 7.32 – 7.26 (m, 2H), 7.18 (dd, *J* = 4.1, 2.9 Hz, 2H), 6.96 (d, *J* = 8.5 Hz, 1H), 3.04 (hept, *J* = 6.9 Hz, 1H), 1.99 (s, 3H), 1.67 (s, 3H), 1.15 (d, *J* = 6.9 Hz, 3H), 0.80 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 158.94, 147.51, 147.46, 140.14, 136.52, 135.51, 134.88, 130.63, 128.98, 127.72, 126.00, 125.72, 125.41, 30.08, 24.18, 23.84, 23.56, 21.77. HRMS (ESI-TOF) calcd for $C_{18}H_{21}ClN^+$ ([M+H]$^+$): 286.1357, found: 286.1357.

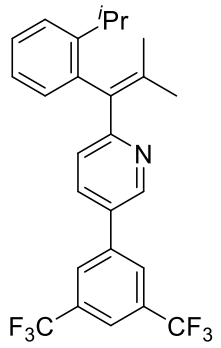
(±)2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)-5-(3,4,5-trifluorophenyl)pyridine (3-1q):



方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.74 (d, *J* = 2.4 Hz, 1H), 7.63 (dd, *J* = 8.3, 2.5 Hz, 1H), 7.30 (d, *J* = 3.4 Hz, 2H), 7.21 (d, *J* = 3.1 Hz, 2H), 7.17 (dd, *J* = 8.2, 6.4 Hz, 2H), 7.10 (d, *J* = 8.2 Hz, 1H), 3.08 (hept, *J* = 6.9 Hz, 1H), 2.05 (s, 3H), 1.70 (s, 3H), 1.17 (d, *J* = 6.8 Hz, 3H), 0.82 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.89, 151.75 (ddd, J_{CF} = 251.49, 10.10, 4.04 Hz), 147.57, 146.71, 140.28, 139.71 (dt, J_{CF} = 254.02, 5.05 Hz), 136.72, 135.35, 134.18 (m), 133.84, 130.72, 130.57 (m), 127.74, 126.01, 125.76, 124.69, 111.10 (dd, J_{CF} = 16.16, 6.06 Hz), 30.14, 24.21, 23.91, 23.65, 21.89. ^{19}F NMR (376 MHz, Chloroform-

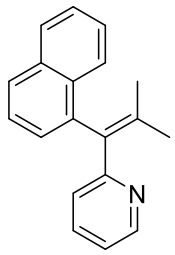
d) δ -133.35 (d, *J* = 20.7 Hz), -161.50 (t, *J* = 20.7 Hz). HRMS (ESI-TOF) calcd for $C_{24}H_{23}F_3N^+$ ($[M+H]^+$): 382.1777, found: 382.1779.

(±)5-(3,5-bis(trifluoromethyl)phenyl)-2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine (3-1r):



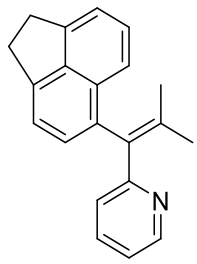
方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.95 – 8.73 (m, 1H), 7.99 (s, 2H), 7.88 (s, 1H), 7.76 (dt, *J* = 8.4, 1.8 Hz, 1H), 7.31 (q, *J* = 1.8 Hz, 2H), 7.23 (d, *J* = 3.0 Hz, 2H), 7.16 (d, *J* = 8.2 Hz, 1H), 3.10 (hept, *J* = 6.8 Hz, 1H), 2.07 (s, 3H), 1.72 (s, 3H), 1.18 (d, *J* = 6.8 Hz, 3H), 0.84 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 161.37, 147.56, 147.02, 140.23, 140.1, 137.04, 135.25, 134.28, 132.54 (q, J_{CF} = 33.33 Hz), 130.74, 130.65, 127.78, 127.14 (q, J_{CF} = 2.02 Hz), 126.03, 125.79, 124.87, 123.33 (q, J_{CF} = 273.71 Hz), 121.59 (m), 30.16, 24.24, 23.95, 23.72, 21.93. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -63.90. HRMS (ESI-TOF) calcd for $C_{26}H_{24}F_6N^+$ ($[M+H]^+$): 464.1807, found: 464.1809.

(±)2-(2-methyl-1-(naphthalen-1-yl)prop-1-en-1-yl)pyridine (3-1s):



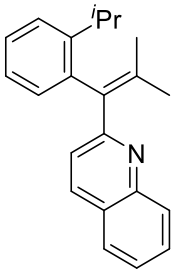
方法 A。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.61 (ddd, *J* = 4.9, 1.9, 1.0 Hz, 1H), 8.04 (m, 1H), 7.89 – 7.81 (m, 1H), 7.77 (dt, *J* = 8.1, 1.1 Hz, 1H), 7.50 – 7.39 (m, 5H), 7.08 (dt, *J* = 8.0, 1.1 Hz, 1H), 7.03 (ddd, *J* = 7.5, 4.9, 1.2 Hz, 1H), 2.08 (s, 3H), 1.62 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.95, 148.90, 140.12, 137.01, 135.93, 134.43, 133.97, 132.23, 128.37, 127.62, 127.28, 126.35, 126.14, 125.72, 124.33, 121.00, 23.21, 21.91. HRMS (ESI-TOF) calcd for $C_{19}H_{18}N^+$ ($[M+H]^+$): 260.1434, found: 260.1434.

(±)2-(1-(1,2-dihydroacenaphthylen-5-yl)-2-methylprop-1-en-1-yl)pyridine (3-1t):



方法 A。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (ddd, *J* = 5.0, 1.9, 0.9 Hz, 1H), 7.59 (d, *J* = 8.2 Hz, 1H), 7.45 (td, *J* = 7.7, 1.9 Hz, 1H), 7.42 – 7.35 (m, 1H), 7.33 (d, *J* = 7.0 Hz, 1H), 7.26 – 7.21 (m, 2H), 7.07 (dt, *J* = 7.8, 1.1 Hz, 1H), 7.02 (ddd, *J* = 7.5, 4.9, 1.2 Hz, 1H), 3.38 (m, 4H), 2.03 (s, 3H), 1.65 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 161.46, 148.88, 146.27, 145.09, 139.67, 136.52, 135.90, 135.53, 134.11, 130.64, 129.38, 127.93, 124.48, 121.40, 120.90, 119.23, 119.17, 30.64, 30.20, 23.19, 21.96. HRMS (ESI-TOF) calcd for $C_{21}H_{20}N^+$ ($[M+H]^+$): 286.1590, found: 286.1590.

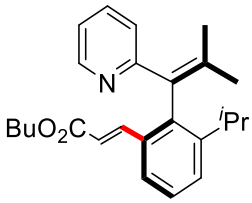
(±)2-(1-(2-isopropylphenyl)-2-methylprop-1-en-1-yl)quinolone (3-1u):



方法 B。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.12 (d, *J* = 8.5 Hz, 1H), 7.95 (d, *J* = 8.5 Hz, 1H), 7.73 (dd, *J* = 8.1, 1.4 Hz, 1H), 7.68 (ddd, *J* = 8.4, 6.9, 1.5 Hz, 1H), 7.48 (ddd, *J* = 8.0, 6.8, 1.1 Hz, 1H), 7.29 (ddd, *J* = 7.1, 5.8, 3.4 Hz, 3H), 7.23 – 7.17 (m, 1H), 7.13 (d, *J* = 8.5 Hz, 1H), 3.26 (hept, *J* = 6.9 Hz, 1H), 2.09 (s, 3H), 1.75 (s, 3H), 1.20 (d, *J* = 6.8 Hz, 3H), 0.77 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 148.02, 147.80, 140.10, 136.88, 136.46, 135.51, 130.94, 129.45, 129.31, 127.67, 127.46, 126.38, 126.07, 125.67, 122.85, 30.09, 24.29, 24.14, 23.65, 21.93. HRMS (ESI-TOF) calcd for $C_{22}H_{24}N^{+}$ ([M+H]$^{+}$): 302.1903, found: 302.1905.

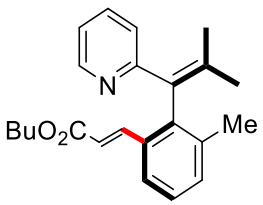
3.9.2 产物结构表征

(*E*)-butyl 3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3aa):



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(32.3 mg, 85%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min^{-1}, λ = 254 nm, t (major) = 7.3 min, t (minor) = 8.6 min, 95% ee; $[\alpha]_D^{20}$ = -259.6 (c = 1.02, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.60 (dd, *J* = 5.0, 1.8 Hz, 1H), 7.96 (d, *J* = 16.0 Hz, 1H), 7.56 (dd, *J* = 5.7, 3.4 Hz, 1H), 7.51 (td, *J* = 7.7, 1.9 Hz, 1H), 7.34 – 7.29 (m, 2H), 7.06 (dd, *J* = 7.4, 5.0 Hz, 1H), 6.89 (d, *J* = 7.9 Hz, 1H), 6.42 (d, *J* = 16.0 Hz, 1H), 4.24 – 4.07 (m, 2H), 3.15 (hept, *J* = 6.9 Hz, 1H), 2.13 (s, 3H), 1.71 – 1.59 (m, 2H), 1.55 (s, 3H), 1.40 (h, *J* = 7.4 Hz, 2H), 1.12 (d, *J* = 6.9 Hz, 3H), 0.92 (t, *J* = 7.4 Hz, 3H), 0.67 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.38, 159.49, 148.72, 148.43, 144.61, 141.19, 136.25, 133.65, 131.89, 128.09, 127.93, 124.64, 123.70, 121.02, 119.17, 64.34, 30.85, 30.26, 24.26, 23.53, 21.70, 19.33, 13.85.
HRMS (ESI-TOF) calcd for $C_{25}H_{32}NO_2^{+}$ ([M+H]$^{+}$): 378.2428, found: 378.2427.

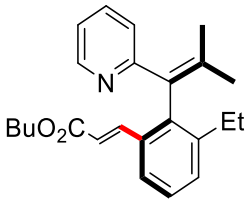
(*E*)-butyl 3-(3-methyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ba):



经制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(16.4 mg, 47%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 8.3 min, t (minor) = 9.1 min, 92% ee; $[\alpha]_D^{20}$ = -239.6 (c = 1.01, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.58 (dd, *J* = 4.9, 1.7 Hz, 1H), 7.95 (d, *J* = 15.9 Hz, 1H), 7.52 (ddd, *J* = 13.2, 6.8, 2.8 Hz, 2H), 7.21 (q, *J* = 3.4, 2.5 Hz, 2H), 7.10 – 7.02 (m, 1H), 6.97 (dd, *J* =

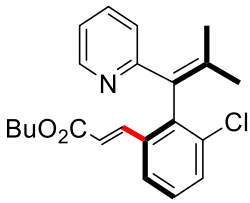
8.0, 1.1 Hz, 1H), 6.39 (d, *J* = 15.9 Hz, 1H), 4.16 (tt, *J* = 6.6, 3.2 Hz, 2H), 2.14 (s, 3H), 2.09 (s, 3H), 1.72 – 1.59 (m, 2H), 1.53 (s, 3H), 1.40 (h, *J* = 7.4 Hz, 2H), 0.93 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.40, 159.26, 148.89, 144.33, 142.85, 138.04, 137.78, 135.89, 133.67, 132.57, 132.05, 127.35, 124.45, 123.65, 120.96, 118.92, 64.32, 30.85, 23.03, 21.67, 20.34, 19.33, 13.88. HRMS (ESI-TOF) calcd for $C_{23}H_{28}NO_2^+$ ([M+H]$^+$): 350.2115, found: 350.2116.

(*E*)-butyl 3-(3-ethyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ca):



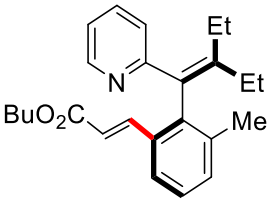
经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 =80/1 为展开剂)(20.7 mg, 57%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 7.6 min, t (minor) = 8.7 min, 91% ee; $[\alpha]_D^{20}$ = -296.3 (c = 1.01, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.56 (dd, *J* = 5.0, 1.7 Hz, 1H), 7.92 (d, *J* = 15.9 Hz, 1H), 7.64 – 7.39 (m, 2H), 7.25 – 7.18 (m, 2H), 7.02 (dd, *J* = 7.5, 4.9 Hz, 1H), 6.89 (d, *J* = 7.9 Hz, 1H), 6.38 (d, *J* = 16.0 Hz, 1H), 4.24 – 3.95 (m, 2H), 2.45 (ddt, *J* = 32.8, 14.6, 7.3 Hz, 2H), 2.08 (s, 3H), 1.67 – 1.55 (m, 2H), 1.49 (s, 3H), 1.37 (h, *J* = 7.4 Hz, 2H), 0.89 (t, *J* = 7.4 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.39, 159.37, 148.60, 144.46, 143.79, 143.05, 138.59, 136.11, 133.79, 132.00, 130.49, 127.68, 124.52, 123.65, 121.02, 119.08, 64.33, 30.84, 26.25, 23.43, 21.70, 19.32, 14.73, 13.86. HRMS (ESI-TOF) calcd for $C_{24}H_{30}NO_2^+$ ([M+H]$^+$): 364.2271, found: 364.2274.

(*E*)-butyl 3-(3-chloro-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3da):



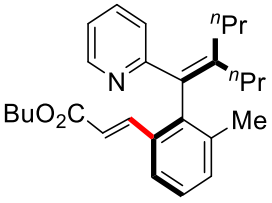
经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(15.9 mg, 43%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 13.0 min, t (minor) =13.6 min, 95% ee; $[\alpha]_D^{20}$ = -185.8 (c = 1.00, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.62 – 8.50 (m, 1H), 7.95 (d, *J* = 16.0 Hz, 1H), 7.64 – 7.50 (m, 2H), 7.41 (d, *J* = 7.9 Hz, 1H), 7.23 (m,, 1H), 7.13 (d, *J* = 7.9 Hz, 1H), 7.05 (dd, *J* = 7.5, 4.9 Hz, 1H), 6.37 (d, *J* = 16.0 Hz, 1H), 4.17 (t, *J* = 6.5 Hz, 2H), 2.09 (s, 3H), 1.68 (d, *J* = 6.9 Hz, 1H), 1.62 (d, *J* = 7.0 Hz, 1H), 1.57 (s, 3H), 1.41 (h, *J* = 7.4 Hz, 2H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.98, 158.40, 148.95, 143.36, 141.49, 139.43, 136.34, 135.86, 135.34, 131.00, 128.47, 126.96, 124.88, 124.65, 121.19, 120.31, 64.50, 30.83, 23.06, 21.81, 19.31, 13.88. HRMS (ESI-TOF) calcd for $C_{22}H_{25}ClNO_2^+$ ([M+H]$^+$): 370.1568, found: 370.1568.

(*E*)-butyl 3-(2-(2-ethyl-1-(pyridin-2-yl)but-1-en-1-yl)-3-methylphenyl)acrylate (3-3ea)



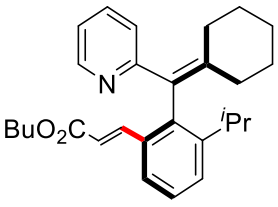
经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(38.0 mg, 99%)。手性 HPLC 分离条件：a Daicel Chiralpak OD-H, *n*-hexane/2-propanol = 97/3, v = 0.6 mL·min-1, λ = 254 nm, t (major) = 17.5 min, t (minor) = 16.8 min, 92% ee; $[\alpha]_D^{20}$ = -196.9 (c = 1.09, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 4.7, 1.8 Hz, 1H), 8.10 (d, *J* = 16.0 Hz, 1H), 7.53 (dtd, *J* = 15.2, 7.6, 3.0 Hz, 2H), 7.20 (q, *J* = 3.4, 2.6 Hz, 2H), 7.03 (ddd, *J* = 7.5, 4.9, 1.1 Hz, 1H), 7.00 – 6.94 (m, 1H), 6.38 (d, *J* = 16.1 Hz, 1H), 4.17 (tt, *J* = 6.6, 3.4 Hz, 2H), 2.80 – 2.64 (m, 1H), 2.47 – 2.32 (m, 1H), 2.20 (s, 3H), 1.89 (q, *J* = 7.7 Hz, 2H), 1.65 (dq, *J* = 8.5, 6.7 Hz, 2H), 1.47 – 1.35 (m, 2H), 1.06 (t, *J* = 7.5 Hz, 3H), 0.92 (q, *J* = 7.4 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.35, 159.52, 149.06, 147.83, 144.57, 142.83, 138.01, 135.84, 133.50, 132.08, 131.74, 127.25, 124.31, 123.57, 121.00, 118.78, 64.34, 30.89, 25.94, 23.73, 20.49, 19.32, 13.86, 13.18, 12.00. HRMS (ESI-TOF) calcd for $C_{25}H_{32}NO_2^+$ ($[M+H]^+$): 378.2428, found: 378.2429.

(*E*)-butyl 3-(3-methyl-2-(2-propyl-1-(pyridin-2-yl)pent-1-en-1-yl)phenyl)acrylate (3-3fa)



经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(35.2 mg, 87%)。手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 95/5, v = 0.8 mL·min-1, λ = 254 nm, t (major) = 7.9 min, t (minor) = 7.0 min, 95% ee; $[\alpha]_D^{20}$ = -167.1 (c = 1.11, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 4.9, 1.8 Hz, 1H), 8.09 (d, *J* = 16.0 Hz, 1H), 7.58 – 7.45 (m, 2H), 7.22 – 7.15 (m, 2H), 7.06 – 7.01 (m, 1H), 6.99 (d, *J* = 7.9 Hz, 1H), 6.37 (d, *J* = 16.0 Hz, 1H), 4.17 (t, *J* = 6.7 Hz, 2H), 2.66 (ddd, *J* = 13.3, 10.0, 6.1 Hz, 1H), 2.34 (ddd, *J* = 13.3, 9.9, 5.5 Hz, 1H), 2.21 (s, 3H), 1.88 – 1.77 (m, 2H), 1.70 – 1.60 (m, 2H), 1.57 – 1.48 (m, 1H), 1.48 – 1.29 (m, 5H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.86 (t, *J* = 7.3 Hz, 3H), 0.75 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.33, 159.74, 149.01, 145.30, 144.68, 142.94, 138.01, 135.75, 133.51, 132.87, 132.07, 127.22, 124.47, 123.56, 120.94, 118.76, 64.32, 35.49, 33.28, 30.91, 21.81, 20.76, 20.58, 19.32, 14.67, 14.63, 13.88. HRMS (ESI-TOF) calcd for $C_{27}H_{36}NO_2^+$ ($[M+H]^+$): 406.2741, found: 406.2741.

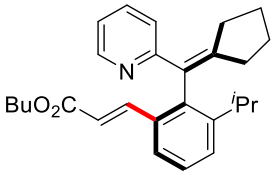
(*E*)-butyl 3-(2-(cyclohexylidene(pyridin-2-yl)methyl)-3-isopropylphenyl)acrylate (3-3ga):



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 =80/1 为展开剂)(41.1 mg, 99%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 99/1, v = 0.3 mL·min-1, λ = 254 nm, t (major) = 13.1 min, t (minor) = 13.6 min, 90% ee; $[\alpha]_D^{20}$ = -247.9 (c = 1.00, $CHCl_3$).

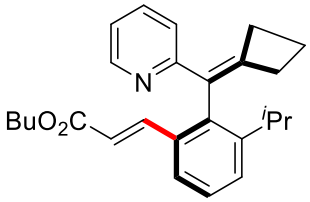
^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 5.0, 1.7 Hz, 1H), 8.17 (d, *J* = 16.0 Hz, 1H), 7.57 (dd, *J* = 5.8, 3.3 Hz, 1H), 7.50 (td, *J* = 7.7, 1.8 Hz, 1H), 7.29 (d, *J* = 5.8 Hz, 2H), 7.03 (dd, *J* = 7.4, 5.0 Hz, 1H), 6.94 (d, *J* = 7.9 Hz, 1H), 6.41 (d, *J* = 16.0 Hz, 1H), 4.18 (qt, *J* = 10.9, 6.6 Hz, 2H), 3.22 (p, *J* = 6.9 Hz, 1H), 2.72 (ddd, *J* = 13.7, 6.4, 3.6 Hz, 1H), 2.52 (ddd, *J* = 13.7, 9.5, 4.1 Hz, 1H), 1.91 (tq, *J* = 13.4, 7.2, 5.9 Hz, 2H), 1.77 (ddd, *J* = 15.4, 7.6, 4.3 Hz, 1H), 1.71 – 1.60 (m, 4H), 1.52 (q, *J* = 5.7, 4.6 Hz, 3H), 1.41 (h, *J* = 7.4 Hz, 2H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.70 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.38, 159.69, 148.95, 148.82, 145.27, 145.17, 141.27, 135.80, 133.55, 129.45, 128.00, 127.72, 124.80, 123.50, 120.87, 118.72, 64.36, 33.38, 31.53, 30.95, 30.28, 28.35, 27.35, 26.76, 24.32, 23.59, 19.35, 13.87. HRMS (ESI-TOF) calcd for $C_{28}H_{36}NO_2^+$ ([M+H]$^+$): 418.2741, found: 418.2741.

(*E*)-butyl 3-(2-(cyclopentylidene(pyridin-2-yl)methyl)-3-isopropylphenyl)acrylate (3-3ha)



经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(35.2 mg, 87%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v =1.0 mL·min-1, λ = 254 nm, t (major) = 3.5 min, t (minor) = 3.8 min, 95% ee; $[\alpha]_D^{20}$ = -101.2 (c = 1.06, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.60 (ddd, *J* = 4.8, 1.9, 1.0 Hz, 1H), 7.84 (d, *J* = 16.0 Hz, 1H), 7.59 (dd, *J* = 7.3, 1.7 Hz, 1H), 7.46 (td, *J* = 7.7, 1.9 Hz, 1H), 7.39 – 7.30 (m, 2H), 7.01 (ddd, *J* = 7.5, 4.8, 1.1 Hz, 1H), 6.76 (dt, *J* = 8.1, 1.1 Hz, 1H), 6.41 (d, *J* = 16.0 Hz, 1H), 4.22 – 4.05 (m, 2H), 3.17 – 2.95 (m, 2H), 2.91 – 2.73 (m, 1H), 1.92 (dt, *J* = 7.5, 4.1 Hz, 2H), 1.89 – 1.81 (m, 1H), 1.70 – 1.57 (m, 5H), 1.43 – 1.29 (m, 2H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.90 (t, *J* = 7.4 Hz, 3H), 0.76 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.31, 159.50, 151.56, 148.81, 148.20, 144.46, 141.45, 135.79, 133.24, 128.27, 128.17, 127.82, 123.83, 122.99, 120.62, 119.10, 64.28, 34.84, 33.41, 30.84, 30.23, 27.42, 25.88, 24.36, 23.79, 19.32, 13.84. HRMS (ESI-TOF) calcd for $C_{27}H_{34}NO_2^+$ ([M+H]$^+$): 404.2584, found: 404.2584.

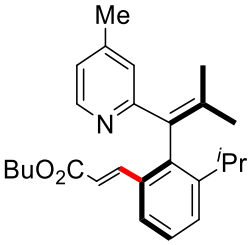
(*E*)-butyl 3-(2-(cyclobutylidene(pyridin-2-yl)methyl)-3-isopropylphenyl)acrylate (3-3ia)



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 =80/1 为展开剂)(16.5 mg, 42%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.7 mL·min-1, λ = 254 nm, t (major) = 3.7 min, t (minor) = 4.1 min, 5% ee; $[\alpha]_D^{20}$ = -0.9 (c = 1.03, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (ddd, *J* = 4.9, 1.9, 1.0 Hz, 1H), 7.84 (d, *J* = 15.9 Hz, 1H), 7.57 (dd, *J* = 7.4, 1.6 Hz, 1H), 7.48 (td, *J* = 7.7, 1.9 Hz, 1H), 7.39 (dd, *J* = 7.8, 1.7 Hz, 1H),

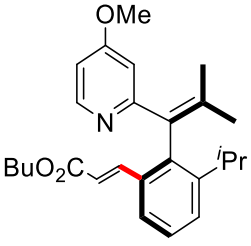
7.34 (t, *J* = 7.6 Hz, 1H), 7.01 (ddd, *J* = 7.5, 4.8, 1.1 Hz, 1H), 6.76 (dt, *J* = 8.0, 1.1 Hz, 1H), 6.38 (d, *J* = 15.9 Hz, 1H), 4.23 – 4.08 (m, 2H), 3.55 – 3.41 (m, 1H), 3.33 – 3.18 (m, 1H), 2.95 (hept, *J* = 6.9 Hz, 1H), 2.50 – 2.30 (m, 2H), 2.09 – 1.99 (m, 2H), 1.62 (ddt, *J* = 8.8, 7.9, 6.5 Hz, 2H), 1.42 – 1.33 (m, 2H), 1.14 (d, *J* = 6.8 Hz, 3H), 0.94 – 0.89 (m, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.35, 158.23, 150.21, 149.29, 148.75, 144.41, 138.07, 135.99, 133.89, 128.73, 127.99, 127.81, 123.80, 121.66, 120.63, 118.97, 64.29, 34.22, 32.47, 30.85, 30.41, 24.75, 23.63, 19.33, 17.86, 13.86. HRMS (ESI-TOF) calcd for $C_{26}H_{32}NO_2^+$ ([M+H]$^+$): 390.2428, found: 390.2428.

(*E*)-butyl 3-(3-isopropyl-2-(2-methyl-1-(4-methylpyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ka):



经过通用方法以 Ag_2SO_4 代替 Ag_3PO_4，经制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 =80/1 为展开剂)(28.2 mg, 72%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.7 mL·min-1, λ = 254 nm, t (major) = 5.0 min, t (minor) = 6.0 min, 88% ee; $[\alpha]_D^{20}$ = -293.2 (c = 1.00, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.44 (d, *J* = 5.0 Hz, 1H), 7.98 (d, *J* = 16.0 Hz, 1H), 7.57 (dd, *J* = 5.6, 3.5 Hz, 1H), 7.35 – 7.28 (m, 2H), 6.92 – 6.81 (m, 1H), 6.67 (d, *J* = 1.6 Hz, 1H), 6.42 (d, *J* = 16.0 Hz, 1H), 4.17 (qt, *J* = 10.9, 6.6 Hz, 2H), 3.16 (hept, *J* = 6.9 Hz, 1H), 2.20 (s, 3H), 2.09 (s, 3H), 1.65 (dq, *J* = 8.3, 6.6 Hz, 2H), 1.52 (s, 3H), 1.46 – 1.33 (m, 2H), 1.11 (d, *J* = 6.8 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.67 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.47, 159.64, 148.73, 148.50, 146.80, 144.83, 141.47, 138.17, 133.65, 132.24, 128.06, 127.78, 125.23, 123.66, 122.03, 119.02, 64.34, 30.88, 30.23, 24.29, 23.55, 23.45, 21.69, 21.22, 19.35, 13.88. HRMS (ESI-TOF) calcd for $C_{26}H_{34}NO_2^+$ ([M+H]$^+$): 392.2584, found: 392.2584.

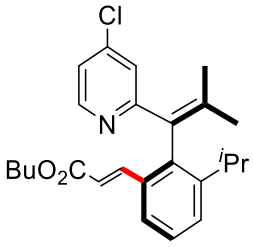
(*E*)-butyl 3-(3-isopropyl-2-(1-(4-methoxypyridin-2-yl)-2-methylprop-1-en-1-yl)phenyl)acrylate (3-3la):



经制备级 TLC 分离得到淡黄色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(33.0 mg, 79%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.7 mL·min-1, λ = 254 nm, t (major) = 5.6 min, t (minor) = 7.9 min, 88% ee; $[\alpha]_D^{20}$ = -298.8 (c = 1.00, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.42 (d, *J* = 5.7 Hz, 1H), 7.97 (d, *J* = 16.0 Hz, 1H), 7.55 (dd, *J* = 6.8, 3.2 Hz, 1H), 7.36 – 7.27 (m, 2H), 6.59 (dd, *J* = 5.7, 2.5 Hz, 1H), 6.45 – 6.36 (m, 2H), 4.25 – 4.07 (m, 2H), 3.70 (s, 3H), 3.18 (hept, *J* = 7.1 Hz, 1H), 2.11 (s, 3H), 1.65

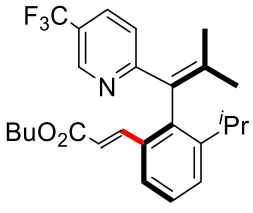
(dq, *J* = 8.4, 6.6 Hz, 2H), 1.53 (s, 3H), 1.48 – 1.34 (m, 2H), 1.12 (d, *J* = 6.9 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.74 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.42, 165.59, 161.36, 150.00, 148.68, 144.77, 141.34, 138.27, 133.53, 132.11, 128.08, 127.84, 123.70, 119.05, 110.90, 106.91, 64.35, 55.03, 30.87, 30.27, 24.31, 23.67, 23.49, 21.72, 19.35, 13.88. HRMS (ESI-TOF) calcd for $C_{26}H_{34}NO_3^+$ ([M+H]$^+$): 408.2533, found: 408.2535.

(*E*)-butyl 3-(2-(1-(4-chloropyridin-2-yl)-2-methylprop-1-en-1-yl)-3-isopropylphenyl)acrylate (3-3ma):



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(40.6 mg, 99%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 7.5 min, t (minor) = 8.7 min, 93% ee; $[\alpha]_D^{20}$ = -326.7 (c = 0.99, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.48 (d, *J* = 5.3 Hz, 1H), 7.90 (d, *J* = 15.9 Hz, 1H), 7.57 (p, *J* = 4.0 Hz, 1H), 7.33 (d, *J* = 4.5 Hz, 2H), 7.07 (dd, *J* = 5.3, 2.0 Hz, 1H), 6.88 (d, *J* = 1.9 Hz, 1H), 6.42 (d, *J* = 15.9 Hz, 1H), 4.17 (qt, *J* = 10.9, 6.6 Hz, 2H), 3.07 (hept, *J* = 6.8 Hz, 1H), 2.12 (s, 3H), 1.66 (dq, *J* = 8.5, 6.7 Hz, 2H), 1.54 (s, 3H), 1.46 – 1.34 (m, 2H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.74 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.33, 161.27, 149.63, 148.55, 144.28, 143.82, 140.52, 139.97, 133.71, 131.31, 128.17, 128.14, 124.60, 123.87, 121.32, 119.40, 64.40, 30.86, 30.32, 24.30, 23.69, 23.61, 21.80, 19.35, 13.88. HRMS (ESI-TOF) calcd for $C_{25}H_{31}ClNO_2^+$ ([M+H]$^+$): 412.2038, found: 412.2033.

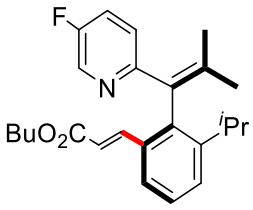
(*E*)-butyl 3-(3-isopropyl-2-(2-methyl-1-(5-(trifluoromethyl)pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3na):



使用通用方法以 AgOAc 替代 Ag_3PO_4，经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 =80/1 为展开剂)(37.4 mg, 84%)。手性 HPLC 分离条件：two Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 11.4 min, t (minor) = 13.3 min, 94% ee; $[\alpha]_D^{20}$ = -239.9 (c = 1.03, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.84 (d, *J* = 2.3 Hz, 1H), 7.90 (d, *J* = 15.9 Hz, 1H), 7.73 (dd, *J* = 8.4, 2.3 Hz, 1H), 7.57 (dd, *J* = 5.5, 3.5 Hz, 1H), 7.34 (d, *J* = 3.6 Hz, 2H), 7.03 (d, *J* = 8.3 Hz, 1H), 6.41 (d, *J* = 15.9 Hz, 1H), 4.16 (tt, *J* = 11.1, 5.3 Hz, 2H), 3.07 (hept, *J* = 6.8 Hz, 1H), 2.15 (s, 3H), 1.71 – 1.63 (m, 2H), 1.58 (s, 3H), 1.41 (p, *J* = 7.5 Hz, 2H), 1.13 (d, *J* = 6.9 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.76 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.27, 163.19 (q, J_{CF} = 2.02 Hz), 148.58, 145.76 (q, J_{CF} = 4.04 Hz),

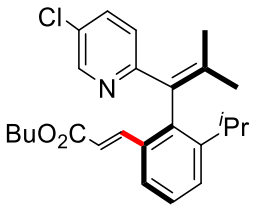
144.17, 140.78, 140.46, 133.74, 132.99 (q, J_{CF} = 3.03 Hz), 131.48, 128.26, 128.15, 123.96, 123.89, 123.82 (q, J_{CF} = 272.72 Hz), 123.54 (q, J_{CF} = 33.33 Hz), 119.46, 64.41, 30.87, 30.38, 24.31, 23.86, 23.66, 21.86, 19.34, 13.84. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -62.28. HRMS (ESI-TOF) calcd for $C_{26}H_{31}F_3NO_2^+$ ([M+H]$^+$): 446.2301, found: 446.2301.

(*E*)-butyl 3-(2-(1-(5-fluoropyridin-2-yl)-2-methylprop-1-en-1-yl)-3-isopropylphenyl)acrylate (3-3oa):



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(37.5 mg, 95%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 7.1 min, t (minor) = 8.1 min, 95% ee; $[\alpha]_D^{20}$ = -255.1 (c = 1.06, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.44 (d, *J* = 2.9 Hz, 1H), 7.93 (d, *J* = 15.9 Hz, 1H), 7.56 (dd, *J* = 6.1, 2.9 Hz, 1H), 7.32 (q, *J* = 4.2, 3.3 Hz, 2H), 7.22 (td, *J* = 8.4, 3.0 Hz, 1H), 6.91 (dd, *J* = 8.7, 4.4 Hz, 1H), 6.41 (d, *J* = 16.0 Hz, 1H), 4.25 – 4.09 (m, 2H), 3.10 (hept, *J* = 6.9 Hz, 1H), 2.09 (s, 3H), 1.65 (dq, *J* = 8.4, 6.7 Hz, 2H), 1.54 (s, 3H), 1.40 (h, *J* = 7.4 Hz, 2H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.73 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.37, 157.47 (d, J_{CF} = 256.54 Hz), 155.96 (d, J_{CF} = 4.04 Hz), 148.55, 144.48, 141.12, 138.40, 136.87 (d, J_{CF} = 23.23 Hz), 133.53, 131.27, 128.11, 127.98, 125.30 (d, J_{CF} = 4.04 Hz), 123.76, 122.68 (d, J_{CF} = 18.18 Hz), 119.20, 64.37, 30.86, 30.28, 24.27, 23.64, 23.50, 21.64, 19.34, 13.87. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -130.37. HRMS (ESI-TOF) calcd for $C_{25}H_{31}FNO_2^+$ ([M+H]$^+$): 396.2333, found: 396.2335.

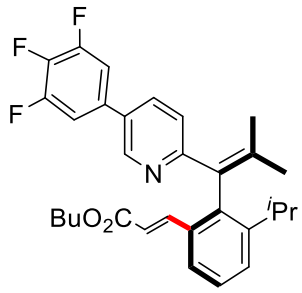
(*E*)-butyl 3-(2-(1-(5-chloropyridin-2-yl)-2-methylprop-1-en-1-yl)-3-isopropylphenyl)acrylate (3-3pa):



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(27.5 mg, 67%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 7.3 min, t (minor) = 9.0 min, 92% ee; $[\alpha]_D^{20}$ = -363.0 (c = 1.01, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.53 (d, *J* = 2.5 Hz, 1H), 7.89 (d, *J* = 15.9 Hz, 1H), 7.55 (dd, *J* = 6.0, 3.0 Hz, 1H), 7.52 – 7.41 (m, 1H), 7.32 (q, *J* = 4.0, 3.2 Hz, 2H), 6.84 (d, *J* = 8.4 Hz, 1H), 6.40 (dd, *J* = 15.9, 0.9 Hz, 1H), 4.24 – 4.03 (m, 2H), 3.07 (hept, *J* = 6.9 Hz, 1H), 3.11 (s, 3H), 1.71 – 1.59 (m, 2H), 1.54 (s, 3H), 1.40 (h, *J* = 7.4 Hz, 2H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.75 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.33, 148.56,

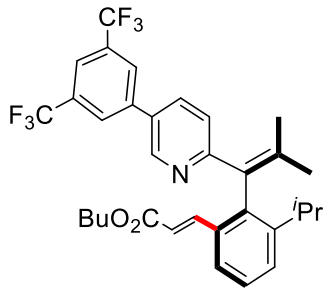
147.61, 144.34, 140.85, 139.19, 135.62, 133.57, 131.20, 129.14, 128.11, 128.05, 125.16, 123.77, 119.25, 64.38, 30.84, 30.30, 24.29, 23.68, 23.65, 21.72, 19.34, 13.88. HRMS (ESI-TOF) calcd for $C_{25}H_{31}ClNO_2^+$ ([M+H]$^+$): 412.2038, found: 412.2037.

(*E*)-butyl 3-(3-isopropyl-2-(2-methyl-1-(5-(3,4,5-trifluorophenyl)pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3qa):



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(50.1 mg, 99%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL · min-1, λ = 254 nm, t (major) = 9.2 min, t (minor) = 13.2 min, 95% ee; $[\alpha]_D^{20}$ = -326.5 (c = 1.00, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.75 (d, *J* = 2.5 Hz, 1H), 7.95 (d, *J* = 15.9 Hz, 1H), 7.62 (dd, *J* = 8.3, 2.5 Hz, 1H), 7.58 (dd, *J* = 6.1, 2.8 Hz, 1H), 7.34 (q, *J* = 4.3, 3.4 Hz, 2H), 7.16 (dd, *J* = 8.2, 6.3 Hz, 2H), 6.99 (d, *J* = 8.2 Hz, 1H), 6.42 (d, *J* = 15.9 Hz, 1H), 4.17 (q, *J* = 6.3 Hz, 2H), 3.13 (hept, *J* = 6.8 Hz, 1H), 2.17 (s, 3H), 1.71 – 1.60 (m, 2H), 1.57 (s, 3H), 1.41 (h, *J* = 7.4 Hz, 2H), 1.14 (d, *J* = 6.8 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H), 0.76 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.36, 159.68, 151.75 (ddd, J_{CF} = 251.49, 10.01, 4.04 Hz), 148.61, 146.73, 144.46, 140.96, 139.74 (dt, J_{CF} = 254.52, 15.15 Hz), 139.49, 134.04 (m), 133.99, 133.71, 131.62, 130.70 (m), 128.10, 128.07, 124.49, 123.81, 119.25, 111.10 (dd, J_{CF} = 16.16, 6.06 Hz), 64.38, 30.87, 30.36, 24.30, 23.75, 23.70, 21.85, 19.34, 13.86. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -133.30 (d, *J* = 20.4 Hz), -161.39 (t, *J* = 20.5 Hz). HRMS (ESI-TOF) calcd for $C_{31}H_{33}F_3NO_2^+$ ([M+H]$^+$): 508.2458, found: 508.2459.

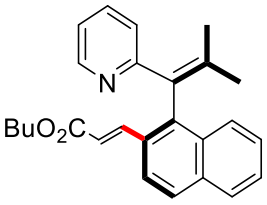
(*E*)-butyl 3-(2-(1-(5-(3,5-bis(trifluoromethyl)phenyl)pyridin-2-yl)-2-methylprop-1-en-1-yl)-3-isopropylphenyl)acrylate (3-3ra):



经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(50.5 mg, 86%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL · min-1, λ = 254 nm, t (major) = 6.5 min, t (minor) = 7.4 min, 94% ee; $[\alpha]_D^{20}$ = -289.2 (c = 1.02, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.85 (d, *J* = 2.4 Hz, 1H), 8.05 – 7.92 (m, 3H), 7.88 (s, 1H), 7.76 (d, *J* = 2.4 Hz, 1H), 7.59 (dd, *J* = 6.5, 2.5 Hz, 1H), 7.35 (d, *J* = 6.3 Hz, 2H), 7.06 (d, *J* = 8.2 Hz, 1H), 6.43 (d, *J* = 15.9 Hz, 1H), 4.17 (q, *J* = 6.2 Hz, 2H), 3.15 (p, *J* = 6.8 Hz, 1H), 2.19 (s, 3H), 1.66 (p, *J* = 6.9 Hz, 2H), 1.59 (s, 3H), 1.41 (h, *J* = 7.4 Hz, 2H), 1.15 (d, *J* = 6.8 Hz, 3H), 0.93 (t, *J* = 7.3 Hz, 3H), 0.79 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR

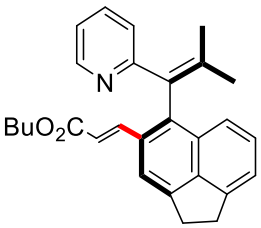
(101 MHz, Chloroform-*d*) δ 167.40, 160.21, 148.56, 147.11, 144.45, 140.89, 140.11, 139.70, 134.34, 133.69, 132.55 (q, J_{CF} = 33.33 Hz), 131.61, 130.72, 128.13, 128.10, 127.12 (q, J_{CF} = 3.03 Hz), 124.64, 123.81, 123.31 (q, J_{CF} = 273.71 Hz), 121.62 (m), 119.22, 64.40, 30.85, 30.39, 24.34, 23.81, 23.77, 21.88, 19.35, 13.89. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -62.93. HRMS (ESI-TOF) calcd for $C_{33}H_{34}F_6NO_2^+$ ([M+H]$^+$): 590.2488, found: 590.2490.

(*E*)-butyl 3-(1-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)naphthalen-2-yl)acrylate (3-3sa):



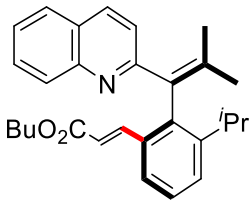
经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(32.0 mg, 83%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.7 mL·min-1, λ = 254 nm, t (major) = 7.9 min, t (minor) = 8.9 min, 91% ee; $[\alpha]_D^{20}$ = -268.6 (c = 1.01, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.60 (ddd, *J* = 4.8, 1.9, 1.0 Hz, 1H), 8.18 (d, *J* = 16.0 Hz, 1H), 8.15 – 8.06 (m, 1H), 7.78 (s, 2H), 7.44 (qd, *J* = 8.0, 1.7 Hz, 3H), 7.06 – 6.95 (m, 2H), 6.54 (d, *J* = 16.0 Hz, 1H), 4.20 (td, *J* = 6.6, 1.0 Hz, 2H), 2.20 (s, 3H), 1.74 – 1.62 (m, 2H), 1.52 (s, 3H), 1.47 – 1.36 (m, 2H), 0.95 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.43, 159.76, 148.97, 143.81, 141.84, 139.66, 135.99, 134.62, 133.58, 131.34, 130.35, 128.09, 128.03, 127.71, 127.06, 126.84, 124.22, 122.91, 121.11, 119.30, 64.44, 30.90, 23.32, 21.91, 19.37, 13.90. HRMS (ESI-TOF) calcd for $C_{26}H_{28}NO_2^+$ ([M+H]$^+$): 386.2115, found: 386.2117.

(*E*)-butyl 3-(5-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)-1,2-dihydroacenaphthylen-4-yl)acrylate (3-3ta):



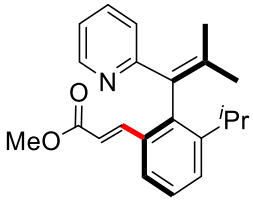
经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(32.5 mg, 79%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 13.3 min, t (minor) =15.1 min, 91% ee; $[\alpha]_D^{20}$ = -233.8 (c = 1.03, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (ddd, *J* = 4.8, 1.8, 1.0 Hz, 1H), 8.19 (d, *J* = 16.0 Hz, 1H), 7.66 (d, *J* = 8.3 Hz, 1H), 7.60 (s, 1H), 7.45 (td, *J* = 7.7, 1.9 Hz, 1H), 7.37 (dd, *J* = 8.3, 6.9 Hz, 1H), 7.27 (d, *J* = 7.0 Hz, 1H), 7.01 (ddd, *J* = 7.5, 5.4, 1.1 Hz, 2H), 6.50 (d, *J* = 15.9 Hz, 1H), 4.20 (td, *J* = 6.6, 0.8 Hz, 2H), 3.39 (m, 4H), 2.17 (s, 3H), 1.73 – 1.62 (m, 2H), 1.54 (s, 3H), 1.51 – 1.36 (m, 2H), 0.95 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.58, 160.16, 148.95, 145.87, 145.72, 144.66, 140.49, 139.38, 138.13, 135.93, 132.09, 131.2, 130.90, 128.62, 124.33, 122.83, 121.01, 120.84, 118.72, 116.21, 64.36, 30.92, 30.60, 30.14, 23.28, 21.93, 19.37, 13.90. HRMS (ESI-TOF) calcd for $C_{28}H_{30}NO_2^+$ ([M+H]$^+$): 412.2271, found: 412.2271.

(*E*)-butyl 3-(3-isopropyl-2-(2-methyl-1-(quinolin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ua):



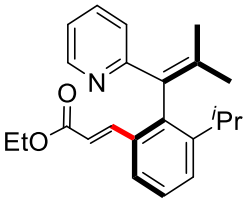
经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(20.1 mg, 47%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.7 mL·min-1, λ = 254 nm, t (major) = 5.3 min, t (minor) = 6.2 min, 96% ee; $[\alpha]_D^{20}$ = -340.3 (c = 1.02, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.09 (d, *J* = 8.5 Hz, 1H), 8.03 (d, *J* = 15.9 Hz, 1H), 7.94 (d, *J* = 8.6 Hz, 1H), 7.72 (dd, *J* = 8.2, 1.3 Hz, 1H), 7.67 (ddd, *J* = 8.5, 6.8, 1.5 Hz, 1H), 7.58 (dd, *J* = 6.3, 3.7 Hz, 1H), 7.48 (ddd, *J* = 8.0, 6.8, 1.1 Hz, 1H), 7.34 (q, *J* = 4.5, 3.8 Hz, 2H), 7.01 (d, *J* = 8.6 Hz, 1H), 6.42 (d, *J* = 15.9 Hz, 1H), 4.25 – 4.04 (m, 2H), 3.30 (hept, *J* = 6.8 Hz, 1H), 2.21 (s, 3H), 1.69 – 1.62 (m, 3H), 1.62 (s, 3H), 1.41 (dt, *J* = 14.9, 7.4 Hz, 2H), 1.15 (d, *J* = 6.8 Hz, 3H), 0.91 (t, *J* = 7.4 Hz, 3H), 0.68 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.41, 159.77, 149.14, 147.82, 144.67, 140.90, 139.61, 135.70, 133.82, 132.80, 129.44, 129.39, 128.20, 128.00, 127.46, 126.37, 126.22, 123.80, 122.54, 119.22, 64.39, 30.87, 30.35, 24.46, 23.85, 23.75, 21.88, 19.35, 13.87. HRMS (ESI-TOF) calcd for $C_{29}H_{34}NO_2^+$ ($[M+H]^+$): 428.2584, found: 428.2586.

(*E*)-methyl 3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ab):



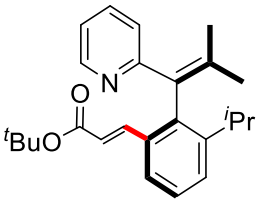
经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(19.3 mg, 57%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 8.2 min, t (minor) = 11.8 min, 88% ee; $[\alpha]_D^{20}$ = -317.0 (c = 0.60, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (dd, *J* = 4.9, 1.7 Hz, 1H), 7.97 (d, *J* = 15.9 Hz, 1H), 7.55 (dd, *J* = 6.1, 3.0 Hz, 1H), 7.49 (td, *J* = 7.8, 1.9 Hz, 1H), 7.31 (q, *J* = 4.1, 3.2 Hz, 2H), 7.04 (dd, *J* = 7.5, 4.9 Hz, 1H), 6.88 (d, *J* = 7.9 Hz, 1H), 6.42 (d, *J* = 16.0 Hz, 1H), 3.76 (s, 3H), 3.14 (hept, *J* = 6.9 Hz, 1H), 2.13 (s, 3H), 1.54 (s, 3H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.68 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.80, 159.72, 148.77, 148.65, 145.05, 141.37, 138.44, 135.90, 133.66, 133.16, 128.14, 127.88, 124.56, 123.76, 120.92, 118.67, 51.75, 30.24, 24.27, 23.55, 23.52, 21.73. HRMS (ESI-TOF) calcd for $C_{22}H_{26}NO_2^+$ ($[M+H]^+$): 336.1958, found: 336.1959.

(*E*)-ethyl 3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ac):



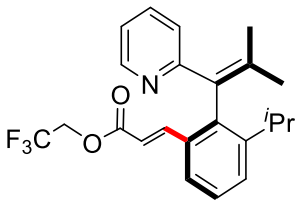
经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(20.9 mg, 60%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL · min-1, λ = 254 nm, t (major) = 8 min, t (minor) = 9.7 min, 92% ee; $[\alpha]_D^{20}$ = -323.8 (c = 1.01 $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.65 – 8.53 (m, 1H), 7.97 (d, *J* = 16.0 Hz, 1H), 7.56 (dd, *J* = 6.0, 3.1 Hz, 1H), 7.49 (td, *J* = 7.7, 1.9 Hz, 1H), 7.31 (q, *J* = 4.0, 3.1 Hz, 2H), 7.03 (dd, *J* = 7.5, 4.8 Hz, 1H), 6.88 (dd, *J* = 7.9, 1.0 Hz, 1H), 6.41 (d, *J* = 15.9 Hz, 1H), 4.22 (qq, *J* = 7.1, 3.8 Hz, 2H), 3.14 (hept, *J* = 6.9 Hz, 1H), 2.13 (s, 3H), 1.54 (s, 3H), 1.30 (t, *J* = 7.1 Hz, 3H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.68 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.36, 159.77, 148.75, 148.66, 144.78, 141.36, 138.40, 135.89, 133.68, 132.19, 128.07, 127.86, 124.56, 123.70, 120.90, 119.07, 60.45, 30.25, 24.28, 23.54, 23.52, 21.68, 14.43. HRMS (ESI-TOF) calcd for $C_{23}H_{28}NO_2^+$ ($[M+H]^+$): 350.2115, found: 350.2115.

(*E*)-tert-butyl 3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ad):



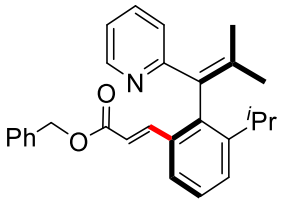
经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(27.9 mg, 74%)。手性 HPLC 分离条件：a Daicel Chiralpak OD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL · min-1, λ = 254 nm, t (minor) = 17.9 min, t (major) = 19.9 min, 89% ee; $[\alpha]_D^{20}$ = -287.8 (c = 1.02 $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (dd, *J* = 5.0, 1.7 Hz, 1H), 7.88 (d, *J* = 15.9 Hz, 1H), 7.54 (dt, *J* = 8.0, 4.0 Hz, 1H), 7.48 (td, *J* = 7.8, 1.9 Hz, 1H), 7.30 (q, *J* = 3.4, 2.5 Hz, 2H), 7.03 (dd, *J* = 7.5, 4.9 Hz, 1H), 6.92 – 6.81 (m, 1H), 6.34 (d, *J* = 15.9 Hz, 1H), 3.15 (hept, *J* = 6.9 Hz, 1H), 2.12 (s, 3H), 1.55 (s, 3H), 1.50 (s, 9H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.68 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.64, 159.84, 148.70, 148.61, 143.60, 141.26, 138.24, 135.88, 133.76, 132.22, 127.83, 127.79, 124.56, 123.60, 120.95, 120.87, 80.31, 30.26, 28.35, 24.30, 23.55, 23.54, 21.66. HRMS (ESI-TOF) calcd for $C_{25}H_{32}NO_2^+$ ($[M+H]^+$): 378.2428, found: 378.2430.

(*E*)-2,2,3-trifluoroethyl 3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3ae):



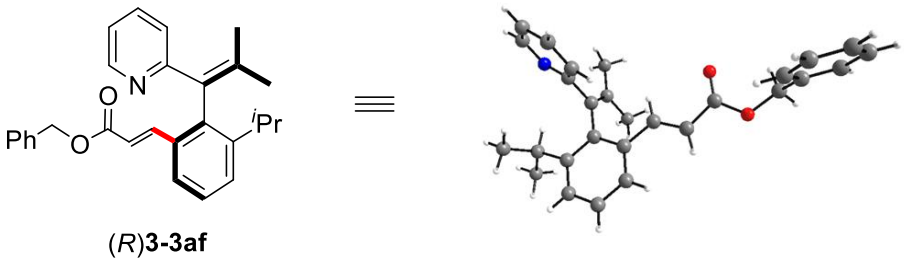
经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 80/1 为展开剂)(19.1 mg, 47%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 7.6 min, t (minor) = 9.0 min, 92% ee; $[\alpha]_D^{20}$ = -294.3 (c = 0.52, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (d, *J* = 4.8 Hz, 1H), 8.10 (d, *J* = 15.9 Hz, 1H), 7.58 (dd, *J* = 7.1, 1.7 Hz, 1H), 7.51 (td, *J* = 7.7, 1.8 Hz, 1H), 7.40 – 7.29 (m, 2H), 7.05 (dd, *J* = 7.4, 5.0 Hz, 1H), 6.90 (d, *J* = 7.9 Hz, 1H), 6.45 (d, *J* = 16.0 Hz, 1H), 4.70 – 4.35 (m, 2H), 3.15 (p, *J* = 6.8 Hz, 1H), 2.12 (s, 3H), 1.54 (s, 3H), 1.13 (d, *J* = 6.8 Hz, 3H), 0.70 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 165.48, 159.69, 148.95, 148.85, 147.53, 141.80, 138.53, 135.87, 133.12, 132.24, 128.77, 127.97, 123.29 (q, J_{CF} = 278.09 Hz), 123.83, 120.99, 116.56, 60.44 (q, J_{CF} = 36.70 Hz), 30.32, 24.27, 23.55, 23.49, 21.61. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -73.81. HRMS (ESI-TOF) calcd for $C_{23}H_{25}F_3NO_2^+$ ($[M+H]^+$): 404.1832, found: 404.1835.

(*E*)-benzyl 3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylate (3-3af):



经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 =80/1 为展开剂)(30.1 mg, 73%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 10.3 min, t (minor) = 15.4 min, 83% ee; $[\alpha]_D^{20}$ = -267.5 (c = 0.65, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (d, *J* = 5.1 Hz, 1H), 8.05 (d, *J* = 16.0 Hz, 1H), 7.56 (dd, *J* = 6.7, 2.3 Hz, 1H), 7.48 (td, *J* = 7.7, 1.8 Hz, 1H), 7.36 (d, *J* = 7.8 Hz, 4H), 7.34 – 7.30 (m, 3H), 7.04 (dd, *J* = 7.4, 5.0 Hz, 1H), 6.88 (d, *J* = 7.9 Hz, 1H), 6.47 (d, *J* = 16.0 Hz, 1H), 5.22 (q, *J* = 13.5 Hz, 2H), 3.15 (hept, *J* = 7.0 Hz, 1H), 2.11 (s, 3H), 1.54 (s, 3H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.69 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.08, 159.77, 148.81, 148.71, 145.42, 138.36, 136.36, 135.87, 133.56, 132.26, 128.66, 128.23, 128.11, 127.89, 124.54, 123.71, 120.91, 118.64, 66.22, 30.28, 24.28, 23.56, 23.53, 21.69. HRMS (ESI-TOF) calcd for $C_{28}H_{30}NO_2^+$ ($[M+H]^+$): 412.2271, found: 412.2273.

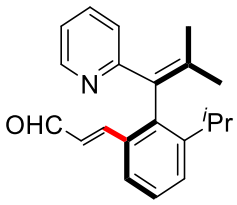
X-ray Data of 3-3af



(*R*)**3-3af**

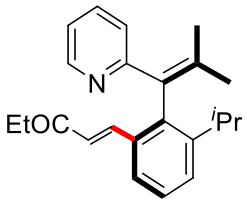
Bond precision:	C-C = 0.0041 A	Wavelength = 1.54178
Cell:	a = 10.1389 (2) b = 15.0961 (3) c = 15.8054 (3)	
alpha = 90	beta = 96.793 (1)	gamma = 90
Temperature: 296 K	Calculated	Reported
Volume	2403.16 (8)	2403.16 (8)
Space group	P 21	P 1 21 1
Hall group	P 2yb	P 2yb
Moiety formula	C_{28} H_{29} N O_2	C_{28} H_{29} N O_2
Sum formula	C_{28} H_{29} N O_2	C_{28} H_{29} N O_2
Mr	411.52	411.52
Dx, g cm^{-3}	1.138	1.138
Z	4	4
Mu (mm^{-1})	0.552	0.552
F000	880.0	880.0
F000’	883.42	
h,k,lmax	12, 18, 19	12, 18, 19
Nref	9486[4934]	9329
Tmin, Tmax	0.793,0.857	0.597, 0.754
Tmin’	0.763	
Correction method = # Reported T	Limits: Tmin = 0.597	Tmax = 0.754
AbsCorr = MULTI-SCAN		
Data completeness	1.89/0.98	Theta(max) = 73.126
R (reflections)	0.0470(9057)	wR2(reflections)=0.1180(9329)
S = 1.060	Npar = 567	
Flack parameter	0.00 (5)	

(*E*)-3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)acrylaldehyde (3-3ag):



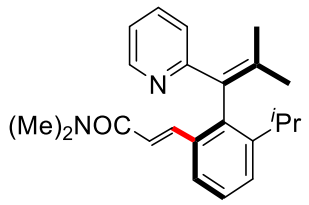
经制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(6.1 mg, 20%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 9.0 min, t (minor) = 10.0 min, 89% ee; $[\alpha]_D^{20}$ = -147.0 (c = 0.53, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 9.62 (d, *J* = 7.8 Hz, 1H), 8.68 – 8.50 (m, 1H), 7.82 (d, *J* = 15.9 Hz, 1H), 7.60 (dd, *J* = 7.1, 1.8 Hz, 1H), 7.54 (td, *J* = 7.8, 1.9 Hz, 1H), 7.42 – 7.31 (m, 2H), 7.07 (dd, *J* = 7.6, 4.9 Hz, 1H), 6.94 (d, *J* = 7.9 Hz, 1H), 6.71 (dd, *J* = 15.9, 7.8 Hz, 1H), 3.13 (hept, *J* = 6.8 Hz, 1H), 2.15 (s, 3H), 1.55 (s, 3H), 1.15 (d, *J* = 6.8 Hz, 3H), 0.73 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 194.52, 159.44, 153.49, 149.02, 148.65, 141.64, 138.65, 135.97, 133.29, 132.13, 129.63, 129.14, 128.08, 124.49, 124.23, 121.11, 30.28, 24.24, 23.67, 23.57, 21.85. HRMS (ESI-TOF) calcd for $C_{21}H_{24}NO^+$ ($[M+H]^+$): 306.1852, found: 306.1853.

(*E*)-1-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)pent-1-en-3-one (3-3ah):



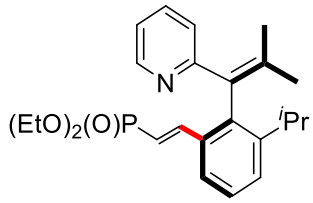
经制备级 TLC 分离得到淡黄色固体(石油醚/乙酸乙酯 = 80/1 为展开剂)(19.2 mg, 57%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 8.2 min, t (minor) = 9.6 min, 94% ee; $[\alpha]_D^{20}$ = -233.1 (c = 0.59, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (dt, *J* = 4.9, 1.2 Hz, 1H), 7.89 (d, *J* = 16.3 Hz, 1H), 7.57 (dd, *J* = 6.1, 3.0 Hz, 1H), 7.51 (td, *J* = 7.8, 1.9 Hz, 1H), 7.32 (q, *J* = 4.1, 3.3 Hz, 2H), 7.11 – 6.99 (m, 1H), 6.91 (d, *J* = 7.9 Hz, 1H), 6.68 (d, *J* = 16.3 Hz, 1H), 3.14 (hept, *J* = 6.9 Hz, 1H), 2.63 (q, *J* = 7.3 Hz, 2H), 2.13 (s, 3H), 1.54 (s, 3H), 1.12 (t, *J* = 7.3 Hz, 6H), 0.71 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 201.64, 159.70, 148.87, 148.53, 142.86, 141.55, 138.29, 135.91, 133.79, 132.37, 128.16, 127.92, 127.33, 124.46, 123.65, 120.97, 33.43, 30.26, 24.26, 23.61, 23.52, 21.70, 8.53. HRMS (ESI-TOF) calcd for $C_{23}H_{28}NO^+$ ($[M+H]^+$): 334.2165, found: 334.2164.

(*E*)-3-(3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)-N,N-dimethylacrylamide (3-3ai):



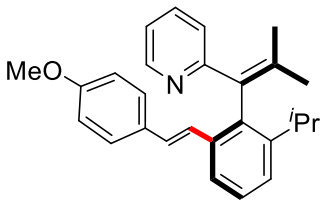
经制备级 TLC 分离得到无色固体(石油醚/乙酸乙酯 = 1/1 为展开剂)(32.0 mg, 92%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 0.7 mL · min-1, λ = 254 nm, t (major) = 10.0 min, t (minor) = 11.9 min, 89% ee; $[\alpha]_D^{20}$ = -260.0 (c = 0.61, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 5.0, 1.7 Hz, 1H), 7.90 (d, *J* = 15.4 Hz, 1H), 7.52 (q, *J* = 4.2 Hz, 1H), 7.47 (td, *J* = 7.7, 1.9 Hz, 1H), 7.31 – 7.27 (m, 2H), 7.01 (ddd, *J* = 7.5, 4.9, 1.2 Hz, 1H), 6.92 (d, *J* = 7.9 Hz, 1H), 6.85 (d, *J* = 15.4 Hz, 1H), 3.24 – 3.17 (m, 1H), 3.15 (s, 3H), 3.03 (s, 3H), 2.11 (s, 3H), 1.55 (s, 3H), 1.12 (d, *J* = 6.9 Hz, 3H), 0.70 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.12, 159.87, 148.70, 148.65, 142.27, 141.10, 138.10, 135.85, 134.65, 132.35, 127.68, 127.34, 124.62, 123.67, 120.81, 118.64, 37.57, 35.93, 30.22, 24.31, 23.64, 23.50, 21.76. HRMS (ESI-TOF) calcd for $C_{23}H_{29}N_2O^+$ ($[M+H]^+$): 349.2274, found: 349.2275.

(*E*)-diethyl 3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)styrylphosphonate (3-3aj):



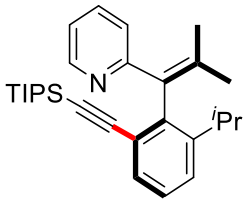
经制备级 TLC 分离得到无色固体(石油醚/乙酸乙酯 = 2/1 为展开剂)(14.8 mg, 36%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 92/8, v = 1.0 mL · min-1, λ = 254 nm, t (major) = 4.3 min, t (minor) = 4.9 min, 90% ee; $[\alpha]_D^{20}$ = -197.2 (c = 1.08, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 5.0, 1.6 Hz, 1H), 7.71 (dd, *J* = 22.8, 17.5 Hz, 1H), 7.55 – 7.45 (m, 2H), 7.31 (d, *J* = 4.5 Hz, 2H), 7.03 (dd, *J* = 7.5, 5.0 Hz, 1H), 6.90 (d, *J* = 7.9 Hz, 1H), 6.22 (dd, *J* = 19.4, 17.6 Hz, 1H), 4.16 – 3.96 (m, 4H), 3.12 (hept, *J* = 6.9 Hz, 1H), 2.11 (s, 3H), 1.54 (s, 3H), 1.29 (td, *J* = 7.1, 3.1 Hz, 6H), 1.12 (d, *J* = 6.9 Hz, 3H), 0.70 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.59, 148.78, 148.51 (d, *J* = 2.7 Hz), 148.47 (d, *J* = 3.3 Hz), 140.75, 138.24, 135.84, 134.31 (d, *J* = 22.5 Hz), 132.22, 127.91 (d, *J* = 5.8 Hz), 124.50, 123.51 (d, *J* = 1.4 Hz), 120.93, 114.86 (d, *J* = 190.9 Hz), 61.93 (d, *J* = 3.3 Hz), 61.87 (d, *J* = 3.2 Hz), 30.21, 24.26, 23.64, 23.55, 21.76, 16.52 (d, *J* = 1.2 Hz), 16.46 (d, *J* = 1.7 Hz). ^{31}P NMR (162 MHz, Chloroform-*d*) δ 19.52. HRMS (ESI-TOF) calcd for $C_{24}H_{33}NO_3P^+$ ($[M+H]^+$): 414.2193, found: 414.2188.

(*E*)-2-(1-(2-isopropyl-6-(4-methoxystyryl)phenyl)-2-methylprop-1-en-1-yl)pyridine (3-3ak):



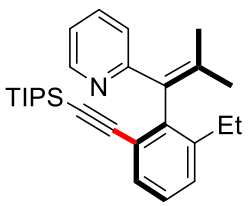
经制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 50/1 为展开剂)(17.6 mg, 46%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 8.8 min, t (minor) = 9.7 min, 88% ee; $[\alpha]_D^{20}$ = -317.4 (c = 0.41, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.60 (dd, *J* = 4.9, 1.8 Hz, 1H), 7.59 (d, *J* = 7.7 Hz, 1H), 7.45 (td, *J* = 7.7, 1.9 Hz, 1H), 7.36 (d, *J* = 8.6 Hz, 2H), 7.29 (d, *J* = 7.7 Hz, 1H), 7.23 (d, *J* = 9.5 Hz, 1H), 7.20 – 7.12 (m, 1H), 7.09 – 6.97 (m, 2H), 6.92 (d, *J* = 8.0 Hz, 1H), 6.89 – 6.77 (m, 2H), 3.79 (s, 3H), 3.13 (hept, *J* = 6.8 Hz, 1H), 2.15 (s, 3H), 1.57 (s, 3H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.67 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.26, 159.21, 148.56, 148.17, 139.56, 137.63, 136.47, 135.94, 132.78, 130.91, 128.96, 127.75, 127.66, 126.22, 125.07, 124.48, 122.30, 120.77, 114.22, 55.45, 30.27, 24.35, 23.69, 23.59, 21.64. HRMS (ESI-TOF) calcd for $C_{27}H_{30}NO^+$ ($[M+H]^+$): 384.2322, found: 384.2320.

2-(1-(2-isopropyl-6-((triisopropylsilyl)ethynyl)phenyl)-2-methylprop-1-en-1-yl)pyridine (3-5a):



经制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(37.1 mg, 86%)。手性 HPLC 分离条件：two Daicel Chiralpak IC, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 17.8 min, t (minor) = 18.4 min, 99% ee; $[\alpha]_D^{20}$ = -286.1 (c = 1.05, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.58 (d, *J* = 4.9 Hz, 1H), 7.52 – 7.37 (m, 2H), 7.25 – 7.18 (m, 3H), 7.02 (dd, *J* = 7.4, 5.0 Hz, 1H), 3.22 (hept, *J* = 7.0 Hz, 1H), 2.00 (s, 3H), 1.65 (s, 3H), 1.11 (d, *J* = 6.9 Hz, 3H), 1.05 (s, 21H), 0.65 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.15, 148.41, 148.34, 143.13, 137.30, 135.69, 133.48, 130.72, 127.23, 126.30, 124.85, 123.95, 120.78, 107.56, 91.11, 30.23, 24.10, 23.53, 23.08, 21.76, 18.78, 11.51. HRMS (ESI-TOF) calcd for $C_{29}H_{42}NSi^+$ ($[M+H]^+$): 432.3081, found: 432.3085.

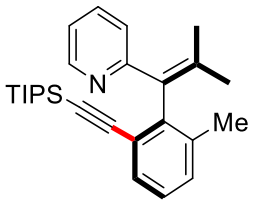
2-(1-(2-ethyl-6-((triisopropylsilyl)ethynyl)phenyl)-2-methylprop-1-en-1-yl)pyridine (3-5b):



经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 100/1 为展开剂)(30.1 mg, 72%)。手性 HPLC 分离条件：two Daicel Chiralpak ICs, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 22.4 min, t (minor) = 25.0 min, 98% ee; $[\alpha]_D^{20}$ = -222.9 (c = 1.02, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.58 (dd, *J* = 5.0, 1.7 Hz, 1H), 7.46 (ddd, *J* = 15.3, 7.5, 2.0 Hz, 2H), 7.24 (d, *J* = 8.0 Hz, 1H), 7.21 – 7.12 (m, 2H), 7.02 (dd, *J* = 7.4, 4.9 Hz, 1H), 2.50 (ddq, *J* =

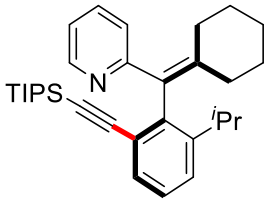
50.4, 14.8, 7.6 Hz, 2H), 2.00 (s, 3H), 1.64 (s, 3H), 1.05 (s, 21H), 0.90 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.97, 148.39, 143.94, 143.63, 137.25, 135.67, 133.44, 130.72, 128.88, 127.02, 124.72, 124.15, 120.81, 107.41, 91.26, 26.35, 23.05, 21.74, 18.77, 14.81, 11.50. HRMS (ESI-TOF) calcd for $C_{28}H_{40}NSi^+$ ([M+H]$^+$): 418.2925, found: 418.2928.

2-(2-methyl-1-(2-methyl-6-((triisopropylsilyl)ethynyl)phenyl)prop-1-en-1-yl)pyridine (3-5c):



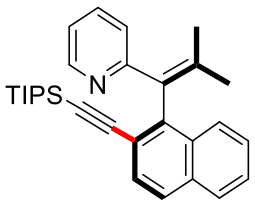
经制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(29.8 mg, 74%)。手性 HPLC 分离条件：two Daicel Chiralpak ICs, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 26.7 min, t (minor) = 27.4 min, 97% ee; $[\alpha]_D^{20}$ = -148.8 (c = 0.98, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 4.9, 1.7 Hz, 1H), 7.48 (td, *J* = 7.7, 2.0 Hz, 1H), 7.42 (dd, *J* = 5.4, 3.7 Hz, 1H), 7.28 (s, 1H), 7.25 (s, 1H), 7.15 – 7.08 (m, 2H), 7.06 – 7.00 (m, 1H), 2.13 (s, 3H), 2.00 (s, 3H), 1.63 (s, 3H), 1.06 (s, 21H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.63, 148.47, 144.62, 137.86, 136.73, 135.65, 133.77, 130.73, 130.42, 126.74, 124.68, 123.94, 120.82, 107.28, 91.53, 22.68, 21.69, 20.36, 18.77, 11.49. HRMS (ESI-TOF) calcd for $C_{27}H_{38}NSi^+$ ([M+H]$^+$): 404.2768, found: 404.2771.

2-(cyclohexylidene(2-isopropyl-6-((triisopropylsilyl)ethynyl)phenyl)methyl)pyridine (3-5d):



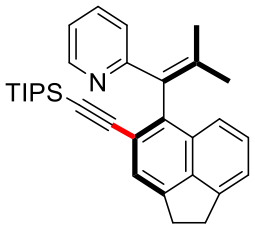
经制备级 TLC 分离得到无色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(25.4 mg, 54%)。手性 HPLC 分离条件：two Daicel Chiralpak ICs, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 20.5 min, t (minor) = 21.3 min, 97% ee; $[\alpha]_D^{20}$ = -133.1 (c = 0.50, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.57 (dd, *J* = 4.8, 1.7 Hz, 1H), 7.47 (td, *J* = 7.7, 1.9 Hz, 1H), 7.42 (dd, *J* = 6.8, 2.1 Hz, 1H), 7.36 (d, *J* = 7.9 Hz, 1H), 7.24 – 7.16 (m, 2H), 7.01 (ddd, *J* = 7.1, 5.0, 1.1 Hz, 1H), 3.35 (hept, *J* = 6.9 Hz, 1H), 2.62 (dt, *J* = 13.4, 5.8 Hz, 1H), 2.33 (dt, *J* = 13.2, 6.4 Hz, 1H), 2.07 – 1.90 (m, 2H), 1.82 – 1.66 (m, 3H), 1.50 (dddt, *J* = 20.3, 12.2, 8.2, 4.0 Hz, 3H), 1.13 (d, *J* = 6.9 Hz, 3H), 1.07 (q, *J* = 3.8, 3.2 Hz, 21H), 0.72 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.05, 148.64, 148.52, 144.12, 142.60, 135.57, 131.06, 130.73, 127.10, 126.22, 125.27, 123.85, 120.75, 108.11, 91.73, 33.15, 31.30, 30.14, 27.92, 27.73, 26.84, 24.09, 23.80, 18.83, 11.61. HRMS (ESI-TOF) calcd for $C_{32}H_{46}NSi^+$ ([M+H]$^+$): 473.3394, found: 473.3398.

2-(2-methyl-1-(2-((triisopropylsilyl)ethynyl)naphthalen-1-yl)prop-1-en-1-yl)pyridine (3-5e):



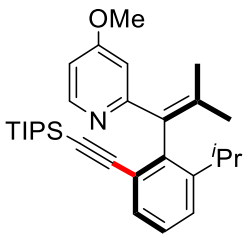
经制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(25.5 mg, 58%)。手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 8.7 min, t (minor) = 10.8 min, 98% ee; $[\alpha]_D^{20}$ = -354.3 (c = 0.63, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.61 (d, *J* = 4.9 Hz, 1H), 8.20 – 8.03 (m, 1H), 7.75 (dd, *J* = 7.1, 3.7 Hz, 1H), 7.70 (d, *J* = 8.5 Hz, 1H), 7.61 (d, *J* = 8.5 Hz, 1H), 7.49 – 7.37 (m, 3H), 7.33 (d, *J* = 7.9 Hz, 1H), 7.01 (dd, *J* = 7.3, 5.1 Hz, 1H), 2.08 (s, 3H), 1.62 (s, 3H), 1.11 (s, 21H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.00, 148.62, 143.61, 138.54, 135.78, 133.44, 132.72, 133.26, 129.44, 127.90, 127.29, 127.17, 126.64, 126.58, 124.61, 121.01, 120.90, 107.59, 92.98, 22.81, 21.91, 18.81, 11.53. HRMS (ESI-TOF) calcd for $C_{30}H_{38}NSi^+$ ($[M+H]^+$): 440.2768, found: 440.2770.

2-(2-methyl-1-(4-((triisopropylsilyl)ethynyl)-1,2-dihydroacenaphthylen-5-yl)prop-1-en-1-yl)pyridine (3-5f):



经制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(30.7 mg, 66%)。手性 HPLC 分离条件：two Daicel Chiralpak ICs, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 18.9 min, t (minor) = 19.9 min, 98% ee; $[\alpha]_D^{20}$ = -162.0 (c = 0.55, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.60 (dd, *J* = 5.0, 1.7 Hz, 1H), 7.69 (d, *J* = 8.3 Hz, 1H), 7.46 – 7.39 (m, 2H), 7.38 – 7.30 (m, 2H), 7.22 (d, *J* = 6.9 Hz, 1H), 6.99 (ddd, *J* = 7.4, 4.9, 1.2 Hz, 1H), 3.36 (s, 4H), 2.06 (s, 3H), 1.65 (s, 3H), 1.10 (s, 21H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.38, 148.58, 145.64, 144.86, 139.59, 139.28, 138.28, 135.71, 132.37, 130.57, 128.39, 124.65, 122.94, 122.33, 122.24, 120.88, 120.28, 108.45, 92.29, 30.61, 29.99, 22.80, 21.91, 18.83, 11.55. HRMS (ESI-TOF) calcd for $C_{32}H_{40}NSi^+$ ($[M+H]^+$): 466.2925, found: 466.2927.

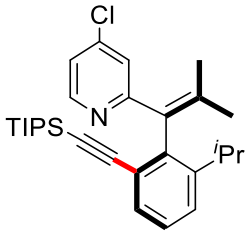
2-(1-(2-isopropyl-6-((triisopropylsilyl)ethynyl)phenyl)-2-methylprop-1-en-1-yl)-4-methoxypyridine (3-5g):



经制备级 TLC 分离得到无色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(35.5 mg, 77%)。手性 HPLC 分离条件：two Daicel Chiralpak ICs, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 27.0 min, t (minor) = 28.0 min, 97% ee; $[\alpha]_D^{20}$ = -314.1 (c = 0.87, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.39 (d, *J* = 5.8 Hz, 1H), 7.42 (dd, *J* = 6.6, 2.2 Hz, 1H), 7.23 – 7.12 (m, 2H), 6.80 (d, *J* = 2.5 Hz, 1H), 6.58 (dd, *J* = 5.8, 2.5 Hz, 1H), 3.69 (s, 3H), 3.25 (hept, *J*

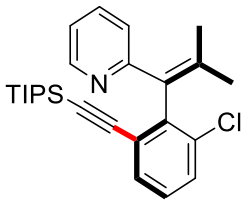
= 6.9 Hz, 1H), 1.99 (s, 3H), 1.64 (s, 3H), 1.10 (d, *J* = 6.9 Hz, 3H), 1.06 (s, 21H), 0.69 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 165.62, 161.87, 149.46, 148.41, 143.11, 137.18, 133.40, 130.80, 127.18, 126.32, 123.76, 110.30, 107.63, 107.53, 90.95, 54.91, 30.19, 24.13, 23.58, 23.01, 21.80, 18.79, 11.53. HRMS (ESI-TOF) calcd for $C_{30}H_{44}NOSi^+$ ([M+H]$^+$): 462.3187, found: 462.3185.

4-chloro-2-(1-(2-isopropyl-6-((triisopropylsilyl)ethynyl)phenyl)-2-methylprop-1-en-1-yl)pyridine (3-5h):



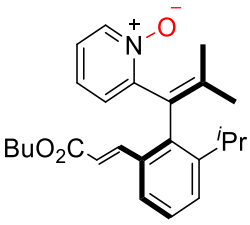
经制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(40.0 mg, 86%)。手性 HPLC 分离条件：two Daicel Chiralpak ICs, *n*-hexane/2-propanol = 99/1, v = 0.4 mL·min-1, λ = 254 nm, t (major) = 27.8 min, t (minor) = 28.7 min, 99% ee; $[\alpha]_D^{20}$ = -232.8 (c = 1.07, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.41 (d, *J* = 5.4 Hz, 1H), 7.38 (dd, *J* = 5.8, 3.1 Hz, 1H), 7.23 – 7.12 (m, 3H), 7.00 (dd, *J* = 5.4, 2.1 Hz, 1H), 3.14 (p, *J* = 6.8 Hz, 1H), 1.91 (s, 3H), 1.58 (s, 3H), 1.06 (d, *J* = 6.9 Hz, 3H), 1.01 (s, 21H), 0.68 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 161.68, 149.25, 148.36, 143.76, 142.31, 138.65, 132.58, 130.91, 127.53, 126.37, 124.89, 123.85, 121.29, 107.29, 91.59, 30.28, 24.11, 23.65, 23.11, 21.79, 18.79, 11.48. HRMS (ESI-TOF) calcd for $C_{29}H_{41}ClNSi^+$ ([M+H]$^+$): 466.2691, found: 466.2694.

2-(1-(2-chloro-6-((triisopropylsilyl)ethynyl)phenyl)-2-methylprop-1-en-1-yl)pyridine (3-5i):



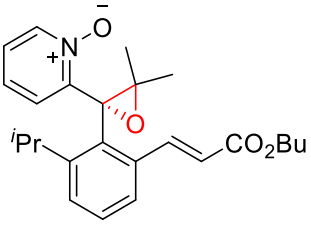
经制备级 TLC 分离得到无色液体(石油醚/乙酸乙酯 = 100/1 为展开剂)(11.8 mg, 28%)。手性 HPLC 分离条件：a Daicel Chiralpak IC, *n*-hexane/2-propanol = 98/2, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 9.3 min, t (minor) = 12.6 min, 98% ee; $[\alpha]_D^{20}$ = -132.1 (c = 0.31, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.59 (dd, *J* = 4.9, 1.7 Hz, 1H), 7.55 – 7.44 (m, 2H), 7.33 (d, *J* = 8.0 Hz, 1H), 7.20 – 7.13 (m, 2H), 7.04 (dd, *J* = 7.4, 4.9 Hz, 1H), 2.07 (s, 3H), 1.68 (s, 3H), 1.05 (s, 21H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 158.42, 148.62, 143.53, 138.56, 135.53, 135.07, 132.28, 131.58, 129.85, 127.90, 126.23, 124.52, 120.91, 105.63, 93.54, 23.07, 21.89, 18.71, 11.39. HRMS (ESI-TOF) calcd for $C_{26}H_{34}ClNNaSi^+$ ([M+Na]$^+$): 446.2041, found: 446.2044.

(*E*)-2-(1-(2-(3-butoxy-3-oxoprop-1-en-1-yl)-6-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine 1-oxide (3-6):



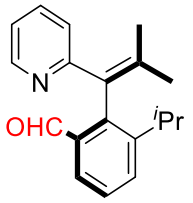
经制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(29.8 mg, 76%)。手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 93/7, v = 1.0 mL·min-1, λ = 254 nm, t (major) = 9.2 min, t (minor) = 11.6 min, 93% ee; $[\alpha]_D^{20}$ = -318.3 (c = 0.51, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.16 (d, *J* = 6.2 Hz, 1H), 7.95 (d, *J* = 16.0 Hz, 1H), 7.50 (dd, *J* = 5.9, 3.2 Hz, 1H), 7.25 (d, *J* = 2.7 Hz, 1H), 7.21 (s, 1H), 6.99 (dtd, *J* = 14.6, 7.7, 4.4 Hz, 2H), 6.88 (d, *J* = 8.1 Hz, 1H), 6.38 (d, *J* = 15.9 Hz, 1H), 4.22 – 4.04 (m, 2H), 3.13 (h, *J* = 6.8 Hz, 1H), 1.86 (s, 3H), 1.61 (dq, *J* = 8.3, 6.7 Hz, 2H), 1.53 (s, 3H), 1.36 (h, *J* = 7.4 Hz, 2H), 1.09 (d, *J* = 6.8 Hz, 3H), 0.88 (t, *J* = 7.4 Hz, 3H), 0.64 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.32, 150.32, 149.85, 144.52, 144.07, 140.39, 139.73, 134.10, 129.99, 128.43, 128.17, 127.97, 124.09, 123.79, 123.74, 119.43, 64.40, 30.86, 29.84, 24.36, 23.62, 23.02, 22.87, 19.34, 13.85. HRMS (ESI-TOF) calcd for $C_{25}H_{32}NO_3^+$ ($[M+H]^+$): 394.2377, found: 394.2375.

(*R*,*E*)-2-(2-(2-(3-butoxy-3-oxoprop-1-en-1-yl)-6-isopropylphenyl)-3,3-dimethyloxiran-2-yl)pyridine 1-oxide (3-7):



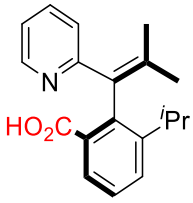
经制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 100/1 为展开剂)(19.2 mg, 47%)。手性 HPLC 分离条件：a Daicel Chiralpak IA-3, *n*-hexane/2-propanol = 97/3, v = 1.0 mL·min-1, λ = 254 nm, t (major) = 26.7 min, t (minor) = 30.7 min, 95% ee; $[\alpha]_D^{20}$ = -514.7 (c = 0.52, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.81 (d, *J* = 16.1 Hz, 1H), 8.03 (d, *J* = 6.4 Hz, 1H), 7.86 (dd, *J* = 8.1, 2.1 Hz, 1H), 7.61 (dd, *J* = 6.5, 2.6 Hz, 1H), 7.32 – 7.26 (m, 3H), 7.15 (td, *J* = 7.5, 7.0, 2.1 Hz, 1H), 6.39 (d, *J* = 16.2 Hz, 1H), 4.27 (dt, *J* = 10.8, 6.8 Hz, 1H), 4.15 (dt, *J* = 10.7, 6.6 Hz, 1H), 3.55 (p, *J* = 6.8 Hz, 1H), 1.69 (p, *J* = 6.9 Hz, 2H), 1.51 – 1.39 (m, 2H), 1.35 (d, *J* = 7.3 Hz, 6H), 1.24 (d, *J* = 6.7 Hz, 3H), 0.95 (t, *J* = 7.4 Hz, 3H), 0.74 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.96, 151.25, 150.27, 146.95, 140.21, 135.79, 130.60, 128.94, 128.46, 126.98, 124.94, 124.54, 123.26, 116.01, 67.69, 66.59, 64.35, 31.00, 28.96, 24.43, 24.02, 23.34, 20.00, 19.36, 13.90. HRMS (ESI-TOF) calcd for $C_{25}H_{32}NO_4^+$ ($[M+H]^+$): 410.2326, found: 410.2323.

3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)benzaldehyde (3-8):



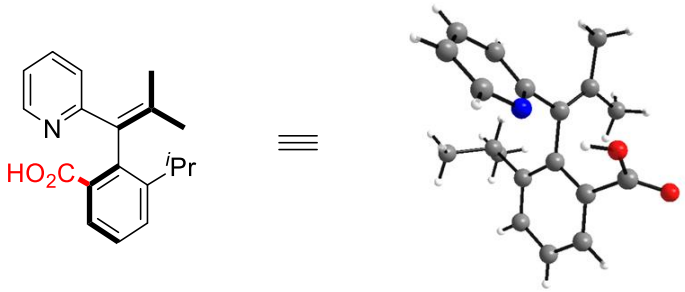
^{1}H NMR (400 MHz, Chloroform-*d*) δ 10.26 (s, 1H), 8.62 – 8.50 (m, 1H), 7.86 (dd, *J* = 7.7, 1.4 Hz, 1H), 7.55 (ddd, *J* = 16.6, 8.2, 1.6 Hz, 2H), 7.40 (t, *J* = 7.7 Hz, 1H), 7.10 – 6.95 (m, 2H), 3.19 (hept, *J* = 6.9 Hz, 1H), 2.09 (s, 3H), 1.59 (s, 3H), 1.18 (d, *J* = 6.9 Hz, 3H), 0.76 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 194.67, 159.27, 149.21, 148.44, 143.70, 138.57, 135.87, 134.67, 131.97, 130.65, 127.97, 124.92, 124.63, 121.10, 29.57, 24.12, 23.79, 23.72, 21.73. HRMS (ESI-TOF) calcd for $C_{19}H_{22}NO^+$ ([M+H]$^+$): 280.1696, found: 280.1693. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 97/3, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 9.4 min, t (minor) = 10.7 min, 91% ee; $[\alpha]_D^{20}$ = -186.1 (c = 0.61, $CHCl_3$).

3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)benzoic acid (3-9):



以通用方法经制备级 TLC 分离得到白色固体(26.0 mg, 88% yield 两步)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.41 (dd, *J* = 5.3, 1.6 Hz, 1H), 7.85 (td, *J* = 7.7, 1.8 Hz, 1H), 7.59 (dd, *J* = 6.4, 2.5 Hz, 1H), 7.51 (d, *J* = 7.8 Hz, 1H), 7.37 – 7.29 (m, 2H), 7.25 – 7.19 (m, 1H), 3.09 (hept, *J* = 6.9 Hz, 1H), 1.88 (s, 3H), 1.61 (s, 3H), 1.16 (d, *J* = 6.8 Hz, 3H), 0.75 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 171.73, 158.85, 147.27, 147.08, 139.13, 138.29, 136.62, 135.96, 131.26, 128.36, 128.02, 127.41, 125.34, 122.19, 30.02, 24.18, 23.82, 22.40, 21.53. HRMS (ESI-TOF) calcd for $C_{19}H_{22}NO^+$ ([M+H]$^+$): 296.1645, found: 296.1643. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min-1, λ = 254 nm, t (major) = 7.5 min, t (minor) = 9.4 min, 93% ee; $[\alpha]_D^{20}$ = -429.0 (c = 0.50, $CHCl_3$).

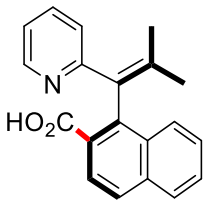
X-ray data of 3-9:



Bond precision:	C-C = 0.0037 A	Wavelength = 1.54178
Cell:	a = 8.3416 (2) b = 25.5213 (5)	c = 8.4670 (2)
alpha = 90	beta = 106.554 (1)	gamma = 90
Temperature: 296 K	Calculated	Reported
Volume	1727.82 (7)	1727.81 (7)
Space group	P 21	P 1 21 1
Hall group	P 2yb	P 2yb
Moiety formula	C_{19} H_{21} N O_2	C_{19} H_{21} N O_2
Sum formula	C_{19} H_{21} N O_2	C_{19} H_{21} N O_2
Mr	295.37	295.37
Dx, g cm^{-3}	1.135	1.135
Z	4	4
Mu (mm^{-1})	0.579	0.579
F000	633.0	633.0
F000’	633.80	
h,k,lmax	10, 31, 10	10, 31, 10
Nref	6839[3502]	6714
Tmin, Tmax	0.779,0.845	0.628, 0.753
Tmin’	0.753	
Correction method = # Reported T	Limits: Tmin = 0.628	Tmax = 0.753
AbsCorr = MULTI-SCAN		
Data completeness	1.92/0.98	Theta(max) = 73.203
R (reflections)	0.0383(6640)	wR2(reflections)=0.1030(6714)
S = 1.048	Npar = 408	

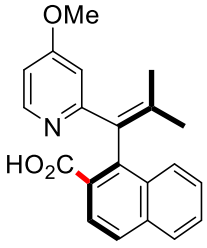
Flack parameter 0.03 (4)

1-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)-2-naphthoic acid(3-9a):



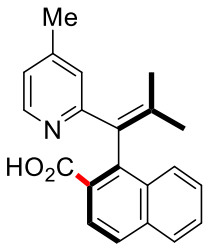
以通用方法经制备级 TLC 分离得到白色固体(22.6 mg, 75% yield 两步)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.38 (d, *J* = 5.0 Hz, 1H), 7.96 (t, *J* = 4.6 Hz, 1H), 7.86 (d, *J* = 10.3 Hz, 4H), 7.72 (d, *J* = 7.9 Hz, 1H), 7.54 – 7.41 (m, 2H), 7.25 – 7.16 (m, 1H), 2.00 (s, 3H), 1.60 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 171.58, 158.36, 147.04, 140.58, 138.57, 136.03, 134.59, 133.36, 130.90, 129.99, 128.67, 128.32, 127.20, 126.99, 126.67, 125.81, 125.61, 122.50, 22.22, 21.73. HRMS (ESI-TOF) calcd for $C_{20}H_{18}NO_2^+$ ([M+H]$^+$): 304.1332, found: 304.1333. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v =1.0 mL·min-1, λ = 254 nm, t (major) = 23.1 min, t (minor) = 17.1 min, 95% ee; $[\alpha]_D^{20}$ = -352.9 (c = 1.00, $CHCl_3$).

1-(1-(4-methoxypyridin-2-yl)-2-methylprop-1-en-1-yl)-2-naphthoic acid(3-9b):



以通用方法经制备级 TLC 分离得到白色固体(11.0 mg, 33% yield 两步)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.21 (d, *J* = 6.0 Hz, 1H), 8.02 – 7.90 (m, 1H), 7.89 – 7.78 (m, 3H), 7.49 (dt, *J* = 6.3, 3.5 Hz, 2H), 7.16 (d, *J* = 2.4 Hz, 1H), 6.71 (dd, *J* = 6.1, 2.5 Hz, 1H), 3.93 (s, 3H), 2.01 (s, 3H), 1.58 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 171.88, 167.35, 159.52, 148.10, 140.43, 135.63, 134.54, 133.75, 130.92, 129.77, 128.68, 128.27, 127.07, 126.91, 126.85, 125.82, 112.25, 107.72, 55.88, 22.19, 21.78. HRMS (ESI-TOF) calcd for $C_{21}H_{20}NO_3^+$ ([M+H]$^+$): 334.1438, found: 334.1436. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 80/20, v =1.0 mL·min-1, λ = 254 nm, t (major) = 13.0 min, t (minor) = 11.5 min, 93% ee; $[\alpha]_D^{20}$ = -350.2 (c = 1.01, $CHCl_3$).

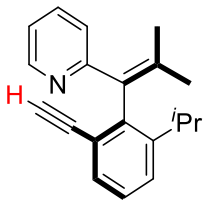
1-(2-methyl-1-(4-methylpyridin-2-yl)prop-1-en-1-yl)-2-naphthoic acid(3-9c):



以通用方法经制备级 TLC 分离得到白色固体(11.0 mg, 35% yield 两步)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.22 (d, *J* = 5.2 Hz, 1H), 8.02 – 7.93 (m, 1H), 7.90 – 7.78 (m, 3H), 7.53 – 7.45 (m, 3H), 7.07 – 6.99 (m, 1H), 2.47 (s, 3H), 1.99 (s, 3H), 1.59 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 171.81, 157.94, 150.49, 146.33, 140.29, 135.97, 134.56, 133.55, 130.92, 129.88, 128.68, 128.24, 127.09, 126.93, 126.81, 126.19, 125.85, 123.48, 22.19, 21.78, 21.73. HRMS (ESI-TOF) calcd for $C_{21}H_{20}NO_2^+$ ([M+H]$^+$): 318.1489, found: 318.1487. 手性 HPLC 分离条件：a Daicel

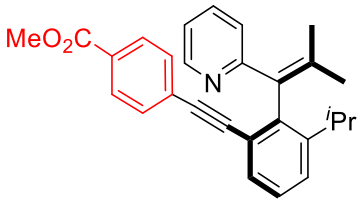
Chiralpak AD-H, *n*-hexane/2-propanol = 80/20, v =1.0 mL·min-1, λ = 254 nm, t (major) = 8.9 min, t (minor) = 7.5 min, 91% ee; $[\alpha]_D^{20}$ = -252.2 (c = 1.32, $CHCl_3$).

2-(1-(2-ethynyl-6-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine (3-10):



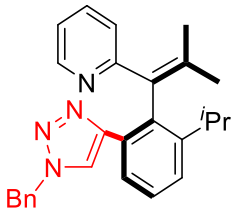
^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.65 – 8.54 (m, 1H), 7.51 (td, *J* = 7.7, 1.9 Hz, 1H), 7.43 (dd, *J* = 7.2, 1.8 Hz, 1H), 7.28 (s, 1H), 7.24 (d, *J* = 7.4 Hz, 1H), 7.11 (d, *J* = 7.9 Hz, 1H), 7.04 (dd, *J* = 7.3, 5.2 Hz, 1H), 3.18 (hept, *J* = 6.9 Hz, 1H), 3.01 (s, 1H), 2.05 (s, 3H), 1.66 (s, 3H), 1.12 (d, *J* = 6.9 Hz, 3H), 0.69 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 160.04, 148.48, 143.47, 137.89, 135.92, 133.09, 130.57, 127.38, 126.81, 124.67, 122.69, 120.84, 84.09, 77.89, 30.32, 24.17, 23.46, 23.13, 21.61. HRMS (ESI-TOF) calcd for $C_{20}H_{22}N^+$ ($[M+H]^+$): 276.1747, found: 276.1746. 手性 HPLC 分离条件：two Daicel Chiralpak ICs, *n*-hexane/2-propanol = 99/1, v = 0.5 mL·min-1, λ = 254 nm, t (major) = 18.6 min, t (minor) = 19.4 min, 98% ee; $[\alpha]_D^{20}$ = -296.2 (c = 0.50, $CHCl_3$).

methyl 4-((3-isopropyl-2-(2-methyl-1-(pyridin-2-yl)prop-1-en-1-yl)phenyl)ethynyl)benzoate (3-11):



^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.68 – 8.53 (m, 1H), 8.02 – 7.91 (m, 2H), 7.49 (ddd, *J* = 9.4, 6.6, 3.8 Hz, 2H), 7.46 – 7.40 (m, 2H), 7.30 – 7.27 (m, 2H), 7.13 (d, *J* = 8.0 Hz, 1H), 7.04 (ddd, *J* = 7.5, 4.9, 1.2 Hz, 1H), 3.90 (s, 3H), 3.21 (hept, *J* = 6.8 Hz, 1H), 2.10 (s, 3H), 1.71 (s, 3H), 1.13 (d, *J* = 6.9 Hz, 3H), 0.69 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.68, 160.12, 148.58, 143.37, 137.68, 135.97, 133.44, 131.45, 129.78, 129.62, 129.23, 128.64, 127.51, 126.91, 124.55, 123.11, 120.89, 93.43, 89.65, 52.36, 30.39, 24.16, 23.41, 23.25, 21.66. HRMS (ESI-TOF) calcd for $C_{28}H_{28}NO_2^+$ ($[M+H]^+$): 410.2115, found: 410.2117. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 95/5, v = 1.0 mL·min-1, λ = 254 nm, t (major) = 4.1 min, t (minor) = 5.3 min, 99% ee; $[\alpha]_D^{20}$ = -272.5 (c = 0.52, $CHCl_3$).

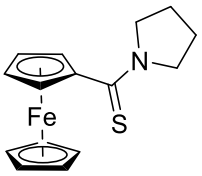
2-(1-(2-(1-benzyl-1H-1,2,3-triazol-4-yl)-6-isopropylphenyl)-2-methylprop-1-en-1-yl)pyridine (3-12):



^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.55 – 8.48 (m, 1H), 8.03 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.62 (s, 1H), 7.49 – 7.35 (m, 2H), 7.33 – 7.27 (m, 4H), 7.20 – 7.13 (m, 2H), 7.00 (dd, *J* = 7.5, 4.9 Hz, 1H), 6.87 (d, *J* = 8.0 Hz, 1H), 5.55 (d, *J* = 14.8 Hz, 1H), 5.40 (d, *J* = 14.9 Hz, 1H), 3.04 (h, *J* = 6.9 Hz, 1H), 1.80

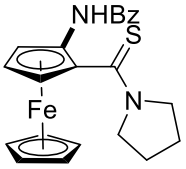
(s, 3H), 1.35 (s, 3H), 1.12 (d, *J* = 6.8 Hz, 3H), 0.71 (d, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.55, 148.71, 147.91, 147.53, 138.09, 137.57, 135.82, 135.18, 133.54, 130.46, 129.08, 128.63, 128.00, 127.96, 126.29, 126.02, 124.59, 121.93, 120.77, 54.04, 30.22, 24.37, 23.81, 23.58, 21.73. HRMS (ESI-TOF) calcd for $C_{27}H_{29}N_4^+$ ([M+H]$^+$): 409.2387, found: 409.2391. 手性 HPLC 分离条件：a Daicel Chiralpak AD-H, *n*-hexane/2-propanol = 90/10, v = 1.0 mL·min-1, λ = 254 nm, t (minor) = 14.1 min, t (major) = 15.4 min, 97% ee; $[\alpha]_D^{20}$ = -165.0 (c = 0.65, $CHCl_3$).

Ferrocenyl (pyrrolidin-1-yl)methanethione (**3-17**):



^{1}H NMR (400 MHz, Chloroform-*d*) δ 4.83 (s, 1H), 4.38 (s, 1H), 4.22 (s, 2H), 3.96 (s, 1H), 3.83 (s, 1H), 2.00 (s, 7H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 195.92, 86.66, 72.08, 70.95, 69.91, 55.49, 53.56, 27.04, 24.23. HRMS (ESI-TOF) calc for $C_{15}H_{17}FeNS^+$ ([M+H]$^+$): 300.0504, found: 300.0511.

***N*-(3-(pyrrolidine-1-carbonothioyl)ferrocenyl)benzamidem (3-19):**



^{1}H NMR (400 MHz, Chloroform-*d*) δ 10.95 (s, 1H), 8.02 (d, *J* = 7.0 Hz, 2H), 7.50 (dq, *J* = 14.2, 7.0 Hz, 3H), 5.84 (s, 1H), 4.30 (s, 2H), 4.21 (s, 5H), 4.03 – 3.54 (m, 4H), 2.20 – 1.80 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 194.54, 134.62, 131.69, 128.76, 127.41, 98.52, 75.99, 65.71, 64.64, 63.46, 54.96, 54.82, 26.85, 24.33. HRMS (ESI-TOF) calc for $C_{22}H_{22}FeN_2OS^+$ ([M+H]$^+$): 419.0875, found：419.0869. 手性 HPLC 分离条件：a Daicel Chiralpak IA, *n*-hexane/2-propanol = 80/20, v = 1.0 mL·min-1, λ = 254 nm, t (major) = 13.7 min, t (minor) = 11.8 min.

3-9a 为配体, 89%, 70.5:29.5 er.

3-9b 为配体, 0 ºC, 96%, 73.6:27.4 er; -20 ºC, 75%, 78.8:21.2 er.

3-9c 为配体, 93%, 71.2:28.8 er.

3-13 为配体, 95%, 50:50 er.

3-14 为配体, 93%, 50:50 er.

3-15 为配体, 89%, 51.2:48.8 er.

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第四章 钯催化硫醚导向不对称烯烃碳氢键烯基化反应构建含共轭烯烃结构的轴手性烯基芳烃

4.1 研究背景

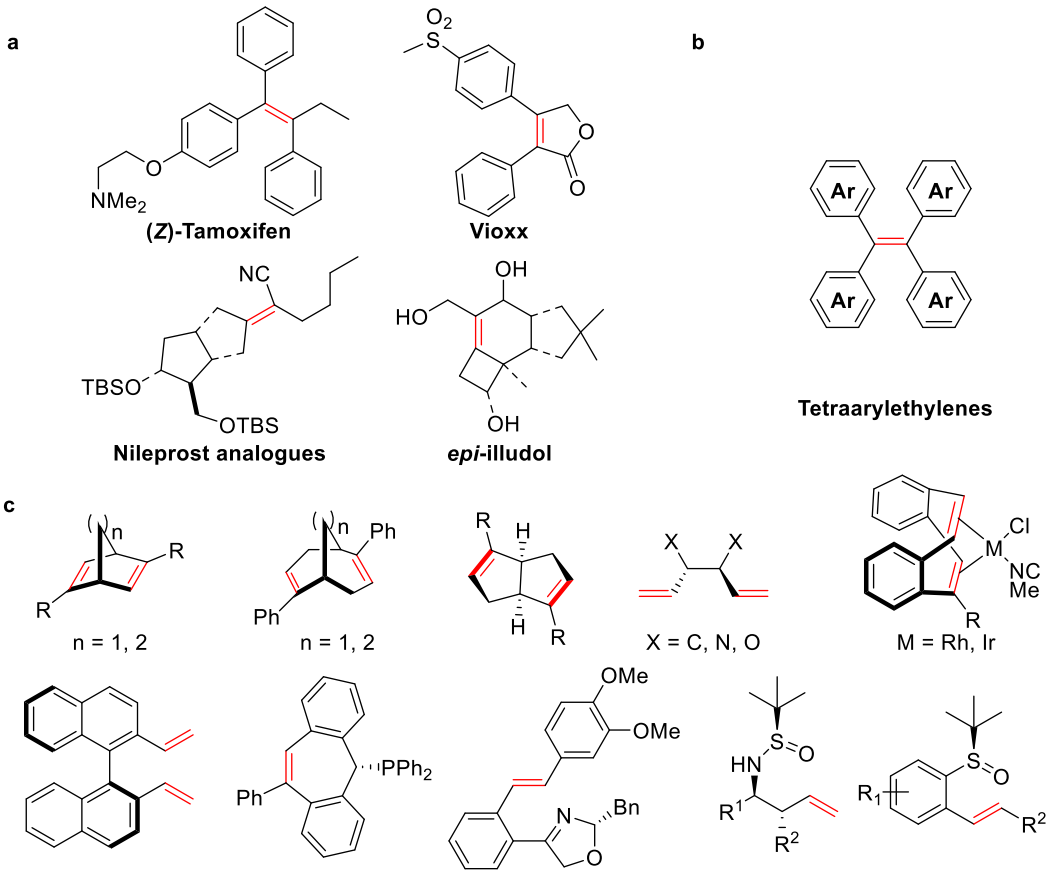


图 4.1 天然产物、材料分子、配体和催化剂中的烯烃结构

烯烃在有机化学中是一类非常重要的结构单元，其广泛存在于天然产物、药物分子和功能性材料中(**图 4.1a, b**)[1]。例如(*Z*)-Tamoxifen 和 Vioxx 等药物分子中均含有一个四取代烯烃结构单元。其中(*Z*)-Tamoxifen 是一种选择性的雌激素受体调节剂，可以作用于乳腺细胞。而 Vioxx 则可以治疗骨关节炎，有着缓解疼痛和治疗原发性痛经的效果。另外，四芳基取代的烯烃化合物作为一类拥有大 π 共轭体系的结构分子，拥有极高的聚集诱导发光效应[1e]。因此其在化学-生物学传感和光电材料领域有着广泛的应用。更加重要的是，手性烯烃作为手性配体和催化剂在不对称催化反应中表现出良好的应用性(**图 4.1c**)[2]。各种结构类型的手性双烯和含配体杂原子的手性单烯化合物均可以作为高效的手性配体或者与

金属结合成相应的手性催化剂，作用于不对称共轭加成反应、不对称烯丙基取代反应以及不对称环化环加成反应等。

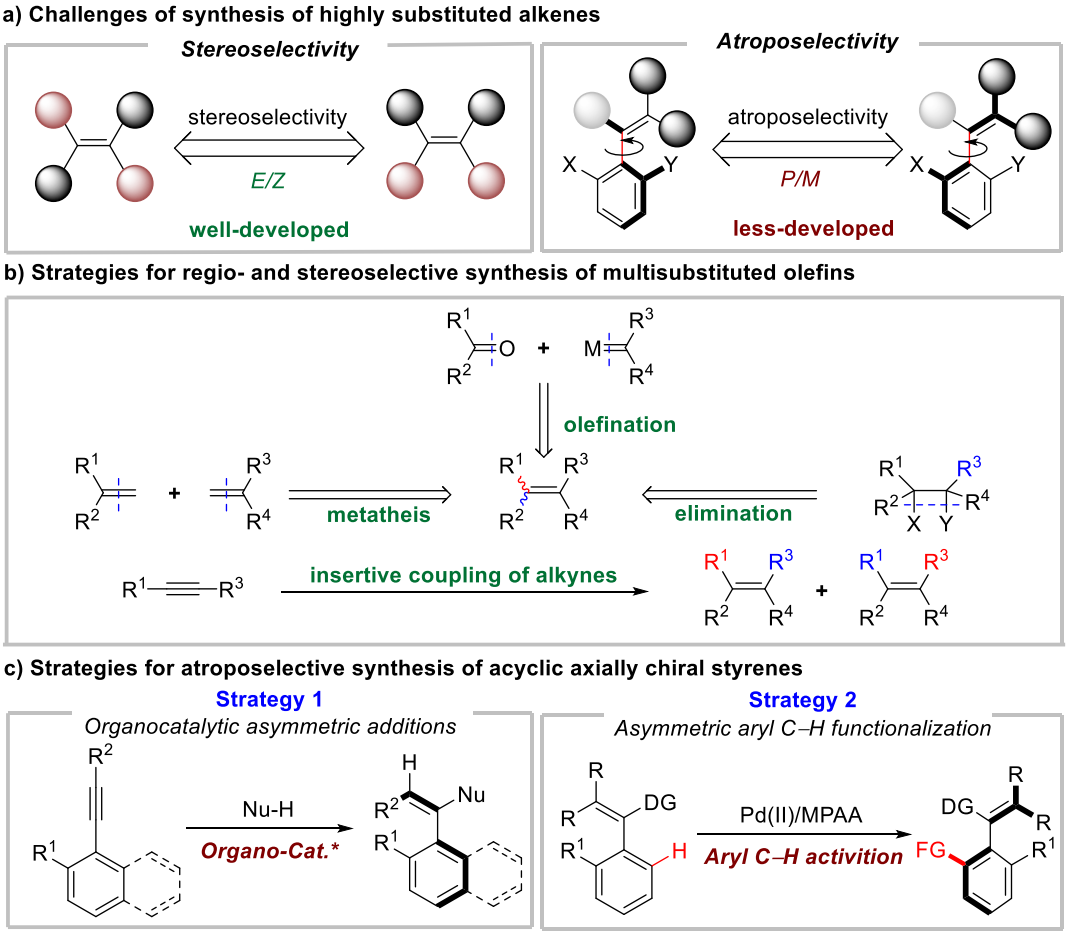


图 4.2 多取代烯烃和轴手性烯基芳烃的合成挑战性

基于多取代烯烃在有机化学中的重要性，如何高效地合成多取代烯烃一直以来是科学家们讨论和研究的热点问题。但是我们知道，多取代烯烃中的四个取代位点均可以被不同的基团所占据，从而导致了烯烃结构多样的 *E/Z* 异构化现象(**图 4.2a**)。与此同时，当多取代烯烃中一个取代位点是带有位阻的芳香环时，连接芳环和烯烃的碳碳单键就会变成一根旋转受阻的手性轴。这时又会产生新的异构体现象——阻转异构现象(**图 4.2a**)[3]。这些都增加了多取代烯烃立体选择性合成的复杂性和挑战性。

经过科学家们的努力探究，几十年来涌现出许多位置和立体选择性地合成多取代烯烃的方法[1d, 4]。例如羰基的烯基化反应，烯烃复分解反应，消除反应以及对炔烃的插入偶联反应均可以比较高效地解决多取代烯烃合成中的 *E/Z* 选择性问题(**图 4.2b**)。但是这些方法却无法解决轴手性烯烃的阻转选择性问题[5]。

相比结构刚性的轴手性联芳化合物，拥有一个开链式多取代烯烃的轴手性烯基芳烃化合物因为其灵活的烯烃结构，导致其拥有较低的翻转能垒。因此催化不对称地合成轴手性烯基芳烃是十分具有挑战性的[5, 6]。至今为止，也仅发展了极少数的策略来解决这一难题**(图 4.2c)**[7–11]。一种是由谭斌[8]、闫海龙[9]和石枫[10]等课题组发展的有机小分子催化不对称加成或取代反应。另一种是由我们课题组[11a,b]和王细胜[11c]课题组发展的不对称芳烃碳氢键官能团化反应。最近，何英课题组发展了铱和手性膦配体催化的串联不对称烯丙基取代异构化策略来构建开链式烯烃-芳烃手性轴[12]。虽然这些方法可以高效地催化不对称合成轴手性烯基芳烃。但是对这一类型轴手性烯烃骨架的潜在应用研究却屈指可数。

4.2 课题设计思路

基于研究背景，我们知道手性烯烃作为手性配体被广泛应用于不对称催化反应中[5]。纵观这些配体结构，我们发现其大致可以分为两类：一是基于手性在碳链骨架上的手性双烯和含氮族原子的烯烃配体[2a, b, d]；二是手性在硫原子上的手性亚砜烯烃配体[2c]。而受到轴手性烯基芳烃化合物结构的启示，我们设想将一个轴手性和硫中心手性相结合的烯烃配体是否可以为手性烯烃配体的应用提供新的思路**(图 4.3a)**。此外，传统手性烯烃的合成往往需要复杂的合成路线或使用化学当量的手性辅基，甚至是历经成本高昂的手性拆分过程。而不对称碳氢键活化策略因为其步骤简单，原子经济性高等优点逐渐成为催化不对称合成手性分子强有力的方法。因此，我们计划使用过渡金属催化的不对称烯烃碳氢键活化策略[13]来快速构建含硫原子的轴手性烯基芳烃骨架。

为了实现这一设想，我们需要解决以下问题：1）轴手性烯基芳烃与轴手性联芳化合物对比，其稳定性和翻转能垒都比较低。因此反应需要在更温和的条件下进行，这与一般比较苛刻的烯烃碳氢键活化条件相冲突[6e–g]；2）与一般的芳烃碳氢键活化相比较，实现烯烃碳氢键官能团化是更加困难的。因为在烯烃碳氢键活化过程中往往会同时存在许多副反应。例如烯烃 *E/Z* 构型的相互异构化，各种破坏烯烃双键的反应和烯丙基碳氢键活化反应等[13]；3）为了实现反应的立体选择性，挑选一个合适的手性配体和导向基团是反应的关键。这一导向基团和配体组合需要克服拥有强 Π 共轭体系的烯烃对金属催化剂的配位干扰，同时在温和的反应条件下实现产物的高效合成和立体选择性控制。在前人的工作和我们课题组长期使用不对称碳氢键活化手段构建手性分子的研究[14]帮助下，我们发展了利用手性螺环磷酸作为手性配体，通过钯催化的不对称烯烃碳氢键烯基化反应来快速构建拥有

一个 1,3-共轭二烯结构单元的轴手性烯基芳烃化合物(**图 4.3b**)。该反应可以以完全的 *Z* 构型选择性，优秀的产率和对映体选择性得到大量的轴手性烯基芳烃化合物(69 examples, up to 99% yield and 99% ee)。同时该策略还被应用于直接构建含多个手性轴的烯基芳烃化合物中。

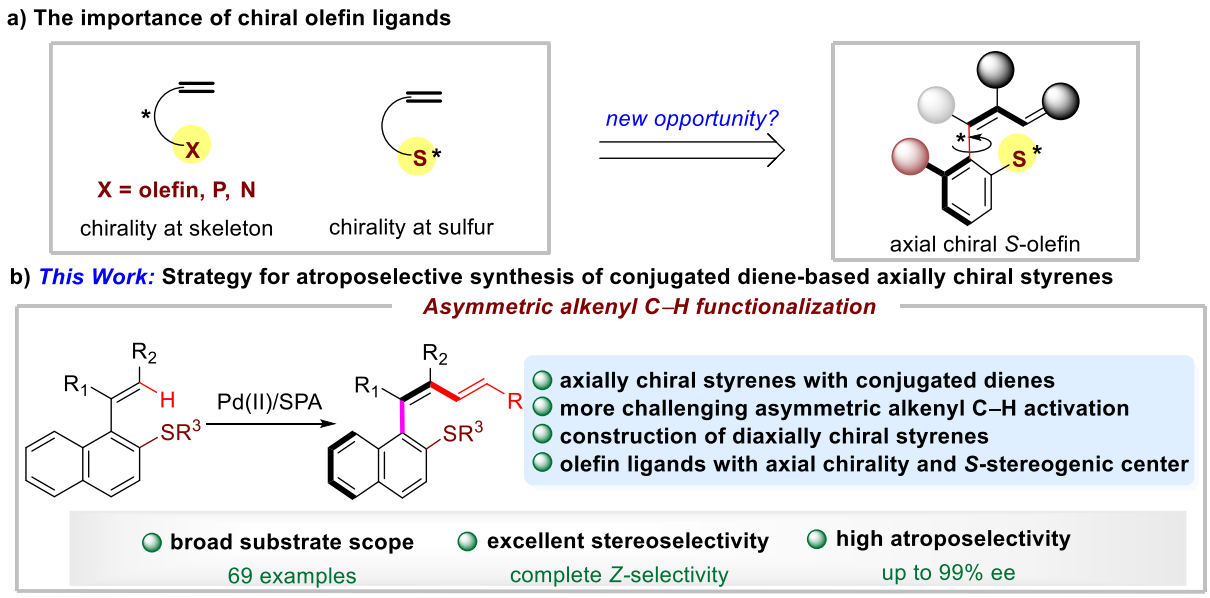


图 4.3 不对称构建含共轭烯烃结构的轴手性烯基芳烃的原始设计

4.3 反应条件优化

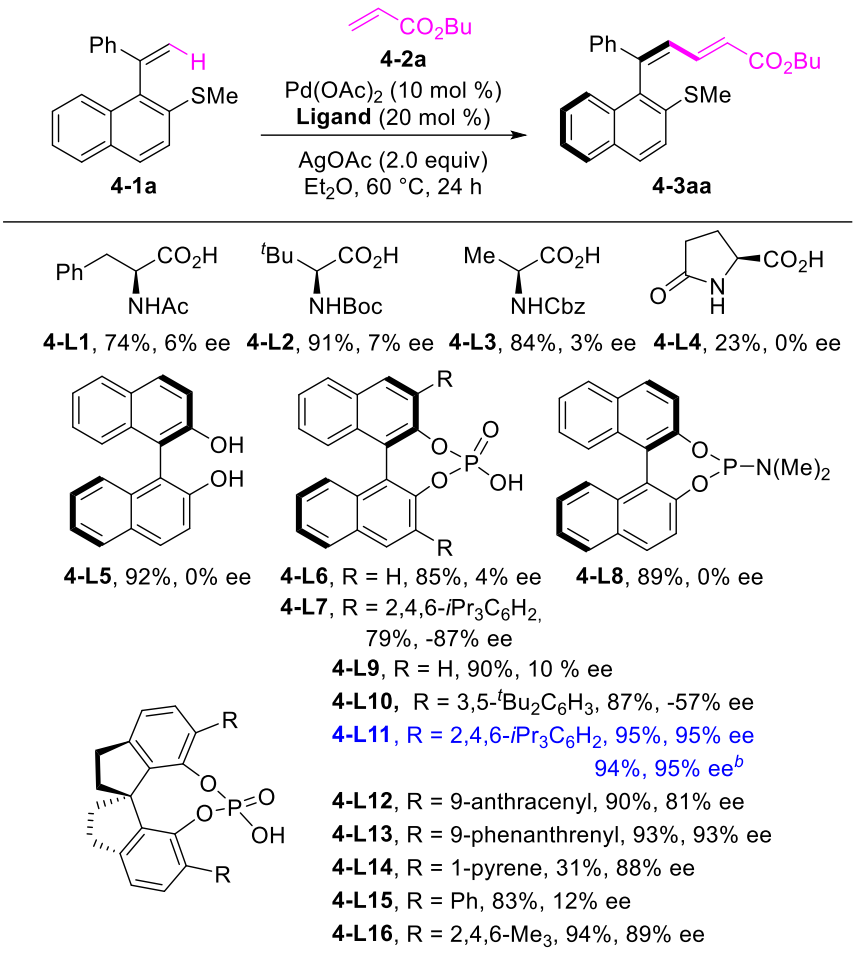
考虑到反应需要合成一类同时具有轴手性和硫中心手性的烯烃配体，同时也受到以往钯催化硫醚导向碳氢键活化反应[15]的启发，我们相信硫醚结构单元可能是一个适合的导向基团。因此我们选择了化合物 **4-1a**，一个带有甲硫基的二取代苯乙烯作为我们的模型底物，丙烯酸正丁酯 **4-2a** 为反应的烯基化试剂，醋酸钯为催化剂，系统的筛选了反应的配体、反应溶剂等条件。

4.3.1 手性配体的筛选

我们首先以 10 mol%的醋酸钯为催化剂，0.1 mmol 的化合物 **4-1a** 为反应底物，加入 3 倍当量的烯基化试剂，2 倍当量的醋酸银，以 1.0 mL 无水乙醚为反应溶剂，反应温度 60 ºC 时，对反应的手性配体进行了筛选(**表 4.1**)。2008 年，余金权[15]课题组证明了单保护氨

基酸(MPAA)是钯催化不对称碳氢键官能团化反应的有效手性配体。同时 MPAA 也被广泛应用于钯催化不对称碳氢键活化构建轴手性联芳化合物中[17]。因此，我们首先筛选了各种类型的 MPAAs(**4-L1–4**)。令我们失望的是，虽然使用 MPAAs 可以顺利的得到相对应的烯基化产物，但是其诱导出来的对映体比率几乎可以被忽略。

表 4.1 手性配体的筛选 [a]



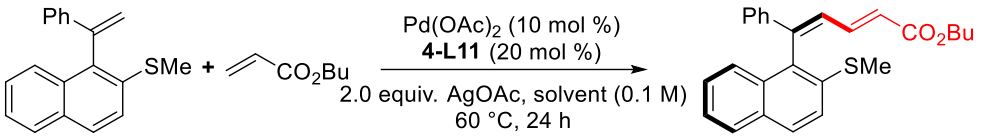
[a] 反应条件:**4-1a** (0.1 mmol), **4-2a** (3.0 equiv), $Pd(OAc)_2$ (10 mol %), AgOAc (2.0 equiv), Ligand (20 mol %), 在 Et_2O(1.0 mL)中于空气氛围在 60 ºC 反应 24 小时。[b] $Pd(OAc)_2$ (5 mol%), **4-L11**(10 mol%)。

之后，BINOL(**4-L5**)和基于 BINOL 骨架的手性磷酸(**4-L6**)和亚磷酰胺配体(**4-L8**)也被进行了测试。反应结果显示所得到的烯基化产物的对映体比率依然不是很理想。令人激动的是，当一个位阻比较大的手性磷酸(TRIP，**4-L7**)被当作手性配体加入到反应中时，我们可以以 79%的产率，-87%的 ee 值得到完全 *Z* 构型的烯基化产物。在之前的工作中，我们发现手性螺环磷酸作为手性配体促进钯催化不对称碳氢键活化构建轴手性联芳化合物[18, 19]。因此我们接着对手性螺环磷酸进行了详细的筛选(**4-L9–4-L16**)。不出我们所料，当使

用一个位阻适合的手性螺环磷酸(**4-L11**)为配体时，我们可以以 95%的产率和 95%的 ee 值以及完全 *Z* 构型选择性地得到目标烯基化产物 **4-3aa**。

4.3.2 反应溶剂和其他条件的筛选

表 4.2 反应溶剂的筛选 [a]



4-1a **4-2a** **4-3aa**

entry	solvent	yield [b] %	ee [c] %
1	DCE	91	86
2	Toluene	89	90
3	MeCN	96	50
4	MeOH	NR	--
5	THF	92	89
6	DMF	90	79
7	Et_2O	95	95
8 [d]	Et_2O	93	94
9 [e]	**Et_2O**	94	95

[a] **4-1a** (0.1 mmol), **4-2a** (3.0 equiv), $Pd(OAc)_2$ (10 mol %), AgOAc (2.0 equiv), Ligand (20 mol %)在相应溶剂(1.0 mL)中于空气氛围在 60 °C 反应 24 小时。[b] 分离产率。[c]ee 值由手性 HPLC 测定。[d]Ligand (10 mol%)。[e] $Pd(OAc)_2$ (5 mol%), Ligand (10 mol%)。

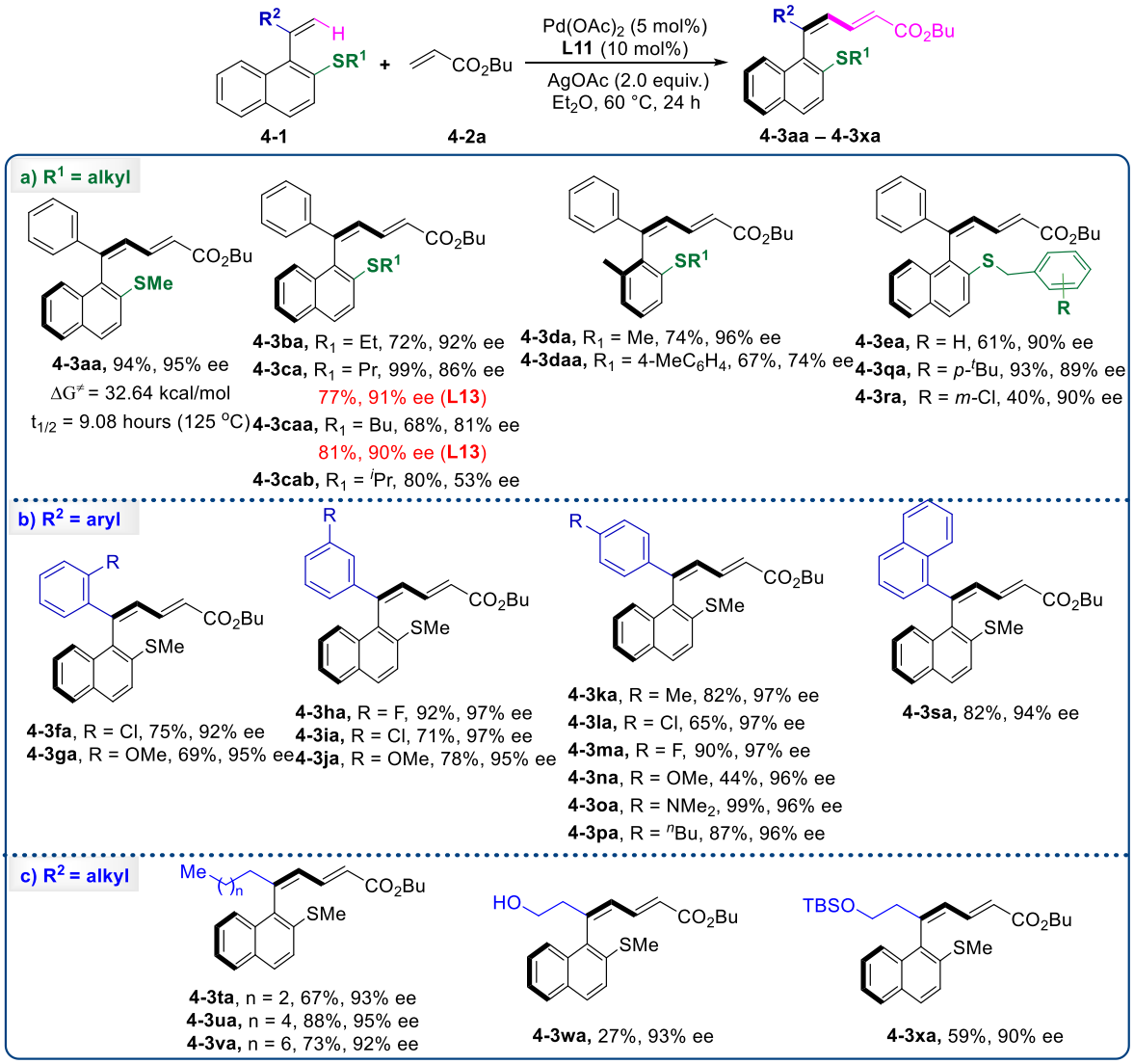
在得到了反应最优的手性配体 **4-L11** 后，我们接下来对反应的溶剂进行了筛选。我们发现绝大多数溶剂都可以顺利的得到目标烯基化产物。其中溶剂的极性对产物的对映体比率影响很大。当选用非质子型极性溶剂乙腈和 *N,N*-二甲基甲酰胺为反应溶剂时，产物的 ee 值有明显的下降(**entry 3**, 50% ee; **entry 6**, 79% ee)。当增加溶剂的极性，选择质子型极性溶剂甲醇为反应溶剂时，在标准的反应条件下几乎不能顺利得到我们想要的烯基化产物(**entry 4**)。之后，其他相对弱极性的溶剂，二氯乙烷、甲苯和四氢呋喃也被进行了测试，发现反应效果均没有在无水乙醚中好。因此，我们确认无水乙醚是烯基化反应的最佳溶剂。最后我们对反应的催化剂和手性配体的比例进行了微调，发现当将催化剂醋酸钯的量减少到 5 mol%，配体的量减少到 10 mol%时，反应的产率和对映体比率均没有受到影响(**entry 8, 9**)。最终我们确认反应的最优条件是 5 mol%的醋酸钯为催化剂，10 mol%的 **4-L11** 为手

性配体，3 倍当量的丙烯酸正丁酯为烯基化试剂，2 倍当量的醋酸银为反应氧化剂，无水乙醚作为反应溶剂，在 60 ºC 下反应 24 小时，可以以 94%的产率和 95%的 ee 值以及完全的 *Z* 构型选择性得到目标烯基化产物 **4-3aa**。

4.4 反应底物拓展

4.4.1 三取代轴手性烯基芳烃产物的合成研究

表 4.3 三取代轴手性烯基芳烃产物普适性研究 [a]



[a] 反应条件:**4-1** (0.1 mmol), **4-2a** (0.3 mmol), $Pd(OAc)_2$ (5 mol%), AgOAc (2.0 equiv), **4-L11** (10 mol%)在 Et_2O(1.0 mL)中于空气氛围在 60 ºC 反应 24 小时。

在得到了最优的烯基化反应条件之后，我们对反应底物的适用性进行了详细的研究。

首先，我们将该不对称碳氢键烯基化反应用于合成一系列三取代的轴手性烯基芳烃化合物(**表 4.3**)。我们先对反应底物中导向基团的位阻效应进行了考察(**表 4.3a**, **4-3aa**–**4-3-ca**, **4-3caa**, **4-3cab**)。我们发现当导向基团的位阻逐渐增大时，相应反应产物的对映体比率会产生明显的下降(**4-3aa**, R^1 = Me, 95% ee; **4-3ba**, R^1 = Et, 92% ee; **4-3ca**, R^1 = Pr, 86% ee; **4-3caa**, R^1 = Bu, 81% ee; **4-3cab**, R^1 = *i*Pr, 53% ee)。我们猜想，这可能是由于手性配体和导向基之间的位阻排斥导致的。之后我们将手性配体中大位阻的 2,4,6-(*i*Pr)$_3$C$_6$H$_2$ 基团替换成相对位阻较小的蒽环，反应产物的对映体比率下降的趋势便得到了抑制(**4-3ca, 4-L11**, 86% ee to **4-L13**, 91% ee; **4-3da, 4-L11**, 81% ee to **4-L13**, 90% ee)。此外，虽然相应产物的对映体比率有稍稍的下降，该方法依然适用于苯硫醚作为导向基团的情况(**4-3da** with R^1 = Me, 96% ee, vs **4-3daa** with R^1 = 4-MeC$_6$H$_4$, 74% ee)。相比之下，苄基取代的硫醚导向基则在反应中表现出更加不错的效果(**4-3ea**, **4-3qa**, **4-3ra**, 89−90% ee)。

接着我们考察了烯烃另一侧苯环取代基的电子效应对反应的影响(**表 4.3b**)。我们发现，不管在苯环的邻、间和对位安装供电子效应的取代基还是吸电子效应的取代基，反应均可以以中等到优秀的产率(44%–99%)和优秀的对映体比率(92%–97% ee)得到相应的三取代的轴手性烯基芳烃产物(**4-3fa**–**4-3pa**)。一个萘基取代的烯烃底物(**4-1s**)也适用该不对称烯烃碳氢键烯基化反应。

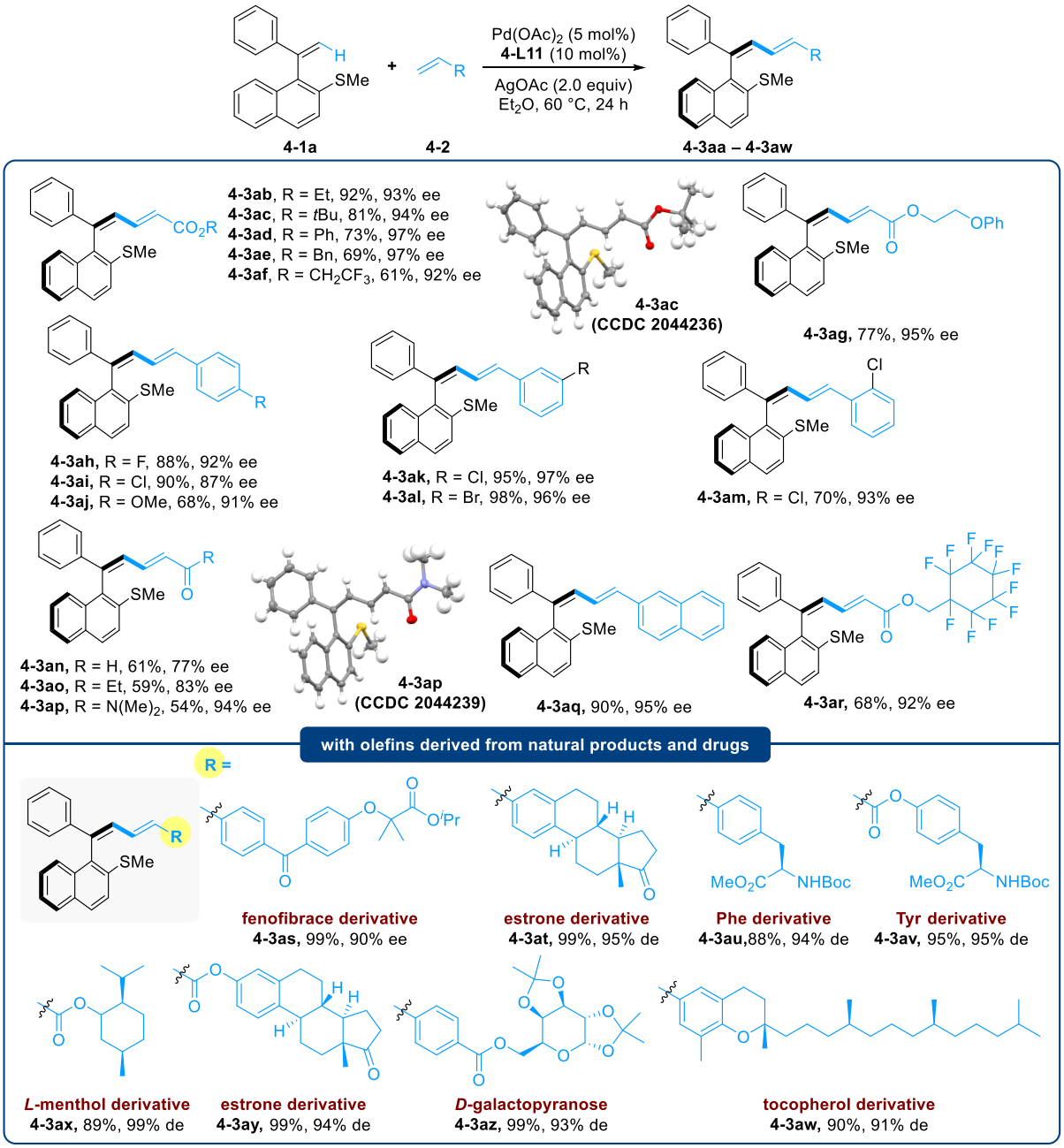
之后，我们将烯烃的取代基拓展到结构更加灵活多变的烷烃取代基(**表 4.3c**)。令我们高兴的是，不同长度的烷基链均可以很好的忍受钯催化不对称烯烃碳氢键烯基化反应，以良好到优秀的产率和优秀的对映体比率得到相应的烯基化产物(**4-3ta**, 67%, 93% ee; **4-3ua**, 88%, 95% ee; **4-3va**, 73%, 92% ee)。然而，当取代的烷基链中带有一个活性的醇羟基时，反应的产率会有很明显的下降(**4-3wa**, 27% yield)，但是羟基的存在并没有影响手性的控制(93% ee)。我们猜想这是因为活性的醇羟基可能会跟钯催化剂进行配位，对硫醚导向钯催化不对称烯烃碳氢键活化过程形成干扰。随后我们将活性的羟基用硅基进行了保护，反应物的活性问题就顺利得到了解决(**4-3xa**, 59%, 90% ee)。

4.4.2 烯基化试剂的拓展

紧接着，我们对反应使用的烯基化试剂进行了普适性研究(**表 4.4**)。我们筛选了各种类型的丙烯酸酯和苯乙烯，发现这些商业易得的试剂均可以作为反应的烯基化试剂，反应拥有良好的活性和对映体选择性(**4-3ab**–**4-3am**, **4-3aq**–**4-3ar**)。其他类型的端烯化合物也被我

们进行了实验。其中丙烯酰胺展现出了很好的活性，反应可以以 54%的产率和 94%的 ee 值得到相应烯基化产物 **4-3ap**。但是当位阻较小且活性更高的丙烯醛和丙烯酮作为反应的烯基化试剂时，相应产物的对映体比率则发生了明显地下降(**4-3an–4-3ao**)。

表 4.4 烯烃底物扩展 [a]



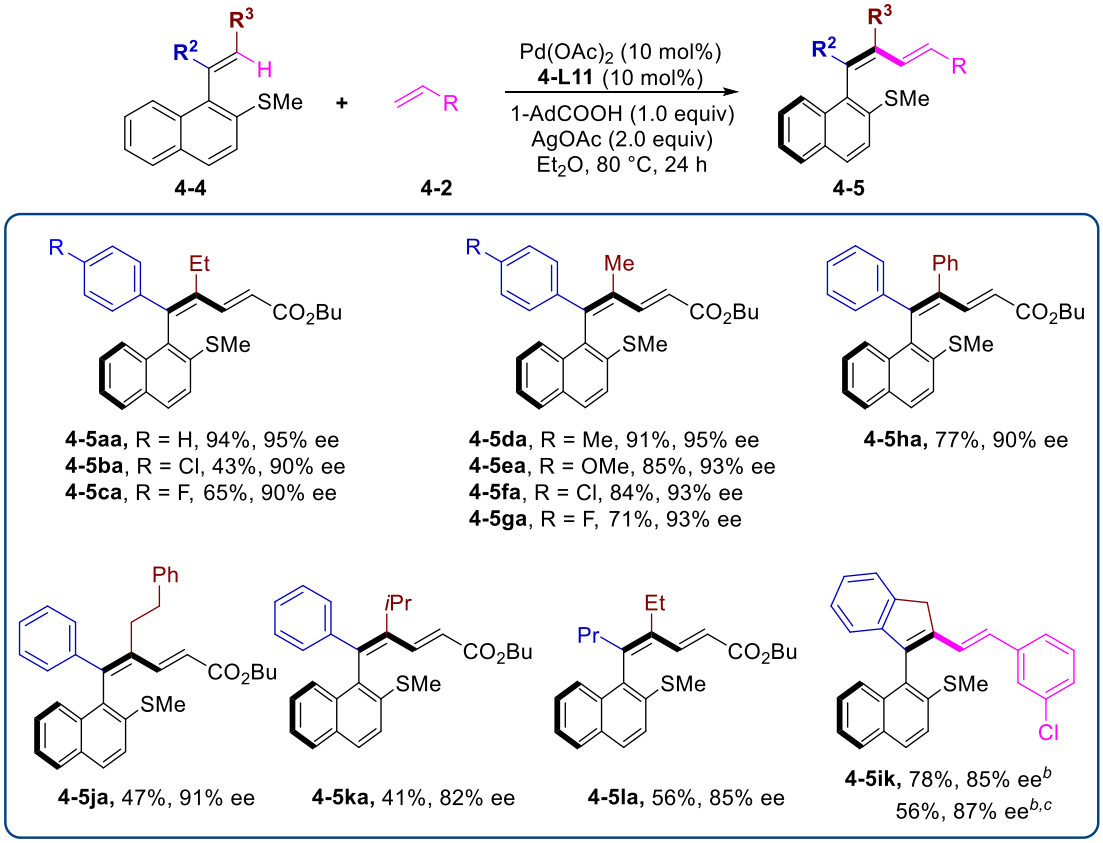
[a] 反应条件:**4-1a** (0.1 mmol), **4-2** (0.3 mmol), $Pd(OAc)_2$ (5 mol%), AgOAc (2.0 equiv), **4-L11** (10 mol%)在 Et_2O(1.0 mL)中于空气氛围在 60 ºC 反应 24 小时。

为了将该反应变的更加有实用前景，我们试验了许多活性分子衍生的烯基化试剂。结

果非常令我们兴奋，比如使用药物分子 fenofibrace 衍生的烯基化试剂时，我们可以以 99%的产率和 90%的 ee 得到对应的产物(**4-3as**)。许多天然产物分子衍生的烯基化试剂也都可以适用在烯基化反应中(estrone, **4-2t**, **4-2y**; *L*-menthol, **4-2x**; tocopherol, **4-2w**; *D*-galactopyranose, **4-2z**)。另外，氨基酸衍生的烯基化试剂(phenylalanine, **4-2u**; tyrosine, **4-2v**)也被证实是适用该不对称反应的偶联试剂。这些激动人心的结果为该方法对天然产物活性分子的后续衍生化研究提供了理论保证。产物 **4-3ac** 和 **4-3ap** 的绝对构型均由单晶衍生确定为 *R* 型，其他产物的绝对构型通过类比推测得到。

4.4.3 四取代轴手性烯基芳烃产物的合成研究

表 4.5 三取代轴手性烯基芳烃产物普适性研究 [a]



[a] 反应条件:**4-4** (0.1 mmol), **4-2** (3.0 equiv), $Pd(OAc)_2$ (10 mol%), AgOAc (2.0 equiv), **4-L11** (10 mol%), 1-AdCOOH (1.0 equiv)为添加剂在 Et_2O(1.0 mL)中于空气氛围在 60 °C 反应 24 小时。[b]60 °C。[c]**4-L13** 为配体。

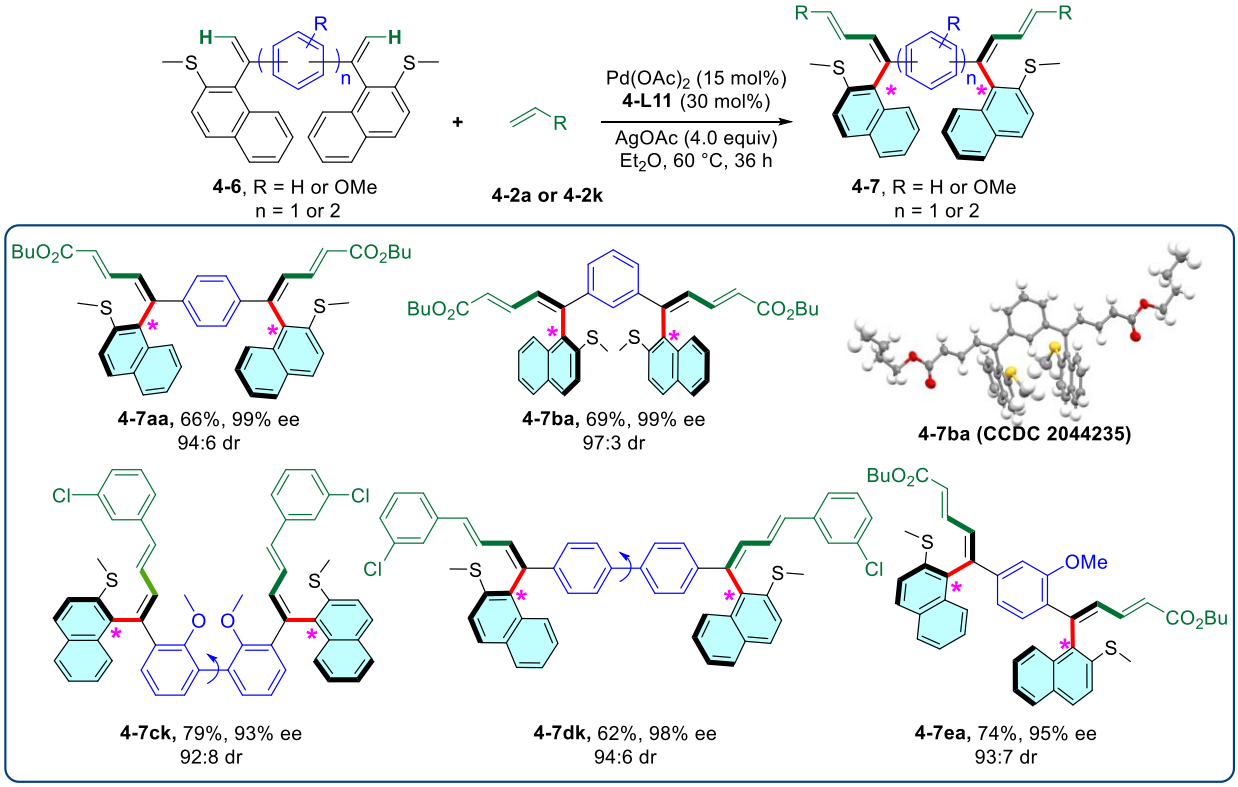
高效位置和立体选择性地合成四取代烯烃一直以来是有机化学界极具挑战性的课题[1d, 4]。值得注意的是，我们发展的钯催化不对称烯烃碳氢键烯基化反应同样也适用对四取

代轴手性烯基芳烃产物的合成(**表 4.5**)。

我们通过额外添加 1 倍当量的 1-金刚烷甲酸，同时将反应温度上升至 80 ºC 来提高三取代内烯烃底物发生碳氢键活化的反应活性。在底物拓展中我们发现，在苯环的对位引入不同电子效应的基团，其反应均可以顺利得到相应的四取代轴手性烯基芳烃产物(**4-5aa**–**4-5ga**, 43−94% yield, 90−95% ee)。接着，三芳基取代的烯烃底物(**4-4h**)也被进行了测试。我们可以以 77%的产率和 90%的 ee 值得到烯基化产物(**4-5ha**)。然后，我们将反应底物拓展到带有烷基链取代的三取代内烯烃底物(**4-4j**–**4-4l**)。该反应对含有线性烷烃取代的四取代轴手性烯基芳烃产物(**4-5ja**, 91% ee; **4-5la**, 85% ee)的手性控制要优于带支链烷烃取代的产物(**4-5ka**, 82% ee)。更重要的是，一个骨架结构的烯烃底物该也可以进行不对称烯烃碳氢键烯基化反应(**4-5ik**, 56%, 87% ee)。该骨架可能可以与过渡金属以 η^5 和 η^3 的配位模式相结合，生成相应的金属配合物，应用于不对称反应中[20]。

4.4.4 双手性轴产物的合成研究

表 4.6 双轴手性烯烃芳烃的合成 [a]



[a] 反应条件:**4-6** (0.05 mmol), **4-2** (6.0 equiv), $Pd(OAc)_2$ (15 mol%), AgOAc (4.0 equiv), **4-L11** (30 mol%)在 Et_2O(0.05 M)中于空气氛围在 60 ºC 反应 36 小时。

研究证明，分子中含有多个手性轴时，可以展现出独特的拓扑学性能，在材料化学和催化邻域表现出良好的应用性[21]。然而，对含有多个手性轴化合物的催化不对称合成却很少被报道[21c–e]。因此我们尝试将该不对称烯烃碳氢键烯基化反应应用到含两个手性轴的轴手性烯基芳烃化合物的合成中(**表 4.6**)。令我们激动的是，当通过对烯基化反应条件进行微调，分别按比例提高催化剂、配体和烯基化试剂的用量，同时延长反应的时间，我们可以以良好的产率和优异的对映体比率以及非对映体比率得到一系列同时具备两个手性轴的轴手性烯基芳烃化合物(**4-7aa**–**4-7ea**, 62−86%, 94−99% ee and up to 97:3 dr)。同时，产物 **4-7ba** 的绝对构型由单晶衍射确定为(*R*,*R*)构型，其余双轴手性化合物的绝对构型由此进行推测。

4.5 合成应用

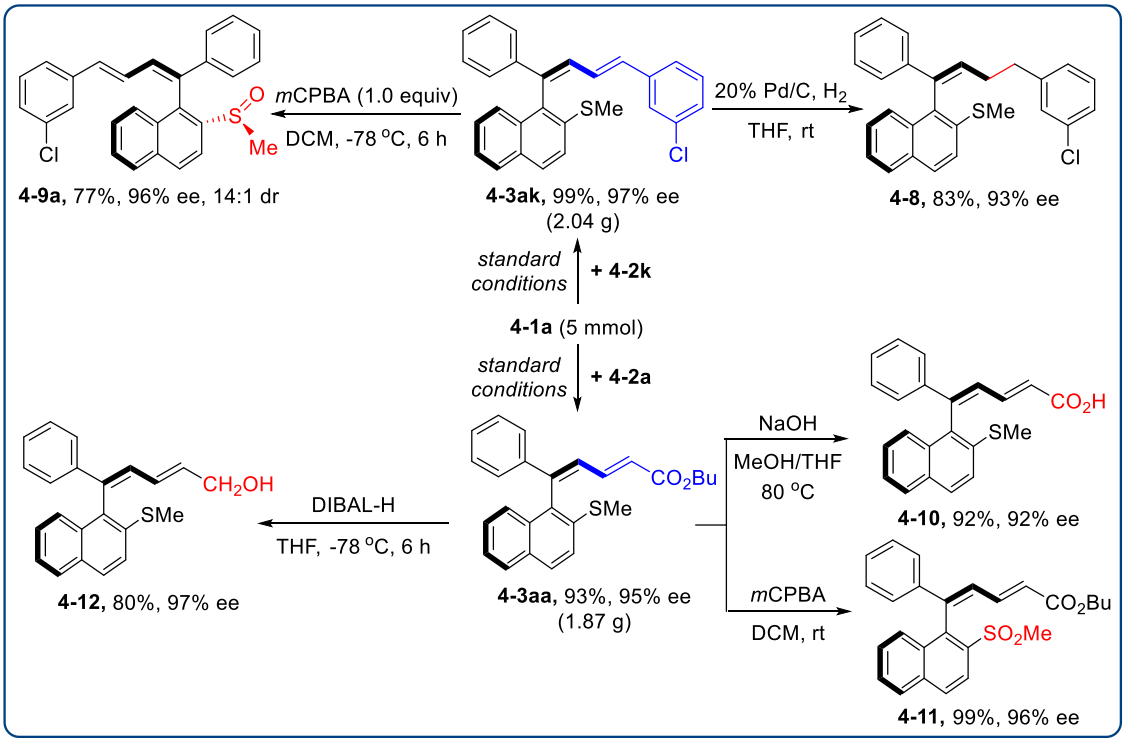


图 4.4 规模扩大反应和衍生化

为了进一步说明该反应的合成实用性，我们首先进了克级规模的扩大反应。在标准反应条件下，5 mmol 的底物 **4-1a**，分别跟烯基化试剂丙烯酸正丁酯 **4-2a** 和间氯苯乙烯 **4-2k** 反应，以不损耗产率和对映体比率的前提下得到相应的轴手性烯基芳烃产物(**4-3aa**, 1.9 g, 93%, 95% ee; **4-3ak**, 2.0 g, 99%, 97% ee)。之后，我们对产物进行了许多衍生化反应，进一

步展现其合成应用前景(**图 4.4**)。产物中的甲硫基可以被 1 倍当量的间氯过氧化苯甲酸在-78 °C 下选择性地氧化成相应的手性亚砜烯烃衍生物(**4-9a**)。值得高兴的是，该氧化反应可以保留手性轴的手性(96% ee)，同时以比较好的结果非对映体选择性地产生一个硫手性中心(14:1 dr)。这为之后衍生物作为一类新型硫烯配体的应用是非常有利的(**图 4.5**)。与此同时，如果将氧化剂的量增加到 2.05 倍当量，**4-3aa** 可以被直接氧化成砜类化合物 **4-11**(99% yield, 96% ee)。另外，产物 **4-3ak** 可以在 Pd/C 存在下被选择性地氢化成烷基链取代的烯烃产物 **4-8**(83%, 93% ee)。同样的，产物中的酯基结构可以被 DIBAL-H 选择性地还原成拥有一个轴手性烯烃结构的丙烯醇化合物 **4-12**(80%, 97% ee)。最后，**4-3aa** 可以在氢氧化钠的甲醇和四氢呋喃混合溶液中被水解成相应的烯基芳烃轴手性骨架的羧酸(**4-10**, 92%, 92% ee)。

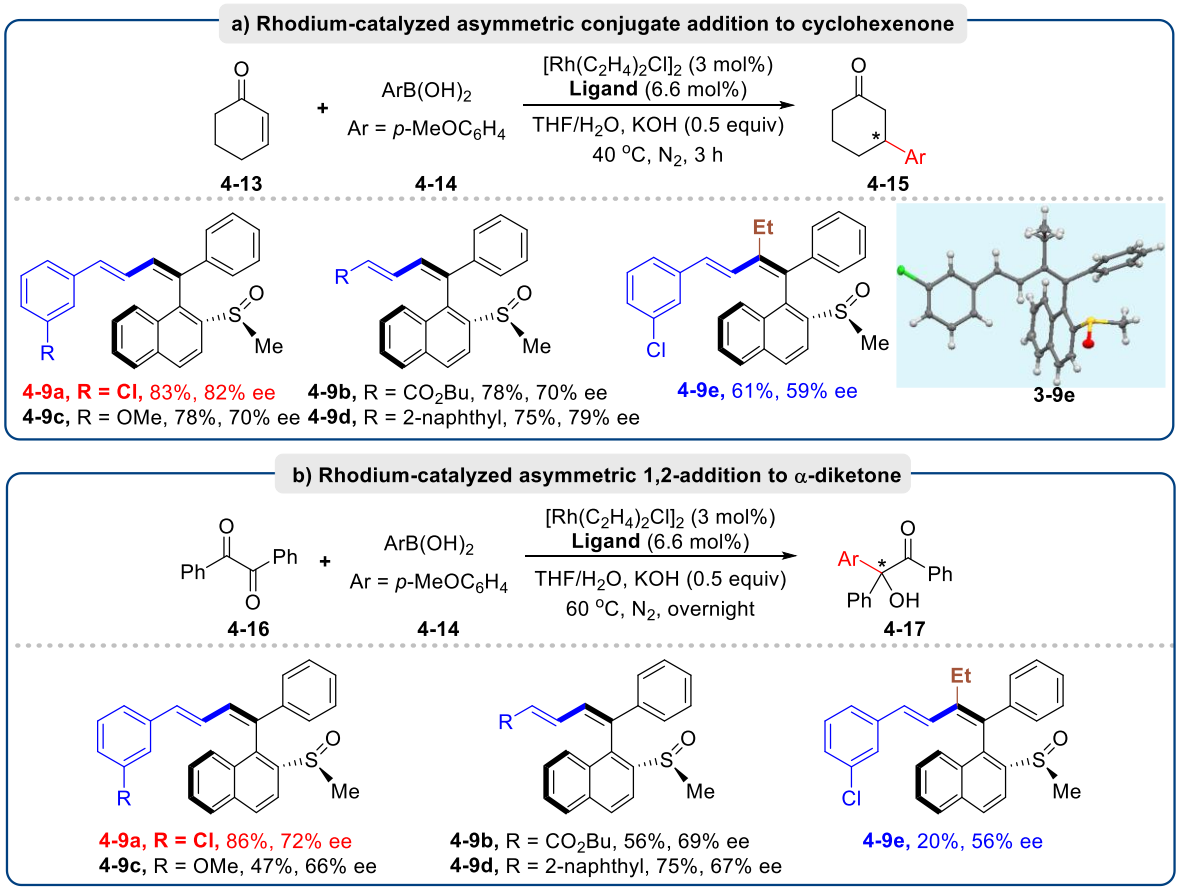


图 4.5 新类型手性硫烯配体的应用

含有一个硫中心手性的手性烯烃配体已经被广泛应用于不对称合成中[2, 22]。而经过我们发展的钯催化不对称烯烃碳氢键活化策略合成的轴手性烯基芳烃化合物 **4-3ak** 可以再历经一步简单的氧化反应，得到具有很好非对映体选择性控制的轴手性亚砜烯烃化合物 **4-**

9a(**图 4.4**)。受此启发，我们利用相同的方法进一步合成了一系列含有手性轴的手性硫烯配体(**4-9a**–**4-9e**)，并且将这些新配体应用到铑催化苯硼酸对环己烯酮的不对称共轭加成反应中(**图 4.5a**)[22a, b]。当化合物 **4-9a** 作为反应的手性配体时，反应可以以良好的产率和对映体选择性得到共轭加成产物 **4-15**(83%, 82% ee)。其他相似骨架的配体(**4-9b**–**4-9d**)也可以在反应中得到类似的结果(70–79% ee)。不幸的是当一个四取代的硫烯配体 **4-9e** 加入到催化反应中时，反应只能以 61%的产率和 59%的对映体比率得到目标加成产物。之后，我们继续将配体应用到铑催化苯硼酸对 *α*-二酮化合物的不对称 1,2-加成反应中(**图 4.5b**)[22c]。目标加成产物在我们开发的新型手性硫烯配体作用下可以得到中等到良好的对映体选择性控制(56–72% ee)。这些初步的探究结果都证实了这一新类型的手性配体在不对称催化反应中拥有良好的应用前景。

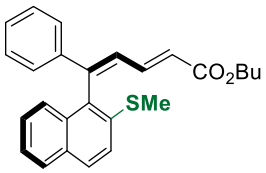
4.6 化合物 4-3aa 翻转能垒和半衰期的测定

翻转能垒是根据对映体的外消旋动力学实验获得的。一阶动力学曲线的斜率给出了外消旋常数($k_{racemisation}$ =2 * $k_{enantiomerisation}$)，根据 Eyring 方程，代入对映异构常数($k_{enantiomerisation}$)，可以求出翻转能垒($\Delta G^{‡}_{enaniomerization}$)，其中 R(气体常数) = 8.31451 J.K^{-1}.mol^{-1}, h(普朗克常数) = 6.62608 x 10-34 J*s 和 k_B(玻尔兹曼常数) = 1.38066 x 10-23 J*K^{-1}。

$$\Delta G^{‡}_{enaniomerization} = RT_1*\ln(k_BT_1/hk_{enantiomerization})$$

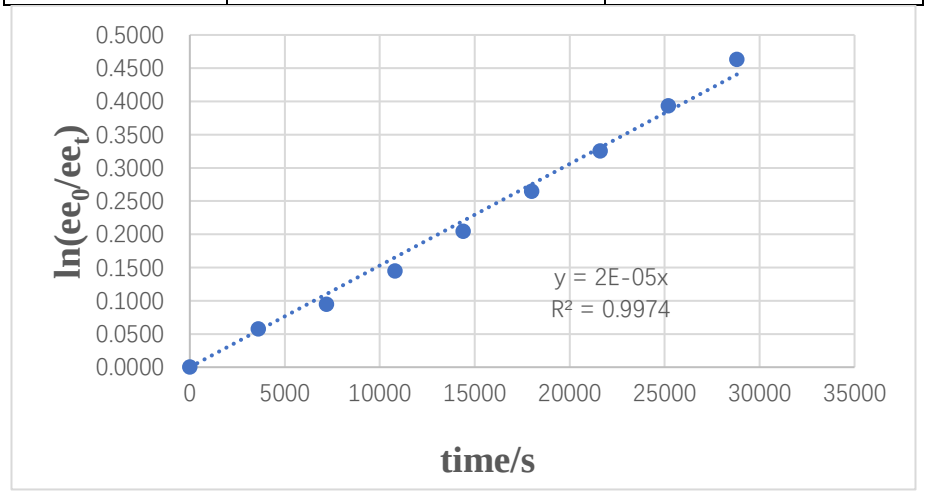
$$t_{1/2}(T_1) = 0.5*\ln2/k_{enantiomerization}$$

为了验证烯基化产物的构象稳定性，我们以 **4-3aa** 为模板底物，分别测试了其在一定温度下的翻转能垒，并且计算出相应温度下的半衰期。在充满氮气的密封管中以异丙醇为溶剂，1.0 mg/mL 的浓度进行反应。通过 HPLC 确定对映体比率。



4-3aa

time (second)	enantiomeric excess (ee)	first order racemization $\ln(ee_0/ee_t)$
0	96.134	0
3600	90.764	0.0575
7200	87.440	0.0948
10800	83.168	0.1449
14400	78.368	0.2043
18000	73.780	0.2647
21600	69.426	0.3255
25200	64.885	0.3931
28800	60.503	0.4631



$k_{racemization}$ (125 ºC) = 2×10^{-5} s^{-1}

$k_{enantiomerization}$ (125 ºC) = 1×10^{-5} s^{-1}

$\Delta G^{\ddagger}_{enaniomerization}$ = 136.587 KJ/mol = 32.64 kcal/mol

$t_{1/2}$ (125 ºC) = 9.08 hours

图 4.6 化合物 **4-3aa** 在 125 ºC 异丙醇中的消旋化反应

通过对以上测量数据的分析和计算，我们可以得到烯基化产物 **4-3aa** 的翻转能垒大约是 32.64 kcal/mol，在 125 ºC，其半衰期为 9.08 小时(**图 4.6**)。

4.7 本章小结

综上所述，我们成功地发展了通过钯催化不对称烯烃碳氢键烯基化反应构筑具有多取代共轭二烯结构的轴手性烯基芳烃化合物。在反应中，硫醚不仅是一个高效的导向基团，可以促进反应以高产率、高对映体选择性以及完全 *Z* 构型选择性地得到相应的轴手性烯基芳烃产物，还可以被简单转化成手性亚砜。该类手性衍生物作为一类新型硫烯配体在铑催化不对称加成反应中展示出良好的手性控制效果。

4.8 实验部分

4.8.1 实验仪器和试剂

测试仪器：Bruker Avance 400 M 核磁共振仪用于样品的 ^{1}H NMR、^{13}C NMR 和 ^{19}F NMR 检测。Waters TOF-MS GCT Premier 质谱仪用于高分辨质谱(EI)的测试，Bruker Apex 111 傅里叶变换离子回旋共振质谱仪用于高分辨质谱(ESI)的测试。Shimadzu HPLC LC-20A 液相色谱仪用于手性样品对映体比率的测定。有机反应用薄层层析法(TLC)跟踪，紫外灯，高锰酸钾显色剂和磷钼酸显色剂进行显色检测。

原料和试剂：一般原料试剂均由商业采购之后未经过纯化直接使用，所用无水溶剂由商业购买或者根据《Purification of Laboratory Chemicals, 6th Ed》做后处理之后再进行使用。醋酸钯从小辣椒公司进行购买。手性螺环磷酸从上海大赛璐有限公司购买。

4.8.2 反应底物的合成

根据已知文献[23]报道的合成方法可以成功合成化合物 **S1**。同时化合物 **S4** 和 **S7** 也可以通过微调已知报道的合成方法被成功合成[24, 25]。

方法 A:在氮气保护和冰浴下，往化合物 **S1** 的 DMF 溶液(0.5 M)中缓慢滴加溶有 NBS(1.2 equiv)的 DMF 溶液。滴加完毕后，将反应混合物置于室温下继续反应 2 小时。反应完全后，往反应物中加入水和乙酸乙酯的混合溶液。将混合物进行分液，水相继续用乙酸乙酯萃取两次。收集有机相溶液，用饱和食盐水进行洗涤，无水硫酸钠干燥，经过减压去除溶剂得到相应的溴代粗产物。最后使用石油醚作为洗脱剂经柱层析分离提纯得到化合物 **S2**。

在配有密封塞干燥的圆底烧瓶中加入 3 mmol%的 $Ni(dppp)Cl_2$，将容器进行氮气保护。之后加入无水四氢呋喃(5.0 mL)，在室温下往反应物中缓慢滴加 DIBAL-H(1.3 equiv)，滴加

完毕后溶液颜色变成黑色。接着将反应物冷却到 0 ºC，在五分钟内往反应物中缓慢滴加相应的端炔化合物(1.0 equiv)。滴加完毕后将反应物放置到室温，继续搅拌两个小时。然后再将反应物冷却至 0 ºC，往反应物中缓慢滴加 MeO-Bpin(3.0 equiv)。之后将反应物加热到 80 ºC，保持回流状态反应 24 小时。反应完全后，使用水合硫酸钠进行淬灭。混合物用乙酸乙酯稀释和洗涤，收集好有机相溶液，用无水硫酸镁干燥后减压除去多余溶剂，经过柱层析分离提纯得到目标产物 **S4**。

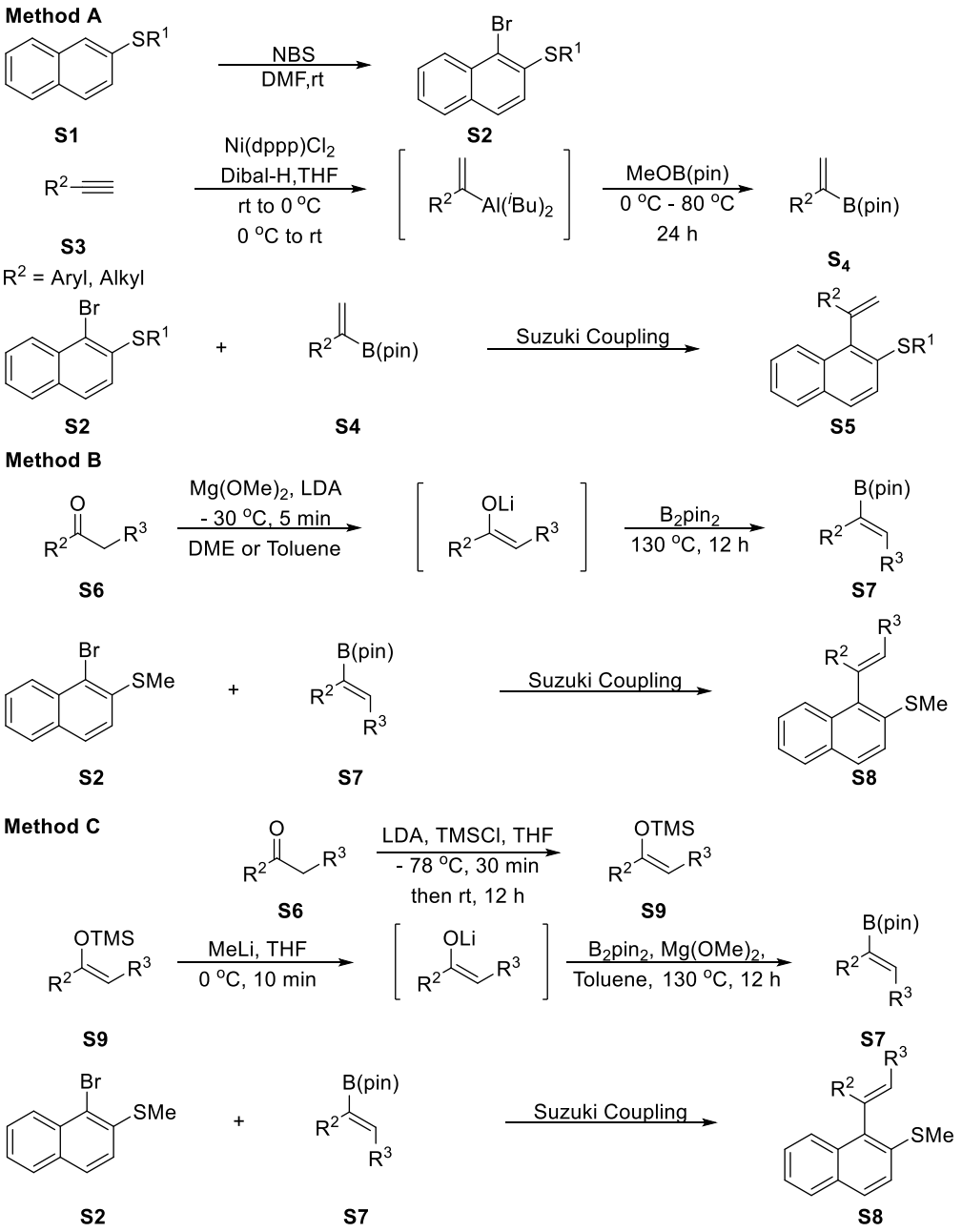
依次在 100 mL 干燥的圆底烧瓶中加入化合物 **S2**(1.0 equiv)，化合物 **S4**(1.1 equiv)，醋酸钯(10 mol%)，SPhos(20 mol%)，碳酸钾(3.0 equiv)和溶剂 THF/H_2O(4:1, 4.0 mL/mmol)。在氮气保护下，将反应物加热至回流状态，并保持 24 小时。等反应完全后，冷却到室温，用饱和氯化铵溶液进行淬灭，乙酸乙酯萃取两次。收集有机相溶液，用无水硫酸钠干燥，减压去除多余有机溶剂后经过柱层析分离提纯得到烯烃底物 **S5**。

方法 B:在氮气氛围下，往干燥的 100 mL 圆底烧瓶中加入原料酮(10 mmol)，$Mg(OMe)_2$ (1.0 equiv)和无水溶剂(DME 或 Toluene，25 mL)。将反应物冷却到-30 ºC，往反应物中滴加 LDA 溶液(1.1 equiv，2.0 M 四氢呋喃溶液)，并保持该温度搅拌 10 分钟。然后在氮气流保护下，往反应中加入 B_2pin_2(1.2 equiv)。之后将反应物加热到 130 ºC，反应 12 小时以上。等到反应完全后，冷却到室温，用乙酸乙酯稀释反应液，经减压除去溶剂后进行柱层析分离，提纯得到相应的烯烃硼酸酯化合物 **S7**。然后将得到的化合物 **S2** 和 **S7** 进行 Suzuki 偶联反应，反应条件参考方法 A。

方法 C: 在氮气氛围下，往干燥的 100 mL 圆底烧瓶中加入无水四氢呋喃(30 mL)。之后将容器冷却到-78 ºC，往反应中加入 LDA(1.1 equiv，2.0 M 四氢呋喃溶液)和相应的酮原料(10 mmol)，添加完成后，反应在该温度下搅拌 30 分钟。紧接着往反应中加入 TMSCl(1.1 equiv)，然后将反应置于室温搅拌 12 小时。等到反应完全后，用饱和氯化铵溶液淬灭，正己烷进行萃取(3 × 30 mL)。将收集到的有机相用无水硫酸钠干燥后，经减压除去多余溶剂，通过柱层析分离得到相应的烯醇硅醚 **S9**。

在氮气氛围下，往干燥的 100 mL 圆底烧瓶中加入得到的烯醇硅醚(5 mmol)和无水四氢呋喃(15.0 mL)。之后将反应冷却到 0 ºC，往反应中加入 MeLi(1.1 equiv)，继续反应 20 分钟。之后旋干溶液，在氮气流保护下依次加入 B_2pin_2(1.2 equiv)，$Mg(OMe)_2$(1.0 equiv)和无水甲苯(15.0 mL)。然后将反应物加热到 130 ºC，搅拌 12 小时。反应物冷却到室温后用饱和氯化铵溶液进行淬灭，乙酸乙酯萃取两次。收集有机相溶液，用无水硫酸钠干燥，减压去除多余有机溶剂后经过柱层析分离提纯得到烯烃硼酸酯产物 **S7**。然后将得到的化合物 **S2** 和

S7 进行 Suzuki 偶联反应，反应条件参考方法 A。



4.8.3 钯催化不对称烯烃碳氢键烯基化反应

通用方法 A：在 50 mL Schlenk 反应管中依次加入醋酸钯(1.2 mg，0.005 mmol)，手性螺环磷酸 **4-L11**(7.2 mg，0.01 mmol)，底物 **4-1**(0.1 mmol)，烯基化试剂 **4-2**(0.3 mmol)，醋酸银(33.4 mg, 0.2 mmol)，最后加入无水乙醚(1.0 mL)。于空气氛围下，在 60 ºC 中反应 24 小时。冷却到室温后，用乙酸乙酯稀释反应体系，通过硅藻土过滤，减压浓缩后经制备硅胶

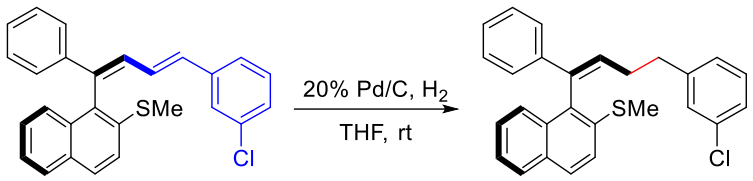
板分离后得到相对应的烯基化产物 **4-3**。

通用方法 B：在 50 mL Schlenk 反应管中依次加入醋酸钯(2.3 mg，0.01 mmol)，手性螺环磷酸 **4-L11**(7.2 mg，0.01 mmol)，底物 **4-4**(0.1 mmol)，烯基化试剂 **4-2**(0.3 mmol)，醋酸银(33.4 mg，0.2 mmol)，1-金刚烷甲酸(18.0 mg，0.1 mmol)，最后加入无水乙醚(1.0 mL)。于空气氛围下，在 60 ºC 中反应 24 小时。冷却到室温后，用乙酸乙酯稀释反应体系，通过硅藻土过滤，减压浓缩后经制备硅胶板分离后得到相对应的烯基化产物 **4-5**。

通用方法 C：在 50 mL Schlenk 反应管中依次加入醋酸钯(1.7 mg，0.0075 mmol)，手性螺环磷酸 **4-L11**(10.9 mg, 0.015 mmol)，底物 **4-6**(0.05 mmol)，烯基化试剂 **4-2**(6.0 equiv)，醋酸银(33.4 mg, 0.2 mmol)，最后加入无水乙醚(1.0 mL)。于空气氛围下，在 60 ºC 中反应 36 小时。冷却到室温后，用乙酸乙酯稀释反应体系，通过硅藻土过滤，减压浓缩后经制备硅胶板分离后得到相对应的烯基化产物 **4-7**。

4.8.4 产物衍生化

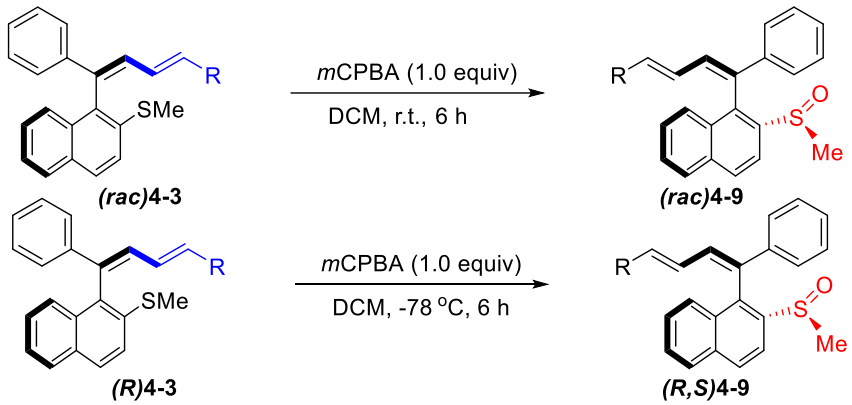
4.8.4.1 化合物 **4-8** 的合成



4-3ak, 99%, 97% ee　　**4-8,** 83%, 93% ee

在氢气流保护下，往 25 mL 圆底烧瓶中依次加入**(*R*)4-3ak**(41.2 mg, 0.1 mmol)，Pd/C(8.2 mg, 20% wt)，无水四氢呋喃(4.0 mL)。将带有氢气球的反应瓶置于室温下反应 12 小时，用饱和氯化铵溶液淬灭。之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **4-8**(34.3 mg，83% yield，93% ee)。对映体比率由手性 HPLC 测定。

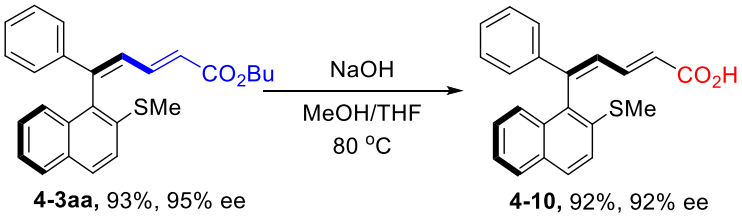
4.8.4.2 手性亚砜产物 **4-9** 的合成



消旋产物的合成(通用方法 D)：在 25 mL 圆底烧瓶中依次加入**(*rac*)4-3**(0.1 mmol)，*m*-CPBA(20.3 mg, 1.0 equiv，85% wt)，二氯甲烷(2.0 mL)。将反应置于室温，反应 2 小时后，用饱和碳酸氢钠溶液淬灭。之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物**(*rac*)4-9**。

手性产物的合成(通用方法 E)：在 25 mL 圆底烧瓶中依次加入**(*R*)4-3**(0.1 mmol)和二氯甲烷(2.0 mL)。将反应冷却到-78 ºC，滴加溶有 *m*-CPBA(20.3 mg, 1.0 eq, 85% wt)的二氯甲烷溶液，滴加完成后，保持低温再反应 12 小时。然后用饱和碳酸氢钠溶液淬灭，之后用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **4-9**。

4.8.4.3 轴手性羧酸 **4-10** 的合成

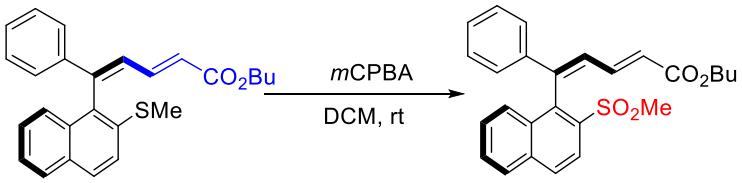


在 25 mL 圆底烧瓶中依次加入**(*R*)4-3aa**(40.2 mg, 0.1 mmol)，氢氧化钠(40.0 mg, 10.0 equiv)，MeOH/THF(2:1, 2.0 mL)。将反应置于 80 ºC 下反应过夜。用 1.0 M/L 的盐酸溶液淬灭，之后用乙酸乙酯萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到手性酸 **4-10a**(43.0 mg, 92% yield)。

之后将得到的羧酸化合物和碳酸钾(3.0 equiv)以及碘甲烷(2.0 equiv)在 THF/MeOH(2:1, 5.0 mL)中反应过夜，可以得到相应的甲基化产物 **4-10b**(28.5 mg, 88%, 92% ee)。对映体比

率由手性 HPLC 测定。

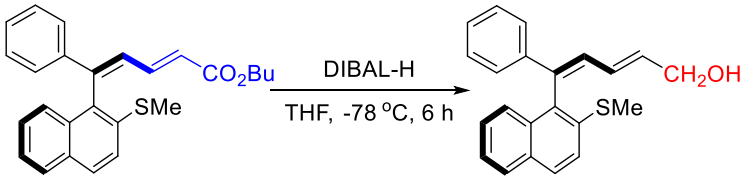
4.8.4.4 砜类化合物 **4-11** 的合成



4-3aa, 93%, 95% ee　　**4-11**, 99%, 96% ee

在 25 mL 圆底烧瓶中依次加入**(*R*)4-3aa**(40.2 mg, 0.1 mmol)，*m*-CPBA(42.6 mg, 2.05 equiv, 85% wt)，二氯甲烷(2.0 mL)。将反应置于室温下反应两个小时。之后用饱和碳酸氢钠溶液淬灭，用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **4-11**(43.0 mg, 99%, 96% ee)。对映体比率由手性 HPLC 测定。

4.8.4.5 丙烯醇化合物 **4-12** 的合成



4-3aa, 93%, 95% ee　　**4-12**, 80%, 97% ee

氮气保护下，往干燥的 25 mL 圆底烧瓶中依次加入**(*R*)4-3aa**(40.2 mg, 0.1 mmol)，无水四氢呋喃(4.0 mL)。将反应置于-78 °C，缓慢加入 DIBAL-H 溶液(5.0 equiv)。滴加完成后，反应保持低温继续搅拌 6 小时。之后用饱和氯化铵溶液淬灭，用二氯甲烷萃取三次，无水硫酸钠干燥，减压浓缩后经柱层析分离提纯得到化合物 **4-12**(26.3 mg, 80%, 97% ee)。对映体比率由手性 HPLC 测定。

4.8.4.6 铑催化的不对称加成反应

在氮气保护下，依次往干燥的 25 mL 圆底烧瓶中加入$[RhCl(C_2H_4)_2]_2$(1.5 mg, 0.0075 mmol of Rh)，化合物 **4-9**，苯硼酸 **4-14**(0.6 mmol)和无水四氢呋喃(1.0 mL)。将反应置于 40 °C 搅拌 30 分钟。之后往反应中加入环己烯酮 **4-13**(0.25 mmol)和氢氧化钾水溶液(167 μL, 0.75 M, 0.125 mmol)。反应保持 40 °C 继续搅拌 3 小时后，减压浓缩后经柱层析分离提纯得到化合物 **4-15**。

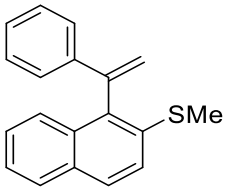
在氮气保护下，依次往干燥的 25 mL 圆底烧瓶中加入$[RhCl(C_2H_4)_2]_2$(1.5 mg, 0.0075

mmol of Rh)，化合物 **4-9**，苯硼酸 **4-14**(0.6 mmol)和无水四氢呋喃(1.0 mL)。将反应置于 40 ºC 搅拌 30 分钟。之后往反应中加入二苯基乙二酮 **4-16**(0.25 mmol)和氢氧化钾水溶液(167 μL, 0.75 M, 0.125 mmol)。反应在 60 ºC 继续搅拌 6 小时后，减压浓缩后经柱层析分离提纯得到化合物 **4-17**。

4.9 结构表征

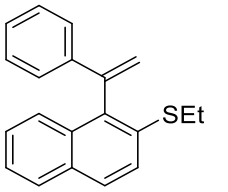
4.9.1 原料结构表征

methyl(1-(1-phenylvinyl)naphthalen-2-yl)sulfane(4-1a)



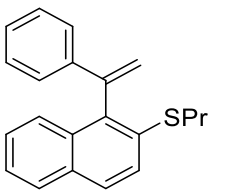
方法 A，白色固体(3 g, 56% yield for 20 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.85 (d, *J* = 8.7 Hz, 1H), 7.83 – 7.76 (m, 2H), 7.48 (d, *J* = 8.8 Hz, 1H), 7.43 – 7.35 (m, 2H), 7.31 (dd, *J* = 7.7, 2.2 Hz, 2H), 7.28 – 7.25 (m, 1H), 7.25 – 7.22 (m, 2H), 6.23 (d, *J* = 1.1 Hz, 1H), 5.33 (d, *J* = 1.1 Hz, 1H), 2.45 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.07, 139.23, 136.71, 134.71, 132.66, 131.33, 128.59, 128.31, 128.03, 127.96, 126.87, 126.29, 125.70, 125.19, 123.47, 117.87, 16.31. HRMS (EI-TOF) calcd for $C_{19}H_{16}S^{+}$ ([M]$^{+}$): 276.0973, found: 276.0974.

ethyl(1-(1-phenylvinyl)naphthalen-2-yl)sulfane(4-1b)



方法 A，白色固体(441 mg, 50% yield for 3 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 – 7.76 (m, 3H), 7.55 (d, *J* = 8.7 Hz, 1H), 7.45 – 7.36 (m, 2H), 7.32 (dq, *J* = 4.6, 2.7 Hz, 2H), 7.28 – 7.24 (m, 3H), 6.23 (s, 1H), 5.32 (s, 1H), 3.02 – 2.82 (m, 2H), 1.23 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.32, 139.52, 138.44, 133.23, 132.91, 131.68, 128.51, 128.10, 127.98, 127.85, 126.76, 126.37, 125.99, 125.46, 125.40, 117.59, 27.42, 14.44. HRMS (EI-TOF) calcd for $C_{20}H_{18}S^{+}$ ([M]$^{+}$): 290.1129, found: 290.1130.

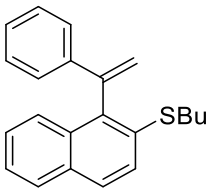
(1-(1-phenylvinyl)naphthalen-2-yl)(propyl)sulfane(4-1c)



方法 A，黄色液体(553 mg, 60% yield for 3 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.80 (dd, *J* = 8.2, 1.2 Hz, 3H), 7.53 (d, *J* = 8.7 Hz, 1H), 7.43 – 7.33 (m, 2H), 7.33 – 7.27 (m, 2H), 7.25 – 7.20 (m, 3H), 6.21 (d, *J* = 1.2 Hz, 1H), 5.29 (d, *J* = 1.1 Hz, 1H), 2.95 – 2.78 (m, 2H), 1.63 – 1.50 (m, 2H), 0.90 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.36, 139.57, 138.51, 133.44, 132.93,

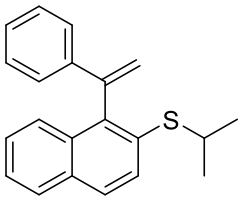
131.67, 128.50, 128.07, 127.97, 127.82, 126.76, 126.38, 126.00, 125.65, 125.38, 117.54, 35.50, 22.69, 13.55. HRMS (EI-TOF) calcd for $C_{21}H_{20}S^+$ ([M]$^+$): 304.1286, found: 304.1288.

butyl(1-(1-phenylvinyl)naphthalen-2-yl)sulfane(4-1ca)



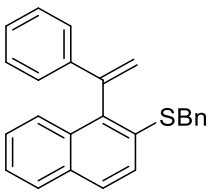
方法 A，黄色液体(497 mg, 52% yield for 3 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.85 – 7.78 (m, 3H), 7.55 (d, *J* = 8.7 Hz, 1H), 7.43 – 7.36 (m, 2H), 7.34 – 7.29 (m, 2H), 7.27 – 7.23 (m, 3H), 6.22 (d, *J* = 1.1 Hz, 1H), 5.31 (d, *J* = 1.1 Hz, 1H), 2.91 (qdd, *J* = 12.7, 8.2, 6.5 Hz, 2H), 1.58 – 1.46 (m, 2H), 1.39 – 1.28 (m, 2H), 0.84 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.35, 139.56, 138.45, 133.50, 132.91, 131.65, 128.50, 128.08, 127.98, 127.82, 126.77, 126.38, 126.00, 125.60, 125.38, 117.57, 33.17, 31.39, 22.05, 13.78. HRMS (EI-TOF) calcd for $C_{22}H_{22}S^+$ ([M]$^+$): 318.1442, found: 318.1441.

isopropyl(1-(1-phenylvinyl)naphthalen-2-yl)sulfane (4-1cb)



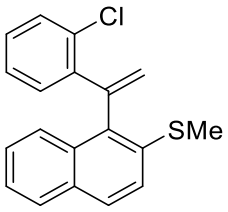
方法 A，黄色液体(600 mg, 60% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.85 – 7.76 (m, 3H), 7.58 (d, *J* = 8.7 Hz, 1H), 7.39 (dddd, *J* = 19.0, 8.2, 6.8, 1.4 Hz, 2H), 7.32 – 7.27 (m, 2H), 7.26 – 7.20 (m, 3H), 6.19 (d, *J* = 1.1 Hz, 1H), 5.26 (d, *J* = 1.1 Hz, 1H), 3.49 (hept, *J* = 6.7 Hz, 1H), 1.27 (d, *J* = 6.7 Hz, 3H), 1.13 (d, *J* = 6.6 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.59, 140.01, 139.87, 133.03, 132.94, 132.04, 128.44, 127.96, 127.81, 127.77, 126.72, 126.48, 126.35, 125.65, 117.37, 37.65, 23.34, 22.97. HRMS (ESI) calcd for $C_{21}H_{21}S^+$ ([M+H]$^+$): 305.1358, found: 305.1358.

benzyl(1-(1-phenylvinyl)naphthalen-2-yl)sulfane (4-1e)



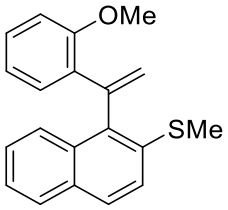
方法 A，黄色液体(656 mg, 47% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.84 – 7.75 (m, 3H), 7.56 (d, *J* = 8.7 Hz, 1H), 7.40 (dddd, *J* = 19.1, 8.2, 6.9, 1.4 Hz, 2H), 7.22 (d, *J* = 16.9 Hz, 10H), 6.18 (d, *J* = 1.1 Hz, 1H), 5.21 (d, *J* = 1.1 Hz, 1H), 4.10 (s, 2H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.27, 139.67, 139.41, 137.51, 132.87, 132.69, 132.03, 129.01, 128.52, 128.50, 128.06, 127.99, 127.80, 127.16, 126.85, 126.75, 126.40, 126.23, 125.66, 117.57, 38.78. HRMS (EI-TOF) calcd for $C_{25}H_{20}S^+$ ([M]$^+$): 352.1286, found: 352.1284.

(1-(1-(2-chlorophenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1f)



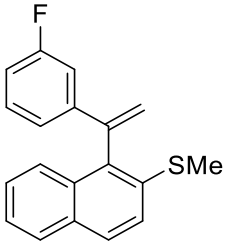
方法 A，黄色固体(365 mg, 59% yield for 2 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.01 – 7.91 (m, 1H), 7.87 – 7.78 (m, 2H), 7.51 – 7.36 (m, 4H), 7.14 (dt, *J* = 8.0, 4.5 Hz, 1H), 7.05 (d, *J* = 4.3 Hz, 2H), 6.33 (d, *J* = 1.2 Hz, 1H), 5.75 (d, *J* = 1.2 Hz, 1H), 2.48 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 141.31, 138.65, 137.82, 134.97, 132.72, 132.44, 131.44, 130.84, 130.63, 128.47, 128.34, 128.09, 127.03, 126.67, 125.60, 125.43, 125.21, 123.63, 16.45. HRMS (EI-TOF) calcd for $C_{19}H_{15}ClS^{+}$ ([M]$^{+}$): 310.0583, found: 310.0584.

(1-(1-(2-methoxyphenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1g)



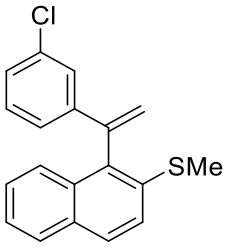
方法 A，黄色泡沫(352 mg, 12% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.94 – 7.85 (m, 1H), 7.81 (dd, *J* = 9.3, 6.4 Hz, 2H), 7.47 (d, *J* = 8.7 Hz, 1H), 7.42 – 7.34 (m, 2H), 7.23 – 7.13 (m, 1H), 6.97 (d, *J* = 8.4 Hz, 1H), 6.85 (dd, *J* = 7.7, 1.8 Hz, 1H), 6.78 – 6.68 (m, 1H), 6.51 (d, *J* = 2.0 Hz, 1H), 5.53 (d, *J* = 2.0 Hz, 1H), 3.87 (s, 3H), 2.46 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 157.98, 141.37, 138.82, 134.39, 132.75, 131.36, 130.30, 128.62, 127.93, 127.89, 126.64, 126.00, 125.04, 123.50, 122.88, 120.54, 111.69, 55.66, 16.39. HRMS (EI-TOF) calcd for $C_{20}H_{18}OS^{+}$ ([M]$^{+}$): 306.1078, found: 306.1077.

(1-(1-(3-fluorophenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1h)



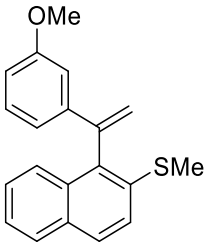
方法 A，黄色固体(432 mg, 49% yield for 3 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.90 – 7.80 (m, 2H), 7.74 (dd, *J* = 7.0, 2.6 Hz, 1H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.46 – 7.35 (m, 2H), 7.25 – 7.17 (m, 1H), 7.09 (dt, *J* = 7.8, 1.4 Hz, 1H), 7.06 – 6.88 (m, 2H), 6.25 (s, 1H), 5.39 (s, 1H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 163.21 (d, J_{CF} = 244.9 Hz), 144.12 (d, J_{CF} = 2.5 Hz), 141.71 (d, J_{CF} = 7.3 Hz), 136.02, 134.87, 132.55, 131.38, 130.01 (d, J_{CF} = 8.4 Hz), 128.58, 128.13, 127.01, 125.44, 125.30, 123.50, 122.02 (d, J_{CF} = 2.8 Hz), 119.06, 114.79 (d, J_{CF} = 21.4 Hz), 113.21 (d, J_{CF} = 22.3 Hz), 16.31. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -113.37. HRMS (EI-TOF) calcd for $C_{19}H_{15}FS^{+}$ ([M]$^{+}$): 294.0879, found: 294.0880.

(1-(1-(3-chlorophenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1i)



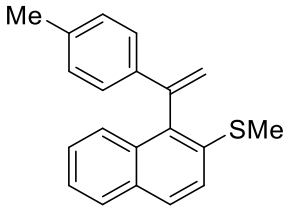
方法 A，黄色液体(660 mg, 43% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 (d, *J* = 8.8 Hz, 1H), 7.85 – 7.81 (m, 1H), 7.75 – 7.70 (m, 1H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.44 – 7.37 (m, 2H), 7.34 (t, *J* = 1.9 Hz, 1H), 7.23 (dt, *J* = 7.6, 1.8 Hz, 1H), 7.18 (t, *J* = 7.6 Hz, 1H), 7.14 (dt, *J* = 7.6, 1.7 Hz, 1H), 6.24 (d, *J* = 0.8 Hz, 1H), 5.39 (d, *J* = 0.8 Hz, 1H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 143.98, 141.24, 135.84, 134.89, 134.61, 132.52, 131.37, 129.84, 128.61, 128.15, 128.00, 127.05, 126.30, 125.41, 125.31, 124.63, 123.47, 119.27, 16.30. HRMS (EI-TOF) calcd for $C_{19}H_{15}ClS^+$ ([M]$^+$): 310.0583, found: 310.0584.

(1-(1-(3-methoxyphenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1j)



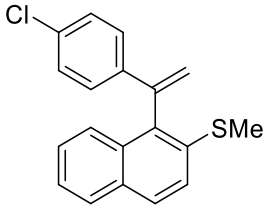
方法 A，黄色液体(780 mg, 51% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 – 7.72 (m, 3H), 7.48 (d, *J* = 8.8 Hz, 1H), 7.42 – 7.32 (m, 2H), 7.18 (t, *J* = 8.2 Hz, 1H), 6.92 – 6.85 (m, 2H), 6.80 (ddd, *J* = 8.2, 2.5, 1.1 Hz, 1H), 6.24 (d, *J* = 1.1 Hz, 1H), 5.34 (d, *J* = 1.2 Hz, 1H), 3.74 (s, 3H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.79, 144.96, 140.77, 136.64, 134.73, 132.67, 131.35, 129.55, 128.34, 128.02, 126.87, 125.69, 125.19, 123.47, 119.02, 118.18, 112.94, 112.40, 55.28, 16.35. HRMS (EI-TOF) calcd for $C_{20}H_{18}OS^+$ ([M]$^+$): 306.1078, found: 306.1079.

methyl(1-(1-(p-tolyl)vinyl)naphthalen-2-yl)sulfane(4-1k)



方法 A，黄色液体(634 mg, 55% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.91 – 7.75 (m, 3H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.45 – 7.34 (m, 2H), 7.22 (d, *J* = 8.2 Hz, 2H), 7.08 (d, *J* = 8.0 Hz, 2H), 6.22 (d, *J* = 1.1 Hz, 1H), 5.29 (d, *J* = 1.1 Hz, 1H), 2.47 (s, 3H), 2.32 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 144.84, 137.82, 136.83, 136.33, 134.63, 132.68, 131.30, 129.35, 128.21, 127.99, 126.84, 126.15, 125.74, 125.15, 123.37, 116.84, 21.32, 16.28. HRMS (EI-TOF) calcd for $C_{20}H_{18}OS^+$ ([M]$^+$): 290.1129, found: 290.1130.

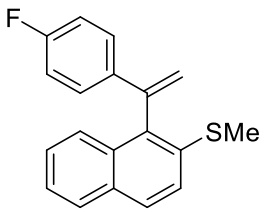
(1-(1-(4-chlorophenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1l)



方法 A，黄色液体(515 mg, 41% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 – 7.80 (m, 2H), 7.76 – 7.71 (m, 1H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.41 (ddt, *J* = 7.2, 4.6, 2.2 Hz, 2H), 7.23 (s, 4H), 6.22 (d, *J* = 0.9 Hz, 1H), 5.35 (d, *J* = 1.0 Hz, 1H), 2.47 (s, 3H). ^{13}C NMR (101

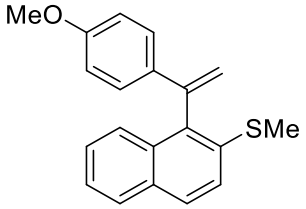
MHz, Chloroform-*d*) δ 144.00, 137.74, 136.07, 134.81, 133.78, 132.52, 131.35, 128.78, 128.53, 128.13, 127.63, 127.02, 125.43, 125.30, 123.43, 118.38, 16.28. HRMS (EI-TOF) calcd for $C_{19}H_{15}ClS^+$ ([M]$^+$): 310.0583, found: 310.0585.

(1-(1-(4-fluorophenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1m)



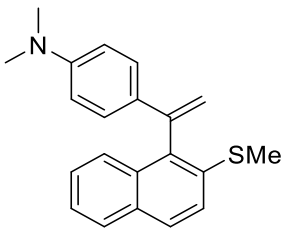
方法 A，黄色液体(484 mg, 41% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.90 – 7.80 (m, 2H), 7.80 – 7.73 (m, 1H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.45 – 7.34 (m, 2H), 7.33 – 7.24 (m, 2H), 6.99 – 6.91 (m, 2H), 6.17 (s, 1H), 5.32 (s, 1H), 2.48 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 162.65 (d, J_{CF} = 247.3 Hz), 144.05, 136.39, 135.39 (d, J_{CF} = 3.3 Hz), 134.72, 132.52, 131.36, 128.45, 128.11, 128.06, 127.98, 126.97, 125.39 (d, J_{CF} = 23.6 Hz), 123.44, 117.63, 115.48 (d, J_{CF} = 21.5 Hz), 16.27. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -114.41. HRMS (EI-TOF) calcd for $C_{19}H_{15}FS^+$ ([M]$^+$): 294.0879, found: 294.0877.

(1-(1-(4-methoxyphenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1n)



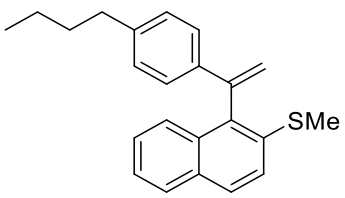
方法 A，黄色液体(490 mg, 16% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 – 7.77 (m, 3H), 7.49 (d, *J* = 8.8 Hz, 1H), 7.43 – 7.36 (m, 2H), 7.25 (d, *J* = 8.5 Hz, 2H), 6.84 – 6.77 (m, 2H), 6.14 (d, *J* = 1.1 Hz, 1H), 5.23 (d, *J* = 1.1 Hz, 1H), 3.77 (s, 3H), 2.48 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.48, 144.40, 136.87, 134.58, 132.62, 131.81, 131.30, 128.20, 128.00, 127.51, 126.83, 125.74, 125.16, 123.36, 115.74, 113.96, 55.33, 16.28. HRMS (EI-TOF) calcd for $C_{20}H_{18}OS^+$ ([M]$^+$): 306.1078, found: 306.1080.

***N,N*-dimethyl-4-(1-(2-(methylthio)naphthalen-1-yl)vinyl)aniline(4-1o)**



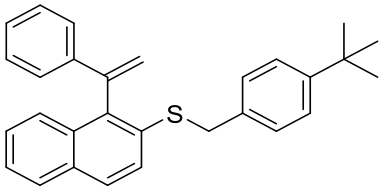
方法 A，黄色液体(715 mg, 22% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.83 (td, *J* = 8.0, 7.2, 4.7 Hz, 3H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.43 – 7.32 (m, 2H), 7.22 – 7.16 (m, 2H), 6.66 – 6.58 (m, 2H), 6.08 (d, *J* = 1.2 Hz, 1H), 5.11 (d, *J* = 1.2 Hz, 1H), 2.93 (s, 6H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 150.21, 144.63, 137.32, 134.46, 132.74, 131.25, 127.95, 127.88, 127.23, 127.13, 126.69, 125.98, 125.06, 123.31, 113.42, 112.27, 40.50, 16.28. HRMS (EI-TOF) calcd for $C_{21}H_{21}NS^+$ ([M]$^+$): 319.1395, found: 319.1396.

(1-(1-(4-butylphenyl)vinyl)naphthalen-2-yl)(methyl)sulfane(4-1p)



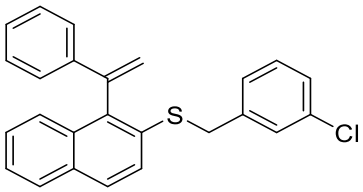
方法 A，黄色液体(830 mg, 25% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 (d, *J* = 8.8 Hz, 1H), 7.81 (ddd, *J* = 12.2, 7.6, 2.2 Hz, 2H), 7.49 (d, *J* = 8.8 Hz, 1H), 7.44 – 7.36 (m, 2H), 7.25 – 7.20 (m, 2H), 7.11 – 7.06 (m, 2H), 6.21 (d, *J* = 1.2 Hz, 1H), 5.29 (d, *J* = 1.1 Hz, 1H), 2.62 – 2.53 (m, 2H), 2.47 (s, 3H), 1.62 – 1.54 (m, 2H), 1.36 (dt, *J* = 14.9, 7.4 Hz, 2H), 0.92 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 144.95, 142.80, 136.94, 136.56, 134.61, 132.68, 131.31, 128.66, 128.20, 127.98, 126.81, 126.14, 125.81, 125.15, 123.43, 116.87, 35.49, 33.58, 22.54, 16.31, 14.09. HRMS (EI-TOF) calcd for $C_{23}H_{24}S^{+}$ ([M]$^{+}$): 332.1599, found: 332.1601.

(4-(tert-butyl)benzyl)(1-(1-phenylvinyl)naphthalen-2-yl)sulfane(4-1q)



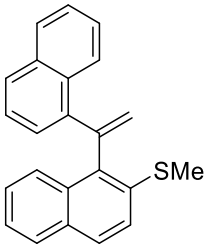
方法 A，白色固体(806 mg, 33% yield for 6 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.79 (ddd, *J* = 8.3, 4.8, 2.6 Hz, 3H), 7.57 (d, *J* = 8.7 Hz, 1H), 7.38 (dddd, *J* = 18.4, 8.3, 6.8, 1.3 Hz, 2H), 7.23 (dt, *J* = 5.1, 3.0 Hz, 7H), 7.13 (d, *J* = 8.3 Hz, 2H), 6.16 (d, *J* = 1.2 Hz, 1H), 5.20 (s, 1H), 4.07 (d, *J* = 1.6 Hz, 2H), 1.27 (s, 9H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 150.09, 145.21, 139.61, 138.98, 134.27, 133.18, 132.84, 131.94, 128.70, 128.51, 128.10, 127.99, 127.80, 126.74, 126.55, 126.40, 126.17, 125.57, 125.45, 117.59, 38.33, 34.58, 31.46. HRMS (EI-TOF) calcd for $C_{29}H_{28}S^{+}$ ([M]$^{+}$): 408.1912, found: 408.1913.

(3-chlorobenzyl)(1-(1-phenylvinyl)naphthalen-2-yl)sulfane(4-1r)



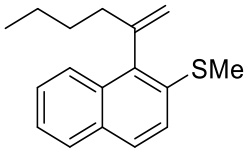
方法 A，黄色液体(832 mg, 36% yield for 6 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 – 7.81 (m, 2H), 7.79 (d, *J* = 8.8 Hz, 1H), 7.51 (d, *J* = 8.6 Hz, 1H), 7.46 – 7.42 (m, 1H), 7.41 – 7.37 (m, 1H), 7.25 (m, 4H), 7.21 – 7.14 (m, 3H), 7.11 (t, *J* = 7.7 Hz, 1H), 7.04 (dt, *J* = 7.4, 1.6 Hz, 1H), 6.20 (d, *J* = 1.0 Hz, 1H), 5.22 (d, *J* = 1.0 Hz, 1H), 4.03 (m, 2H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.19, 139.79, 139.64, 139.60, 134.28, 132.89, 132.13, 131.92, 129.67, 129.06, 128.59, 128.20, 128.02, 127.92, 127.80, 127.38, 127.11, 126.86, 126.31, 126.27, 125.85, 117.58, 38.27. HRMS (EI-TOF) calcd for $C_{25}H_{19}ClS^{+}$ ([M]$^{+}$): 386.0896, found: 386.0899.

methyl(1-(1-(naphthalen-1-yl)vinyl)naphthalen-2-yl)sulfane(4-1s)



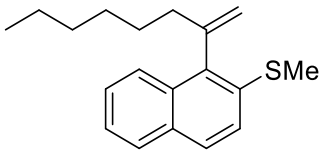
方法 A，黄色固体(750 mg, 23% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.86 (d, *J* = 8.5 Hz, 1H), 8.06 – 8.00 (m, 1H), 7.93 – 7.87 (m, 1H), 7.87 – 7.79 (m, 2H), 7.73 (d, *J* = 8.1 Hz, 1H), 7.60 (ddd, *J* = 8.5, 6.8, 1.5 Hz, 1H), 7.54 (ddd, *J* = 8.1, 6.7, 1.3 Hz, 1H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.40 (qd, *J* = 7.0, 3.5 Hz, 2H), 7.25 (t, *J* = 7.7 Hz, 1H), 7.10 (dd, *J* = 7.2, 1.2 Hz, 1H), 6.17 (d, *J* = 1.6 Hz, 1H), 5.85 (d, *J* = 1.6 Hz, 1H), 2.42 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 143.04, 138.99, 138.64, 135.29, 134.51, 133.07, 131.52, 131.18, 128.80, 128.27, 128.10, 127.92, 127.08, 126.35, 126.18, 125.84, 125.72, 125.66, 125.17, 125.13, 124.45, 123.71, 16.42. HRMS (EI-TOF) calcd for $C_{23}H_{18}S^{+}$ ([M]$^{+}$): 326.1129, found: 326.1130.

(1-(hex-1-en-2-yl)naphthalen-2-yl)(methyl)sulfane(4-1t)



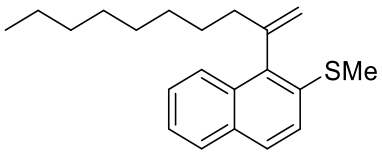
将方法 A 进行微调，制备烯基硼酸酯在 0 °C 下反应 24 小时，偶联时选择 $Pd(PPh_3)_4$ 为配体后经过柱层析得到无色液体(315 mg, 30% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.88 (d, *J* = 8.3 Hz, 1H), 7.83 – 7.73 (m, 2H), 7.50 – 7.38 (m, 3H), 5.56 (d, *J* = 1.9 Hz, 1H), 5.07 (d, *J* = 1.9 Hz, 1H), 2.53 (s, 3H), 2.44 (dq, *J* = 16.0, 8.1 Hz, 2H), 1.64 – 1.56 (m, 2H), 1.41 (p, *J* = 7.3 Hz, 2H), 0.92 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 147.31, 139.55, 132.88, 131.85, 131.47, 128.07, 127.61, 126.47, 125.52, 125.09, 123.86, 116.18, 36.76, 29.81, 22.91, 16.61, 14.19. HRMS (EI-TOF) calcd for $C_{17}H_{20}S^{+}$ ([M]$^{+}$): 256.1286, found: 256.1284.

methyl(1-(oct-1-en-2-yl)naphthalen-2-yl)sulfane(4-1u)



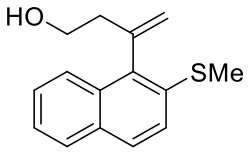
将方法 A 进行微调，制备烯基硼酸酯在 0 °C 下反应 24 小时，偶联时选择 $Pd(PPh_3)_4$ 为配体后经过柱层析得到无色液体(766mg, 45% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.90 – 7.85 (m, 1H), 7.81 – 7.73 (m, 2H), 7.48 – 7.38 (m, 3H), 5.55 (d, *J* = 1.8 Hz, 1H), 5.07 (d, *J* = 1.8 Hz, 1H), 2.52 (s, 3H), 2.43 (m, 2H), 1.64 – 1.56 (m, 2H), 1.42 – 1.33 (m, 2H), 1.31 – 1.25 (m, 4H), 0.90 – 0.85 (m, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 147.34, 139.51, 132.85, 131.82, 131.44, 128.07, 127.60, 126.47, 125.51, 125.08, 123.80, 116.15, 36.99, 31.96, 29.48, 27.60, 22.80, 16.57, 14.25. HRMS (EI-TOF) calcd for $C_{19}H_{24}S^{+}$ ([M]$^{+}$): 284.1599, found: 284.1598.

(1-(dec-1-en-2-yl)naphthalen-2-yl)(methyl)sulfane(4-1v)



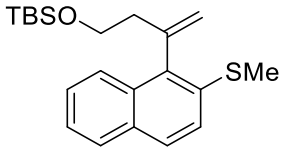
将方法 A 进行微调，制备烯基硼酸酯在 0 °C 下反应 24 小时，偶联时选择 $Pd(PPh_3)_4$ 为配体后经过柱层析得到无色液体(586 mg, 24% yield for 8 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 (dd, *J* = 8.3, 1.4 Hz, 1H), 7.82 – 7.73 (m, 2H), 7.49 – 7.38 (m, 3H), 5.56 (d, *J* = 1.7 Hz, 1H), 5.07 (d, *J* = 1.6 Hz, 1H), 2.53 (s, 3H), 2.52 – 2.35 (m, 2H), 1.66 – 1.56 (m, 2H), 1.41 – 1.33 (m, 2H), 1.32 – 1.23 (m, 8H), 0.92 – 0.84 (m, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 147.35, 139.49, 132.86, 131.82, 131.43, 128.07, 127.60, 126.47, 125.51, 125.08, 123.77, 116.15, 36.97, 32.03, 29.82, 29.69, 29.46, 27.62, 22.81, 16.57, 14.26. HRMS (EI-TOF) calcd for $C_{21}H_{28}S^+$ ($[M]^+$): 312.1912, found: 312.1912.

3-(2-(methylthio)naphthalen-1-yl)but-3-en-1-ol(4-1w)



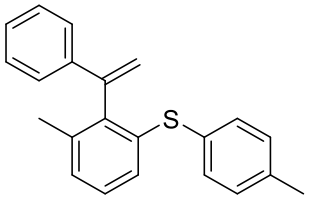
将方法 A 进行微调，制备烯基硼酸酯时使用 Dibal-H(2.3 equiv)，并在 25 °C 下反应 24 小时后经过柱层析得到黄色液体(495 mg, 40% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.85 – 7.75 (m, 3H), 7.51 – 7.42 (m, 3H), 5.71 (d, *J* = 1.8 Hz, 1H), 5.25 (d, *J* = 1.8 Hz, 1H), 3.72 – 3.50 (m, 2H), 2.84 (ddd, *J* = 14.1, 9.2, 4.8 Hz, 1H), 2.75 – 2.63 (m, 1H), 2.55 (s, 3H), 2.38 – 2.30 (br, 1H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 143.21, 137.79, 132.88, 131.63, 131.50, 128.28, 128.20, 126.84, 125.48, 125.27, 123.90, 121.16, 60.22, 41.76, 16.95. HRMS (EI-TOF) calcd for $C_{15}H_{16}OS^+$ ($[M]^+$): 244.0922, found: 244.0921.

tert-butyldimethyl((3-(2-(methylthio)naphthalen-1-yl)but-3-en-1-yl)oxy)silane(4-1x)



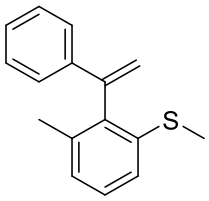
将方法 A 进行微调，制备烯基硼酸酯时在 25 °C 下反应 24 小时后经过柱层析得到黄色液体(634 mg, 30% yield for 6 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 – 7.72 (m, 3H), 7.50 – 7.36 (m, 3H), 5.58 (ddt, *J* = 6.8, 5.5, 1.4 Hz, 1H), 4.64 – 4.44 (m, 2H), 2.51 (s, 3H), 2.03 (s, 3H), 0.94 (s, 9H), 0.14 (d, *J* = 2.5 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 140.07, 133.82, 133.19, 132.71, 131.64, 131.49, 128.12, 127.60, 126.56, 125.29, 125.08, 123.77, 60.49, 26.13, 18.53, 17.68, 16.49, -4.80, -4.90. HRMS (EI-TOF) calcd for $C_{21}H_{30}OSiS^+$ ($[M]^+$): 358.1787, found: 358.1786.

(3-methyl-2-(1-phenylvinyl)phenyl)(p-tolyl)sulfane(4-1da)



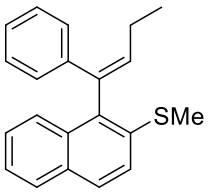
化合物合成过程如下：在氮气氛围下往 100 mL 密封管中依次加入叔丁醇钾(1.1 equiv)，Pd_2dba_3(2.5 mol %)，DPEphos(10 mol %)和溶有 2-溴-1-碘-3-甲基苯(1.0 equiv)和苯硫酚(1.0 equiv)的甲苯(0.1M)溶液。之后将反应混合物至于 100 °C 油浴中反应过夜。待反应完全后冷却到室温，将混合物用乙酸乙酯稀释后过滤得到滤液，经减压蒸馏除去多余溶剂，并经过柱层析方式分离得到粗产物。之后再 100 mL 三口烧瓶中依次加入分离得到的粗产物(1.0 equiv)，化合物 **S4**(1.1 equiv)，$Pd(OAc)_2$ (0.1 equiv)，SPhos (0.2 equiv)，K_2CO_3 (3.0 equiv)和 THF/H_2O (4/1, 4 mL/mmol)，并将容器充换氮气三次。然后将混合物加热到回流，反应 24 小时。反应完全后，冷却到室温，用饱和氯化铵水溶液淬灭，乙酸乙酯萃取后收集的有机相使用无水硫酸钠干燥。经过减压浓缩后通过柱层析(石油醚/乙酸乙酯 = 200/1 为洗脱剂)得到烯烃底物 **4-1da** 为一个黄色液体(450 mg, 71% yield for 2 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.38 – 7.27 (m, 5H), 7.25 (d, *J* = 7.8 Hz, 2H), 7.14 – 7.00 (m, 4H), 6.88 (dd, *J* = 7.5, 1.6 Hz, 1H), 6.03 (d, *J* = 1.1 Hz, 1H), 5.21 (d, *J* = 1.0 Hz, 1H), 2.34 (s, 3H), 2.15 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.90, 140.67, 138.98, 137.85, 137.81, 137.32, 133.49, 131.56, 130.12, 128.57, 127.86, 127.82, 127.64, 126.69, 126.12, 116.33, 21.31, 20.30. HRMS (ESI) calcd for $C_{22}H_{20}S^+$ ([M+H]$^+$): 317.1358, found: 305.1361.

methyl(3-methyl-2-(1-phenylvinyl)phenyl)sulfane (4-1d)



经过与 **4-1da** 合成方式相同的步骤得到黄色液体(510 mg, 43% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.27 (ddt, *J* = 15.7, 7.8, 3.9 Hz, 6H), 7.06 (dd, *J* = 17.4, 7.8 Hz, 2H), 6.03 (q, *J* = 1.1 Hz, 1H), 5.21 (q, *J* = 1.1 Hz, 1H), 2.35 (s, 3H), 2.13 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.75, 139.55, 138.68, 138.19, 136.89, 128.57, 127.90, 127.87, 126.37, 126.00, 121.93, 116.47, 20.16, 15.98. HRMS (ESI) calcd for $C_{16}H_{16}S^+$ ([M+H]$^+$): 241.1045, found: 241.1045.

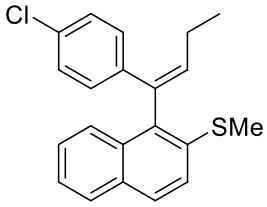
(*E*)-methyl(1-(1-phenylbut-1-en-1-yl)naphthalen-2-yl)sulfane(4-4a)



***方法* B**，白色固体(1.1 g, 64% yield for 6 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.96 (dd, *J* = 8.0, 1.6 Hz, 1H), 7.84 – 7.76 (m, 2H), 7.47 – 7.38 (m, 3H), 7.37 – 7.29 (m, 3H), 7.27 (d, *J* = 8.3 Hz, 2H), 7.23 – 7.16 (m, 1H), 5.76 (t, *J* = 7.4 Hz, 1H), 2.63 – 2.52 (m, 2H), 2.47 (s, 3H), 1.18 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 139.26, 139.09, 137.61, 136.09, 135.15, 132.96, 131.39, 129.46, 128.03, 127.95, 126.88, 126.70, 125.76, 124.90, 123.18, 23.13, 16.13, 14.48.

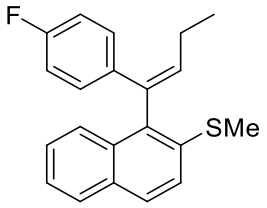
HRMS (EI-TOF) calcd for $C_{21}H_{20}S^+$ ([M]$^+$): 304.1286, found: 304.1287.

(*E*)-(1-(1-(4-chlorophenyl)but-1-en-1-yl)naphthalen-2-yl)(methyl)sulfane(4-4b)



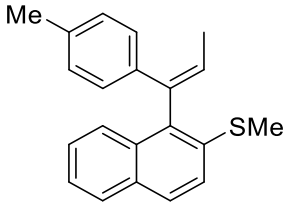
方法 B，白色固体(670 mg, 50% yield for 4 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.92 – 7.86 (m, 1H), 7.85 – 7.75 (m, 2H), 7.42 (qd, *J* = 7.1, 6.7, 1.5 Hz, 3H), 7.24 (s, 4H), 5.77 (t, *J* = 7.4 Hz, 1H), 2.59 – 2.48 (m, 2H), 2.47 (s, 3H), 1.17 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 138.48, 138.22, 137.70, 135.23, 135.03, 132.83, 132.57, 131.40, 130.78, 128.17, 128.14, 126.86, 125.47, 125.00, 123.12, 23.14, 16.07, 14.40. HRMS (EI-TOF) calcd for $C_{21}H_{19}ClS^+$ ([M]$^+$): 338.0896, found: 338.0897.

(*E*)-(1-(1-(4-fluorophenyl)but-1-en-1-yl)naphthalen-2-yl)(methyl)sulfane(4-4c)



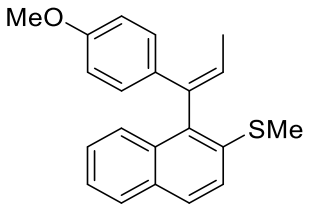
方法 B，白色固体(496 mg, 31% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.96 – 7.88 (m, 1H), 7.83 – 7.77 (m, 2H), 7.46 – 7.36 (m, 3H), 7.31 – 7.27 (m, 2H), 7.01 – 6.91 (m, 2H), 5.75 (t, *J* = 7.3 Hz, 1H), 2.59 – 2.51 (m, 2H), 2.47 (s, 3H), 1.18 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 161.67 (d, J_{CF} = 246.1 Hz), 138.77, 137.61, 135.20 (d, J_{CF} = 3.2 Hz), 135.10 (d, J_{CF} = 4.1 Hz), 132.81, 131.40, 131.05 (d, J_{CF} = 7.9 Hz), 128.10, 126.80, 125.53, 124.97, 123.14, 114.86 (d, J_{CF} = 21.1 Hz), 23.09, 16.06, 14.42. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -115.31. HRMS (EI-TOF) calcd for $C_{21}H_{19}FS^+$ ([M]$^+$): 322.1192, found: 322.1190.

(*E*)-methyl(1-(1-(p-tolyl)prop-1-en-1-yl)naphthalen-2-yl)sulfane(4-4d)



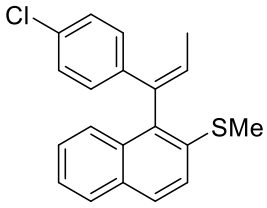
方法 B，白色固体(500 mg, 32% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.97 – 7.89 (m, 1H), 7.79 (d, *J* = 8.4 Hz, 2H), 7.40 (ddd, *J* = 12.7, 8.3, 6.1 Hz, 3H), 7.23 (d, *J* = 7.9 Hz, 2H), 7.10 (d, *J* = 7.9 Hz, 2H), 5.84 (q, *J* = 7.1 Hz, 1H), 2.47 (s, 3H), 2.32 (s, 3H), 2.13 (d, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 139.37, 137.65, 136.47, 136.09, 135.09, 133.06, 131.40, 129.43, 129.41, 128.71, 127.99, 127.88, 126.66, 125.89, 124.89, 123.14, 21.33, 16.11, 15.75. HRMS (EI-TOF) calcd for $C_{21}H_{20}S^+$ ([M]$^+$): 304.1286, found: 304.1288.

(*E*)-(1-(1-(4-methoxyphenyl)prop-1-en-1-yl)naphthalen-2-yl)(methyl)sulfane(4-4e)



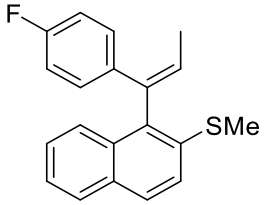
方法 B，白色固体(710 mg, 44% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.94 – 7.88 (m, 1H), 7.78 (d, *J* = 8.5 Hz, 2H), 7.44 – 7.34 (m, 3H), 7.26 – 7.23 (m, 2H), 6.82 (dd, *J* = 8.1, 1.5 Hz, 2H), 5.84 – 5.74 (m, 1H), 3.76 (d, *J* = 1.1 Hz, 3H), 2.46 (d, *J* = 1.0 Hz, 3H), 2.11 (dd, *J* = 7.1, 1.1 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 158.36, 139.43, 137.27, 135.05, 133.01, 131.53, 131.41, 130.70, 128.79, 128.00, 127.87, 126.66, 125.87, 124.90, 123.16, 113.40, 55.27, 16.12, 15.74. HRMS (EI-TOF) calcd for $C_{21}H_{20}OS^{+}$ ([M]$^{+}$): 320.1235, found: 320.1235.

(*E*)-(1-(1-(4-chlorophenyl)prop-1-en-1-yl)naphthalen-2-yl)(methyl)sulfane(4-4f)



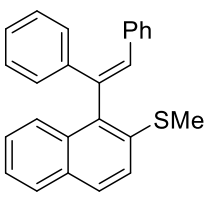
方法 B，白色固体(542 mg, 34% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.88 (d, *J* = 8.2 Hz, 1H), 7.85 – 7.73 (m, 2H), 7.42 (m, 3H), 7.26 (s, 4H), 5.90 (q, *J* = 7.1 Hz, 1H), 2.47 (s, 3H), 2.11 (d, *J* = 7.2 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 138.63, 137.46, 136.73, 135.26, 132.90, 132.53, 131.42, 130.88, 130.66, 128.19, 128.12, 126.86, 125.55, 125.03, 123.16, 16.07, 15.73. HRMS (EI-TOF) calcd for $C_{20}H_{17}ClS^{+}$ ([M]$^{+}$): 324.0740, found: 324.0739.

(*E*)-(1-(1-(4-fluorophenyl)prop-1-en-1-yl)naphthalen-2-yl)(methyl)sulfane(4-4g)



方法 B，黄色固体(641mg, 42% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.91 – 7.86 (m, 1H), 7.82 – 7.76 (m, 2H), 7.45 – 7.38 (m, 3H), 7.32 – 7.27 (m, 2H), 7.02 – 6.94 (m, 2H), 5.87 (q, *J* = 7.1 Hz, 1H), 2.47 (s, 3H), 2.10 (d, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 161.61 (d, J_{CF} = 246.1 Hz), 138.89, 136.77, 135.14, 134.93 (d, J_{CF} = 3.1 Hz), 132.88, 131.40, 131.16 (d, J_{CF} = 7.8 Hz), 130.04, 128.11, 126.80, 125.61, 125.00, 123.14, 114.88 (d, J_{CF} = 21.3 Hz), 16.07, 15.69. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -115.33. HRMS (EI-TOF) calcd for $C_{20}H_{17}FS^{+}$ ([M]$^{+}$): 308.1035, found: 308.1033.

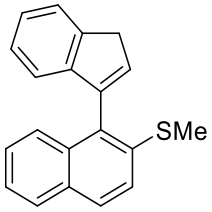
(*E*)-(1-(1,2-diphenylvinyl)naphthalen-2-yl)(methyl)sulfane(4-4h)



方法 C，黄色固体(282 mg, 16% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.06 – 8.00 (m, 1H), 7.86 – 7.78 (m, 2H), 7.47 (d, *J* = 8.7 Hz, 1H), 7.41 (tt, *J* = 6.9, 5.1 Hz, 2H), 7.33 – 7.28 (m, 4H), 7.26 – 7.20 (m, 3H), 7.17 – 7.13 (m, 3H), 6.72 (s, 1H), 2.49 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 139.08, 139.04, 138.80, 137.37, 135.37, 133.46, 132.79, 131.49, 130.04, 129.58,

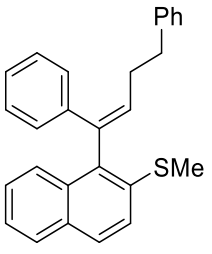
128.34, 128.30, 128.13, 127.39, 127.24, 126.94, 125.68, 125.11, 123.45, 16.25. HRMS (EI-TOF) calcd for $C_{25}H_{20}S^+$ ([M]$^+$): 352.1286, found: 352.1288.

(1-(1H-inden-3-yl)naphthalen-2-yl)(methyl)sulfane(4-4i)



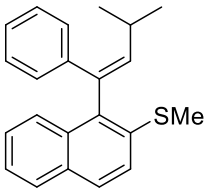
化合物合成过程如下：2,3-二氢茚酮(1.0 equiv)和 2,6-二甲基吡啶(1.2 equiv)溶解在适量二氯甲烷中，随后逐滴加入 Tf_2O(1.25 equiv)，并将反应至于室温下反应。待反应完全后加入等溶剂当量的水淬灭后使用二氯甲烷萃取，收集有机相，用无水硫酸钠干燥。将滤液旋干经快速柱层析分离得到粗产物。之后在氮气氛围下将粗产物(1.0 equiv)，联频哪醇硼酸酯(1.2 equiv)，醋酸钾(2.5 equiv)，$Pd(PPh_3)_4$ (5.0 mol%)和甲苯(10 mL/mmol)依次加入 100 mL 圆底烧瓶中，然后将混合物加热到 80 °C 反应过夜。反应完全后加水淬灭反应，然后使用乙酸乙酯进行萃取。有机相经干燥后过滤减压浓缩后经过柱层析(石油醚/乙酸乙酯 =4/1 为洗脱剂)分离得到相应的烯烃硼酸酯。之后将得到的烯烃硼酸酯进行方法 A 中描述的 Suziki 偶联反应得到黄色泡沫状产物 **4-4i**(1.08 g, 19% yield for 20 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.90 (d, *J* = 8.7 Hz, 1H), 7.88 – 7.83 (m, 1H), 7.64 – 7.59 (m, 2H), 7.54 (d, *J* = 8.8 Hz, 1H), 7.42 (ddd, *J* = 8.1, 6.8, 1.3 Hz, 1H), 7.34 (ddd, *J* = 8.3, 6.7, 1.4 Hz, 1H), 7.28 - 7.24 (td, *J* = 7.4 Hz, 1H), 7.20 (td, *J* = 7.5, 1.1 Hz, 1H), 6.89 – 6.84 (m, 1H), 6.65 (t, *J* = 2.1 Hz, 1H), 3.75 (t, *J* = 1.6 Hz, 2H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.29, 143.87, 141.83, 135.49, 135.08, 132.73, 131.29, 131.13, 128.49, 128.09, 126.64, 126.33, 125.73, 125.22, 125.08, 124.05, 123.43, 120.69, 38.95, 16.40. HRMS (EI-TOF) calcd for $C_{20}H_{16}S^+$ ([M]$^+$): 288.0973, found: 288.0971.

(*E*)-(1-(1,4-diphenylbut-1-en-1-yl)naphthalen-2-yl)(methyl)sulfane(4-4j)



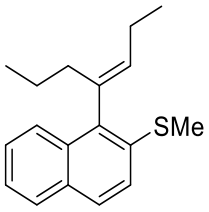
方法 B，黄色液体(972 mg, 26% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-d) δ 7.82 – 7.73 (m, 3H), 7.43 (d, *J* = 8.8 Hz, 1H), 7.40 – 7.35 (m, 2H), 7.33 – 7.29 (m, 2H), 7.27 (d, *J* = 2.7 Hz, 3H), 7.25 – 7.18 (m, 5H), 5.84 – 5.77 (m, 1H), 2.97 – 2.85 (m, 4H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 141.78, 139.09, 139.03, 137.47, 135.04, 134.77, 132.89, 131.36, 129.46, 128.80, 128.51, 127.99, 127.94, 126.96, 126.74, 126.04, 125.83, 124.91, 123.22, 36.04, 31.43, 16.16. HRMS (EI-TOF) calcd for $C_{27}H_{24}S^+$ ([M]$^+$): 380.1599, found: 380.1597.

(*E*)-methyl(1-(3-methyl-1-phenylbut-1-en-1-yl)naphthalen-2-yl)sulfane(4-4k)



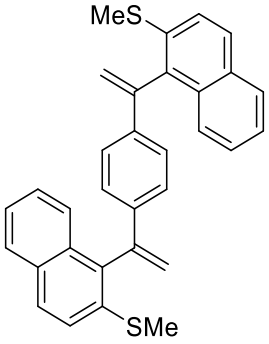
方法 B，白色固体(1.06 g, 34% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.96 (d, *J* = 8.2 Hz, 1H), 7.79 (d, *J* = 8.7 Hz, 2H), 7.45 – 7.38 (m, 3H), 7.37 – 7.33 (m, 2H), 7.29 (d, *J* = 7.4 Hz, 2H), 7.24 – 7.17 (m, 1H), 5.57 (d, *J* = 10.4 Hz, 1H), 3.09 (dp, *J* = 10.4, 6.5 Hz, 1H), 2.47 (s, 3H), 1.20 (t, *J* = 6.6 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-d) δ 143.05, 139.54, 139.07, 135.16, 134.25, 132.87, 131.40, 129.35, 128.04, 127.99, 127.95, 126.85, 126.70, 125.67, 124.87, 123.20, 28.42, 23.45, 23.02, 16.12. HRMS (EI-TOF) calcd for $C_{22}H_{22}S^{+}$ ([M]$^{+}$): 318.1442, found: 318.1440.

(*E*)-(1-(hept-3-en-4-yl)naphthalen-2-yl)(methyl)sulfane(4-4l)



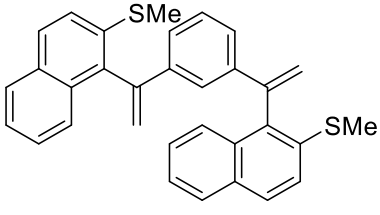
方法 C，无色液体(320 mg, 12% yield for 10 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.88 (dd, *J* = 8.3, 1.4 Hz, 1H), 7.80 – 7.69 (m, 2H), 7.45 – 7.36 (m, 3H), 5.43 (t, *J* = 7.2 Hz, 1H), 2.53 - 2.46 (m, 5H), 2.37 (p, *J* = 7.5 Hz, 2H), 1.37 (dp, *J* = 9.0, 7.4 Hz, 2H), 1.14 (t, *J* = 7.5 Hz, 3H), 0.87 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 139.95, 136.32, 134.96, 134.01, 132.66, 131.40, 128.04, 127.32, 126.17, 125.90, 124.84, 123.39, 34.71, 22.08, 21.74, 16.31, 14.91, 14.37. HRMS (EI-TOF) calcd for $C_{18}H_{22}S^{+}$ ([M]$^{+}$): 270.1442, found: 270.1440.

1,4-bis(1-(2-(methylthio)naphthalen-1-yl)vinyl)benzene(4-6a)



方法 A，黄色固体(390 mg, 16% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.80 (ddd, *J* = 10.0, 8.1, 1.9 Hz, 4H), 7.76 – 7.71 (m, 2H), 7.45 (dd, *J* = 8.7, 4.0 Hz, 2H), 7.40 – 7.34 (m, 4H), 7.21 (s, 4H), 6.20 (d, *J* = 4.8 Hz, 2H), 5.33 – 5.28 (d, *J* = 4.8 Hz, 2H), 2.45 (s, 3H), 2.44 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 144.68, 144.67, 138.63, 138.58, 136.55, 136.53, 134.65, 134.61, 132.55, 132.54, 131.26, 128.27, 127.98, 126.81, 126.41, 125.74, 125.15, 123.36, 117.78, 16.28. HRMS (EI-TOF) calcd for $C_{32}H_{26}S_{2}^{+}$ ([M]$^{+}$): 474.1476, found: 474.1476.

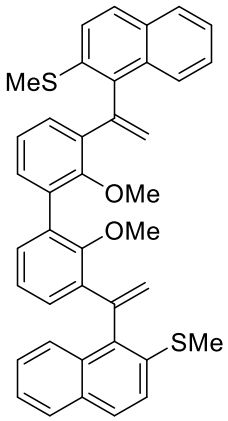
1,3-bis(1-(2-(methylthio)naphthalen-1-yl)vinyl)benzene(4-6b)



方法 A，白色泡沫(568 mg, 24% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.76 (td, *J* = 7.9, 6.3 Hz, 4H), 7.70 – 7.62 (m, 2H), 7.42 – 7.29 (m, 4H), 7.32 – 7.25 (m, 3H), 7.27 – 7.15 (m, 3H), 6.14 (dd, *J* = 14.8, 1.1 Hz, 2H), 5.26 (s, 2H), 2.36 (s, 3H), 2.15 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.02, 144.85, 139.27, 139.06,

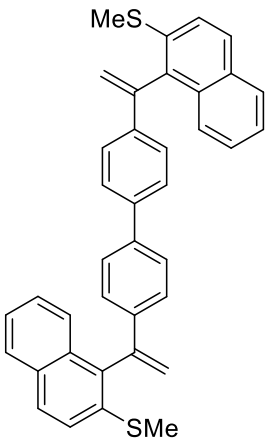
136.83, 136.69, 134.58, 134.44, 132.41, 132.38, 131.22, 128.63, 128.60, 128.17, 128.07, 127.88, 126.68, 125.69, 125.59, 125.42, 125.11, 125.07, 124.83, 124.66, 123.57, 117.70, 117.51, 16.46, 16.22. HRMS (EI-TOF) calcd for $C_{32}H_{26}S_2^+$ ([M]$^+$): 474.1476, found: 474.1474.

(((2,2'-dimethoxy-[1,1'-biphenyl]-3,3'-diyl)bis(ethene-1,1-diyl))bis(naphthalene-2,1-diyl))bis(methylsulfane)(4-6c)



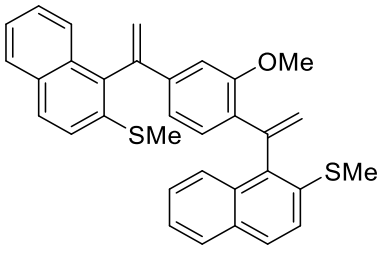
方法 A，黄色固体(732 mg, 17% yield for 7.2 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.03 (dt, *J* = 6.3, 3.3 Hz, 2H), 7.87 – 7.80 (m, 4H), 7.48 (d, *J* = 8.8 Hz, 2H), 7.42 (ddd, *J* = 6.9, 4.8, 2.5 Hz, 4H), 7.29 (t, *J* = 4.7 Hz, 2H), 6.93 (d, *J* = 6.8 Hz, 4H), 6.64 – 6.54 (m, 2H), 5.54 (t, *J* = 2.2 Hz, 2H), 3.36 (s, 6H), 2.45 (s, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 156.18, 141.96, 139.04, 134.20, 133.16, 133.11, 133.05, 132.94, 131.55, 131.42, 129.93, 128.05, 127.95, 126.70, 126.20, 125.19, 124.07, 123.41, 122.92, 122.88, 59.35, 16.63. HRMS (EI-TOF) calcd for $C_{40}H_{34}O_2S_2^+$ ([M]$^+$): 610.2000, found: 610.1998.

4,4'-bis(1-(2-(methylthio)naphthalen-1-yl)vinyl)-1,1'-biphenyl(4-6d)



方法 A，黄色固体(862 mg, 31% yield for 5 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 (d, *J* = 8.8 Hz, 2H), 7.84 – 7.78 (m, 4H), 7.52 – 7.45 (m, 6H), 7.42 – 7.38 (m, 4H), 7.37 – 7.33 (m, 4H), 6.28 (d, *J* = 1.1 Hz, 2H), 5.35 (d, *J* = 1.0 Hz, 2H), 2.47 (s, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 144.59, 140.15, 138.11, 136.54, 134.72, 132.63, 131.32, 128.35, 128.05, 127.13, 126.91, 126.63, 125.67, 125.22, 123.42, 117.80, 16.30. HRMS (EI-TOF) calcd for $C_{38}H_{30}S_2^+$ ([M]$^+$): 550.1789, found: 550.1789.

(((2-methoxy-1,4-phenylene)bis(ethene-1,1-diyl))bis(naphthalene-2,1-diyl))bis(methylsulfane)(4-6e)

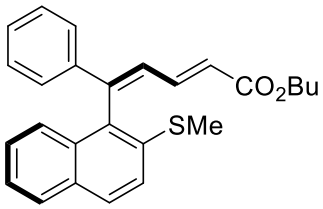


方法 A，黄色泡沫(544 mg, 12% yield for 9 mmol scale)。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.84 – 7.73 (m, 6H), 7.43 (m, 3H), 7.36 (m, 3H), 7.05 (dd, *J* = 23.0, 1.7 Hz, 1H), 6.65 (dd, *J* = 9.7, 8.1 Hz, 1H), 6.57 – 6.47 (m, 2H), 6.20 (dd, *J* = 5.7, 1.1 Hz, 1H), 5.49 (t, *J* = 2.1 Hz, 1H), 5.31 (d, *J* = 1.2 Hz, 1H), 3.79 (d, *J*

= 15.4 Hz, 3H), 2.46 – 2.42 (m, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 158.10, 144.91, 141.15, 139.44, 139.34, 138.68, 136.59, 134.65, 134.34, 132.64, 131.30, 131.25, 130.29, 128.29, 127.95, 127.90, 127.85, 126.79, 126.61, 126.02, 125.78, 125.16, 125.01, 123.44, 122.84, 118.96, 118.87, 117.83, 109.29, 109.10, 55.55, 16.36, 16.35. HRMS (EI-TOF) calcd for $C_{33}H_{28}OS_2^+$ ([M]$^+$): 504.1582, found: 504.1582.

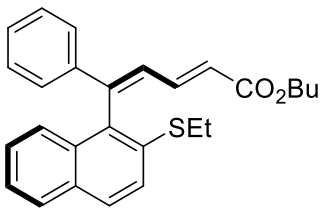
4.9.2 产物结构表征

(*R*)-(2*E*,4*Z*)-butyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3aa)



根据通用方法 A 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 20/1 为展开剂)(38.3 mg, 94%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 5.9 min (major), t = 7.0 min (minor), 95% ee. $[\alpha]_D^{20}$ = 44.1 (c = 0.67, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 (d, *J* = 8.7 Hz, 1H), 7.83 (d, *J* = 7.3 Hz, 1H), 7.53 (d, *J* = 8.3 Hz, 1H), 7.49 (d, *J* = 8.8 Hz, 1H), 7.41 – 7.36 (m, 1H), 7.36 – 7.33 (m, 1H), 7.31 (dd, *J* = 6.9, 3.0 Hz, 2H), 7.28 – 7.19 (m, 4H), 6.83 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.07 (d, *J* = 15.1 Hz, 1H), 4.00 (t, *J* = 6.6 Hz, 2H), 2.43 (s, 3H), 1.51 (dq, *J* = 8.3, 6.6 Hz, 2H), 1.26 (h, *J* = 7.4 Hz, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-d) δ 167.04, 146.37, 141.67, 138.74, 135.49, 132.71, 132.48, 131.36, 129.10, 128.86, 128.78, 128.25, 127.71, 127.33, 126.84, 125.39, 125.21, 123.37, 123.23, 64.20, 30.74, 19.21, 16.03, 13.78. HRMS (EI-TOF) calcd for $C_{26}H_{26}O_2S^+$ ([M]$^+$): 402.1654, found: 402.1653.

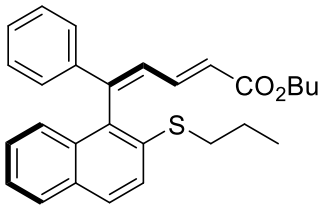
***(R)*-(2*E*,4*Z*)-butyl 5-(2-(ethylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ba)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(30.9 mg, 72%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 6.0 min (major), t = 5.7 min (minor), 92% ee. $[\alpha]_D^{20}$ = 85.6 (c = 1.053, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 (dd, *J* = 8.8, 0.8 Hz, 1H), 7.83 (d, *J* = 7.4 Hz, 1H), 7.55 (d, *J* = 8.7 Hz, 2H), 7.40 (ddd, *J* = 8.1, 6.8, 1.3 Hz, 1H), 7.36 – 7.33 (m, 1H), 7.32 – 7.28 (m, 2H), 7.27 – 7.24 (m, 3H), 7.21 (dd, *J* = 11.5, 0.7 Hz, 1H), 6.83 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.06 (dd, *J* = 15.2, 0.7 Hz, 1H), 4.00 (td, *J* = 6.6, 2.1 Hz, 2H), 2.92 (q, *J* = 7.3 Hz, 2H), 1.51 (dq, *J* = 8.4, 6.7 Hz, 2H), 1.30 – 1.22 (m, 2H), 1.19 (t, *J* = 7.4 Hz, 3H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.05, 146.68, 141.78, 138.99, 134.30, 134.11,

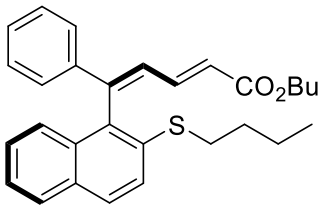
132.70, 131.66, 128.90, 128.79, 128.73, 128.21, 127.44, 127.25, 126.90, 125.59, 125.48, 125.15, 123.04, 64.17, 30.72, 27.11, 19.20, 14.49, 13.78. HRMS (EI-TOF) calcd for $C_{27}H_{28}O_2S^+$ ([M]$^+$): 416.1810, found: 416.1809.

***(R)*-(2*E*,4*Z*)-butyl 5-phenyl-5-(2-(propylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3ca)**



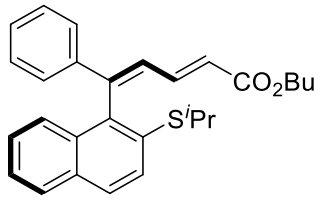
根据通用方法 A 使用 **L13** 为配体经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(33.4 mg, 77%)。手性 HPLC 分离条件： a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 6.1 min (major), t = 4.9 min (minor), 91% ee. $[\alpha]_D^{20}$ = 65.6 (c = 1.093, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 (dd, *J* = 8.7, 1.5 Hz, 1H), 7.83 (d, *J* = 8.3 Hz, 1H), 7.55 (dt, *J* = 8.5, 2.1 Hz, 2H), 7.43 – 7.38 (m, 1H), 7.37 – 7.33 (m, 1H), 7.33 – 7.28 (m, 2H), 7.28 – 7.25 (m, 3H), 7.21 (dd, *J* = 11.6, 1.6 Hz, 1H), 6.82 (ddd, *J* = 15.2, 11.4, 1.7 Hz, 1H), 6.06 (dd, *J* = 15.3, 1.5 Hz, 1H), 4.00 (td, *J* = 6.6, 1.5 Hz, 2H), 2.87 (td, *J* = 7.4, 2.0 Hz, 2H), 1.56 – 1.47 (m, 4H), 1.31 – 1.20 (m, 2H), 0.86 (dtd, *J* = 16.7, 7.4, 1.7 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.01, 146.74, 141.79, 139.00, 134.36, 134.29, 132.68, 131.63, 128.85, 128.75, 128.70, 128.19, 127.42, 127.23, 126.89, 125.56, 125.46, 125.34, 122.96, 64.13, 35.13, 30.71, 22.69, 19.18, 13.77, 13.46. HRMS (EI-TOF) calcd for $C_{28}H_{30}O_2S^+$ ([M]$^+$): 430.1967, found: 430.1967.

***(R)*-(2*E*,4*Z*)-butyl 5-(2-(butylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3caa)**



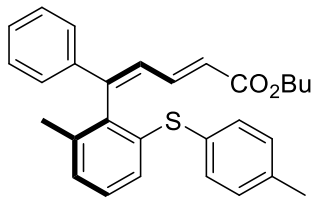
根据通用方法 A 使用 **L13** 为配体经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(35.9 mg, 81%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 96/4, flow = 0.6 mL/min, 254 nm), t = 10.3 min (major), t = 11.0 min (minor), 90% ee. $[\alpha]_D^{20}$ = 53.6 (c = 0.633, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 (d, *J* = 8.7 Hz, 1H), 7.83 (d, *J* = 8.1 Hz, 1H), 7.55 (dd, *J* = 8.7, 2.2 Hz, 2H), 7.40 (ddd, *J* = 8.1, 6.8, 1.3 Hz, 1H), 7.37 – 7.33 (m, 1H), 7.32 – 7.28 (m, 2H), 7.27 – 7.23 (m, 3H), 7.21 (d, *J* = 11.5 Hz, 1H), 6.82 (ddt, *J* = 14.1, 11.5, 1.2 Hz, 1H), 6.06 (d, *J* = 15.2 Hz, 1H), 4.00 (t, *J* = 6.6 Hz, 2H), 2.88 (tt, *J* = 8.6, 4.3 Hz, 2H), 1.50 (dp, *J* = 9.3, 6.9 Hz, 4H), 1.36 – 1.18 (m, 4H), 0.83 (dt, *J* = 10.2, 7.3 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.03, 146.77, 141.81, 139.05, 134.40, 134.38, 132.70, 131.66, 128.88, 128.76, 128.71, 128.21, 127.46, 127.25, 126.92, 125.59, 125.49, 125.41, 122.99, 77.16, 64.16, 32.91, 31.43, 30.73, 22.01, 19.20, 13.79, 13.70. HRMS (EI-TOF) calcd for $C_{29}H_{32}O_2S^+$ ([M]$^+$): 444.2123, found: 444.2125.

(*R*)-butyl (2*E*,4*Z*)-5-(2-(isopropylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3cab)



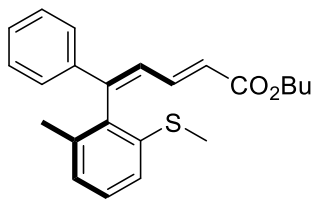
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(34.5 mg, 80%)。手性 HPLC 分离条件：an AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 5.1 min (major), t = 4.7 min (minor), 53% ee. $[\alpha]_D^{20}$ = 45.4 (c = 0.93, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.84 (t, *J* = 8.7 Hz, 2H), 7.59 (dd, *J* = 15.0, 8.5 Hz, 2H), 7.45 – 7.37 (m, 1H), 7.37 – 7.33 (m, 1H), 7.33 – 7.28 (m, 2H), 7.27 – 7.14 (m, 4H), 6.80 (ddd, *J* = 15.2, 11.6, 1.1 Hz, 1H), 6.05 (d, *J* = 15.2 Hz, 1H), 4.10 – 3.84 (m, 2H), 3.52 (p, *J* = 6.7 Hz, 1H), 1.50 (p, *J* = 6.9 Hz, 2H), 1.33 – 1.17 (m, 5H), 1.13 (dd, *J* = 6.6, 1.0 Hz, 3H), 0.93 – 0.77 (m, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.03, 146.97, 141.85, 139.27, 135.69, 133.94, 132.78, 131.96, 128.77, 128.72, 128.67, 128.18, 127.22, 126.99, 125.83, 125.79, 122.85, 64.16, 37.33, 30.74, 23.21, 23.18, 19.21, 13.80. HRMS (ESI) calcd for $C_{28}H_{30}O_2S^+$ ($[M+H]^+$): 431.2039, found: 431.2039.

(*R*)-butyl (2*E*,4*Z*)-5-(2-methyl-6-(p-tolylthio)phenyl)-5-phenylpenta-2,4-dienoate (4-3daa)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(29.3 mg, 67%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 5.2 min (major), t = 4.6 min (minor), 74% ee. $[\alpha]_D^{20}$ = -150.4 (c = 1.0, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.39 – 7.29 (m, 5H), 7.21 (d, *J* = 8.1 Hz, 2H), 7.14 (t, *J* = 7.7 Hz, 1H), 7.08 (dd, *J* = 7.7, 5.7 Hz, 3H), 7.01 – 6.88 (m, 3H), 6.02 (dd, *J* = 13.2, 1.2 Hz, 1H), 4.10 (td, *J* = 6.6, 2.1 Hz, 2H), 2.30 (s, 3H), 2.06 (s, 3H), 1.66 – 1.55 (m, 2H), 1.42 – 1.29 (m, 2H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.19, 147.27, 141.56, 138.43, 138.03, 137.48, 136.98, 133.65, 130.93, 130.10, 128.83, 128.79, 128.57, 127.94, 127.24, 126.63, 126.21, 122.75, 64.27, 30.85, 21.28 , 20.10, 19.32, 13.90. HRMS (ESI) calcd for $C_{29}H_{30}O_2S^+$ ($[M+H]^+$): 443.2039, found: 443.2037.

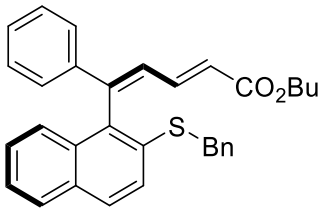
(*R*)-butyl (2*E*,4*Z*)-5-(2-methyl-6-(methylthio)phenyl)-5-phenylpenta-2,4-dienoate (4-3da)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(27.1 mg, 74%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 5.1 min (major), t = 6.4 min (minor), 96% ee. $[\alpha]_D^{20}$ = -97.1 (c = 1.02,

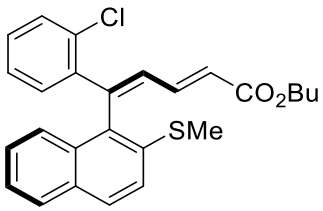
$CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.34 – 7.25 (m, 6H), 7.12 – 6.93 (m, 4H), 6.07 (d, *J* = 14.3 Hz, 1H), 4.08 (t, *J* = 6.6 Hz, 2H), 2.32 (s, 3H), 2.04 (s, 3H), 1.58 (q, *J* = 6.9 Hz, 2H), 1.40 – 1.28 (m, 2H), 0.90 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.25, 147.21, 141.62, 138.29, 138.08, 137.04, 135.61, 128.88, 128.80, 128.63, 126.54, 126.34, 122.99, 122.17, 64.29, 30.80, 19.94, 19.29, 15.76, 13.87. HRMS (ESI) calcd for $C_{23}H_{26}O_2S^+$ ($[M+H]^+$): 367.1726, found: 367.1730.

***(R)*-(2*E*,4*Z*)-butyl 5-(2-(benzylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ea)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(29.7 mg, 61%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 94/6, flow = 0.8 mL/min, 254 nm), t = 12.5 min (major), t = 13.4 min (minor), 90% ee. $[\alpha]_D^{20}$ = 65.2 (c = 0.966, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.85 – 7.70 (m, 2H), 7.54 (dd, *J* = 11.1, 8.5 Hz, 2H), 7.40 (ddd, *J* = 8.2, 6.8, 1.4 Hz, 1H), 7.33 (ddd, *J* = 8.3, 6.8, 1.4 Hz, 1H), 7.27 – 7.21 (m, 6H), 7.18 (d, *J* = 3.5 Hz, 5H), 6.81 (dd, *J* = 15.2, 11.6 Hz, 1H), 6.06 (d, *J* = 15.2 Hz, 1H), 4.12 – 4.03 (m, 2H), 4.01 (t, *J* = 6.6 Hz, 2H), 1.56 – 1.46 (m, 2H), 1.31 – 1.17 (m, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.04, 146.67, 141.70, 139.09, 137.18, 135.07, 133.69, 132.62, 131.97, 128.99, 128.85, 128.75, 128.73, 128.55, 128.23, 127.67, 127.27, 127.23, 126.94, 126.43, 125.84, 125.67, 123.10, 64.22, 38.28, 30.74, 19.21, 13.80. HRMS (EI-TOF) calcd for $C_{32}H_{30}O_2S^+$ ($[M]^+$): 478.1967, found: 478.1965.

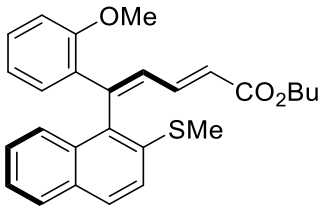
***(R)*-(2*E*,4*E*)-butyl 5-(2-chlorophenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3fa)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(33.2 mg, 75%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 6.1 min (major), t = 7.9 min (minor), 92% ee. $[\alpha]_D^{20}$ = 140.9 (c = 0.966, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.88 (d, *J* = 8.7 Hz, 1H), 7.84 – 7.79 (m, 1H), 7.73 – 7.67 (m, 1H), 7.48 (dd, *J* = 9.1, 1.3 Hz, 2H), 7.44 – 7.36 (m, 2H), 7.24 (d, *J* = 11.6 Hz, 1H), 7.14 (ddd, *J* = 8.0, 6.9, 2.0 Hz, 1H), 7.05 – 6.96 (m, 2H), 6.88 (dd, *J* = 15.2, 11.6 Hz, 1H), 6.10 (d, *J* = 15.2 Hz, 1H), 4.03 (t, *J* = 6.6 Hz, 2H), 2.48 (s, 3H), 1.53 (dq, *J* = 8.5, 6.7 Hz, 2H), 1.36 – 1.22 (m, 2H), 0.86 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.98, 142.28, 141.33, 138.10, 136.00, 134.69, 132.65, 132.59, 131.40, 131.10, 130.95, 129.31, 128.94,

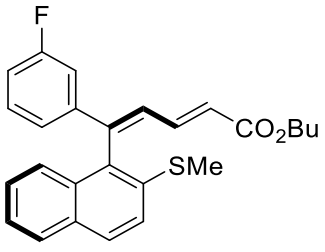
128.28, 127.53, 126.77, 125.43, 125.15, 124.08, 123.40, 64.25, 30.72, 19.20, 16.12, 13.79. HRMS (EI-TOF) calcd for $C_{26}H_{25}ClO_2S^+$ ([M]$^+$): 436.1264, found: 436.1265.

(*R*)-(2*E*,4*Z*)-butyl 5-(2-methoxyphenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3ga)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(30.5 mg, 69%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.2 mL/min, 254 nm), t = 4.2 min (major), t = 5.3 min (minor), 95% ee. $[\alpha]_D^{20}$ = 126.2 (c = 0.8, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 (d, *J* = 8.8 Hz, 1H), 7.81 (dd, *J* = 7.5, 1.8 Hz, 1H), 7.62 (dd, *J* = 7.8, 1.7 Hz, 1H), 7.56 (d, *J* = 11.8 Hz, 1H), 7.48 (d, *J* = 8.7 Hz, 1H), 7.42 – 7.31 (m, 2H), 7.20 (ddd, *J* = 8.8, 7.3, 1.8 Hz, 1H), 6.98 (dd, *J* = 8.3, 1.1 Hz, 1H), 6.88 – 6.75 (m, 2H), 6.70 (td, *J* = 7.6, 1.1 Hz, 1H), 6.03 (d, *J* = 15.2 Hz, 1H), 3.99 (t, *J* = 6.6 Hz, 2H), 3.93 (s, 3H), 2.46 (s, 3H), 1.55 – 1.45 (m, 2H), 1.32 – 1.16 (m, 2H), 0.85 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.28, 158.18, 142.99, 142.67, 135.42, 134.38, 132.68, 132.26, 131.34, 130.79, 129.44, 128.80, 128.13, 127.72, 127.17, 125.49, 125.26, 123.32, 122.64, 120.72, 111.79, 64.06, 55.77, 30.75, 19.22, 16.06, 13.80. HRMS (EI-TOF) calcd for $C_{27}H_{28}O_3S^+$ ([M]$^+$): 432.1759, found: 432.1760.

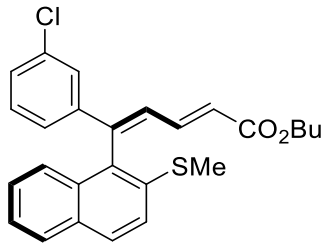
(*R*)-(2*E*,4*Z*)-butyl 5-(3-fluorophenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3ha)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(38.1 mg, 92%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 8.2 min (major), t = 6.5 min (minor), 97% ee. $[\alpha]_D^{20}$ = 97.8 (c = 1.047, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.92 (d, *J* = 8.7 Hz, 1H), 7.88 – 7.81 (m, 1H), 7.51 (d, *J* = 8.7 Hz, 2H), 7.39 (dddd, *J* = 19.9, 8.3, 6.8, 1.4 Hz, 2H), 7.25 – 7.19 (m, 2H), 7.11 (dt, *J* = 8.0, 1.2 Hz, 1H), 7.03 – 6.91 (m, 2H), 6.83 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.12 (dd, *J* = 15.3, 0.7 Hz, 1H), 4.02 (t, *J* = 6.6 Hz, 2H), 2.46 (s, 3H), 1.53 (dq, *J* = 8.5, 6.6 Hz, 2H), 1.35 – 1.16 (m, 2H), 0.86 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.90, 163.21 (d, J_{CF} = 246.4 Hz), 145.02 (d, J_{CF} = 3.0), 141.24, 141.15 (d, J_{CF} = 7.1 Hz), 135.64, 132.35, 131.93, 131.36, 130.21 (d, J_{CF} = 8.1 Hz), 129.35, 128.77, 128.36, 127.48, 125.48, 124.92, 124.08, 123.23, 122.51 (d, J_{CF} = 3.0 Hz), 115.68 (d, J_{CF} = 21.2 Hz), 113.63 (d, J_{CF} = 22.2

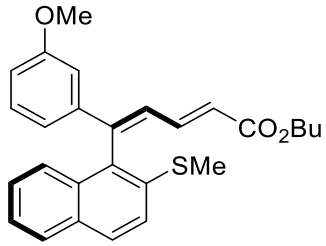
Hz), 64.30, 30.70, 19.20, 15.95, 13.78. ^{19}F NMR (376 MHz, Chloroform-d) δ -113.90. HRMS (EI-TOF) calcd for $C_{26}H_{25}FO_2S^+$ ([M]$^+$): 420.1559, found: 420.1560.

(*R*)-(2*E*,4*Z*)-butyl 5-(3-chlorophenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3ia)



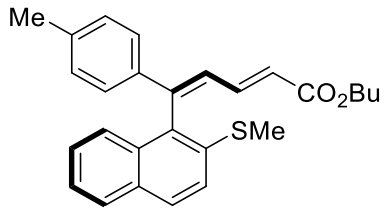
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(31.8 mg, 71%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 7.5 min (major), t = 6.2 min (minor), 97% ee. $[\alpha]_D^{20}$ = 89.7 (c = 0.833, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.92 (d, *J* = 8.8 Hz, 1H), 7.85 (dd, *J* = 8.0, 1.5 Hz, 1H), 7.54 – 7.47 (m, 2H), 7.45 – 7.40 (m, 1H), 7.39 – 7.33 (m, 2H), 7.26 – 7.23 (m, 1H), 7.23 – 7.15 (m, 2H), 7.13 (dt, *J* = 7.8, 1.7 Hz, 1H), 6.80 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.11 (d, *J* = 15.2 Hz, 1H), 4.01 (t, *J* = 6.6 Hz, 2H), 2.46 (s, 3H), 1.53 (dq, *J* = 8.3, 6.7 Hz, 2H), 1.36 – 1.20 (m, 2H), 0.85 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.90, 144.86, 141.21, 140.73, 135.66, 134.84, 132.33, 131.78, 131.36, 130.01, 129.39, 128.91, 128.81, 128.38, 127.52, 126.65, 125.49, 125.14, 124.90, 124.15, 123.24, 64.32, 30.70, 19.20, 15.96, 13.79. HRMS (EI-TOF) calcd for $C_{26}H_{25}ClO_2S^+$ ([M]$^+$): 436.1264, found: 436.1265.

(*R*)-(2*E*,4*Z*)-butyl 5-(3-methoxyphenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3ja)



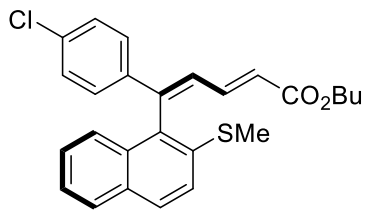
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(33.5 mg, 78%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 9.7 min (major), t = 7.4 min (minor), 95% ee. $[\alpha]_D^{20}$ = 100.8 (c = 0.835, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 (d, *J* = 8.8 Hz, 1H), 7.82 (dd, *J* = 7.7, 1.6 Hz, 1H), 7.52 (dd, *J* = 8.2, 1.5 Hz, 1H), 7.48 (d, *J* = 8.7 Hz, 1H), 7.42 – 7.37 (m, 1H), 7.34 (ddd, *J* = 8.3, 6.8, 1.5 Hz, 1H), 7.24 – 7.12 (m, 2H), 6.95 – 6.76 (m, 4H), 6.08 (d, *J* = 15.2 Hz, 1H), 4.00 (t, *J* = 6.6 Hz, 2H), 3.72 (s, 3H), 2.44 (s, 3H), 1.56 – 1.45 (m, 2H), 1.31 – 1.19 (m, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.05, 159.87, 146.19, 141.61, 140.20, 135.48, 132.53, 132.47, 131.33, 129.73, 129.12, 128.24, 127.99, 127.32, 125.36, 125.17, 123.36, 123.24, 119.53, 113.89, 112.84, 64.21, 55.28, 30.71, 19.20, 16.00, 13.78. HRMS (EI-TOF) calcd for $C_{27}H_{28}O_3S^+$ ([M]$^+$): 432.1759, found: 432.1760.

***(R)*-(2*E*,4*Z*)-butyl 5-(2-(methylthio)naphthalen-1-yl)-5-(p-tolyl)penta-2,4-dienoate (4-3ka)**



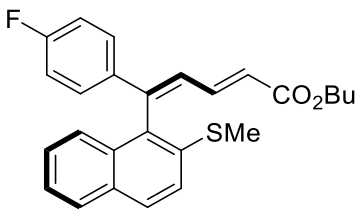
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(34.0 mg, 82%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 95/5, flow = 0.7 mL/min, 254 nm), t = 11.6 min (major), t = 12.5 min (minor), 97% ee. $[\alpha]_D^{20}$ = 78.5 (c = 1.023, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.91 (d, *J* = 8.7 Hz, 1H), 7.87 – 7.79 (m, 1H), 7.58 – 7.46 (m, 2H), 7.38 (dddd, *J* = 22.2, 8.3, 6.8, 1.4 Hz, 2H), 7.24 – 7.16 (m, 3H), 7.08 (d, *J* = 8.0 Hz, 2H), 6.83 (dd, *J* = 15.2, 11.6 Hz, 1H), 6.07 (d, *J* = 15.2 Hz, 1H), 4.01 (t, *J* = 6.6 Hz, 2H), 2.45 (s, 3H), 2.31 (s, 3H), 1.52 (dq, *J* = 8.5, 6.7 Hz, 2H), 1.36 – 1.17 (m, 2H), 0.86 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.15, 146.28, 141.86, 139.08, 135.79, 135.40, 132.71, 132.49, 131.31, 129.60, 129.02, 128.23, 127.31, 126.76, 126.73, 125.35, 125.23, 123.22, 122.72, 64.16, 30.73, 21.40, 19.21, 15.98, 13.79. HRMS (EI-TOF) calcd for $C_{27}H_{28}O_2S^+$ ($[M]^+$): 416.1810, found: 416.1812.

***(R)*-(2*E*,4*Z*)-butyl 5-(4-chlorophenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3la)**



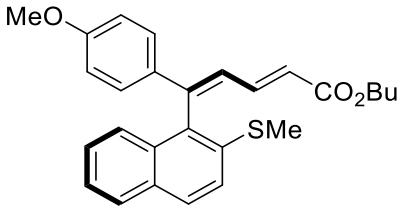
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(28.1 mg, 65%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 12.7 min (major), t = 10.9 min (minor), 97% ee. $[\alpha]_D^{20}$ = 68.2 (c = 0.8867, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.91 (d, *J* = 8.8 Hz, 1H), 7.84 (dd, *J* = 8.1, 1.5 Hz, 1H), 7.52 – 7.45 (m, 2H), 7.38 (dddd, *J* = 21.3, 8.3, 6.8, 1.4 Hz, 2H), 7.24 (d, *J* = 9.3 Hz, 4H), 7.19 (d, *J* = 11.5 Hz, 1H), 6.80 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.09 (d, *J* = 15.2 Hz, 1H), 4.00 (t, *J* = 6.6 Hz, 2H), 2.44 (s, 3H), 1.52 (dq, *J* = 8.4, 6.7 Hz, 2H), 1.32 – 1.13 (m, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.96, 145.00, 141.37, 137.18, 135.58, 134.75, 132.33, 131.97, 131.34, 129.31, 129.03, 128.37, 128.09, 128.07, 127.49, 125.49, 124.92, 123.72, 123.20, 64.28, 30.71, 19.20, 15.93, 13.78. HRMS (EI-TOF) calcd for $C_{26}H_{25}O_2ClS^+$ ($[M]^+$): 436.1264, found: 436.1263.

***(R)*-(2*E*,4*Z*)-butyl 5-(4-fluorophenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3ma)**



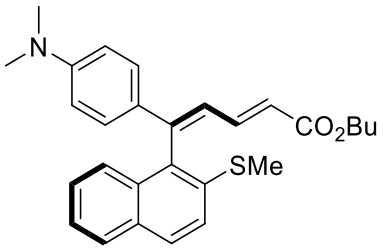
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(37.9 mg, 90%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 9.8 min (major), t = 8.2 min (minor), 97% ee. $[\alpha]_D^{20}$ = 63.0 (c = 0.913, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.92 (d, *J* = 8.7 Hz, 1H), 7.85 (dd, *J* = 8.0, 1.5 Hz, 1H), 7.51 (dd, *J* = 8.8, 3.4 Hz, 2H), 7.39 (dddd, *J* = 20.1, 8.3, 6.8, 1.4 Hz, 2H), 7.32 – 7.27 (m, 2H), 7.16 (d, *J* = 11.5 Hz, 1H), 6.99 – 6.91 (m, 2H), 6.82 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.08 (d, *J* = 15.2 Hz, 1H), 4.01 (t, *J* = 6.6 Hz, 2H), 2.46 (s, 3H), 1.53 (dq, *J* = 8.4, 6.6 Hz, 2H), 1.36 – 1.18 (m, 2H), 0.86 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.03, 163.2 (d, J_{CF} = 250.5 Hz), 145.17, 141.53, 134.85 (d, J_{CF} = 3.0 Hz), 132.30 (d, J_{CF} = 7.1 Hz), 131.35, 129.24, 128.66, 128.58, 128.34, 127.51 (d, J_{CF} = 2.0 Hz), 127.45, 125.46, 124.98, 123.26 (d, J_{CF} = 9.1 Hz), 115.82 (d, J_{CF} = 21.2 Hz), 64.24, 30.71, 19.20, 15.92, 13.78. ^{19}F NMR (376 MHz, Chloroform-d) δ -112.44. HRMS (EI-TOF) calcd for $C_{26}H_{25}O_2FS^+$ ([M]$^+$): 420.1559, found: 420.1558.

(*R*)-(2*E*,4*Z*)-butyl 5-(4-methoxyphenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3na)



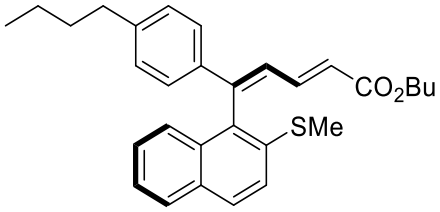
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(19.8 mg, 44%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 80/20, flow = 1.2 mL/min, 254 nm), t = 6.5 min (major), t = 5.7 min (minor), 96% ee. $[\alpha]_D^{20}$ = 74.5 (c = 0.786, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.90 (d, *J* = 8.7 Hz, 1H), 7.84 (dd, *J* = 7.9, 1.5 Hz, 1H), 7.51 (dd, *J* = 11.4, 8.7 Hz, 2H), 7.37 (dddd, *J* = 21.6, 8.2, 6.8, 1.4 Hz, 2H), 7.25 (d, *J* = 9.3 Hz, 2H), 7.15 (d, *J* = 11.6 Hz, 1H), 6.89 – 6.74 (m, 3H), 6.03 (d, *J* = 15.2 Hz, 1H), 4.00 (t, *J* = 6.6 Hz, 2H), 3.77 (s, 3H), 2.45 (s, 3H), 1.52 (dq, *J* = 8.4, 6.6 Hz, 2H), 1.32 – 1.14 (m, 2H), 0.85 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.25, 160.33, 145.93, 142.01, 135.37, 132.74, 132.47, 131.33, 131.17, 129.02, 128.23, 127.31, 125.70, 125.37, 125.25, 123.22, 122.16, 114.28, 64.14, 55.38, 30.75, 19.23, 15.99, 13.81. HRMS (EI-TOF) calcd for $C_{27}H_{28}O_3S^+$ ([M]$^+$): 432.1759, found: 432.1758.

(*R*)-(2*E*,4*Z*)-butyl 5-(4-(dimethylamino)phenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3oa)



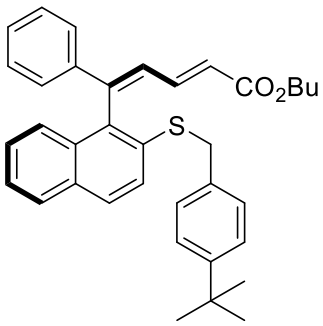
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =10/1 为展开剂)(44.8 mg, 99%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 96/4, flow = 0.8 mL/min, 254 nm), t = 9.5 min (major), t = 9.0 min (minor), 96% ee. $[\alpha]_D^{20}$ = 21.3 (c = 0.96, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 (d, *J* = 8.7 Hz, 1H), 7.84 (dd, *J* = 7.9, 1.4 Hz, 1H), 7.56 (d, *J* = 8.3 Hz, 1H), 7.50 (d, *J* = 8.7 Hz, 1H), 7.36 (dddd, *J* = 21.9, 8.2, 6.8, 1.4 Hz, 2H), 7.23 – 7.17 (m, 2H), 7.13 (d, *J* = 11.6 Hz, 1H), 6.83 (dd, *J* = 15.1, 11.6 Hz, 1H), 6.63 – 6.53 (m, 2H), 5.99 (d, *J* = 15.1 Hz, 1H), 4.00 (t, *J* = 6.6 Hz, 2H), 2.94 (s, 6H), 2.45 (s, 3H), 1.52 (dq, *J* = 8.4, 6.7 Hz, 2H), 1.36 – 1.16 (m, 2H), 0.85 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.48, 150.80, 146.58, 142.53, 135.23, 133.13, 132.58, 131.26, 128.74, 128.10, 127.99, 127.14, 126.07, 125.47, 125.24, 123.16, 120.48, 112.12, 63.95, 40.24, 30.76, 19.22, 15.97, 13.79. HRMS (EI-TOF) calcd for $C_{28}H_{31}NO_2S^+$ ($[M]^+$): 445.2076, found: 445.2073.

(*R*)-(2*E*,4*Z*)-butyl 5-(4-butylphenyl)-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-3pa)



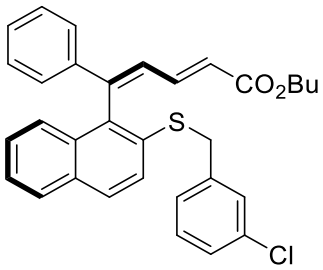
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(40.5 mg, 87%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 7.6 min (major), t = 6.8 min (minor), 96% ee. $[\alpha]_D^{20}$ = 76.1 (c = 1.056, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 (d, *J* = 8.8 Hz, 1H), 7.83 (dd, *J* = 8.0, 1.4 Hz, 1H), 7.51 (dd, *J* = 17.2, 8.5 Hz, 2H), 7.36 (dddd, *J* = 21.2, 8.3, 6.8, 1.4 Hz, 2H), 7.26 – 7.16 (m, 3H), 7.07 (d, *J* = 8.2 Hz, 2H), 6.82 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.05 (d, *J* = 15.2 Hz, 1H), 4.00 (t, *J* = 6.6 Hz, 2H), 2.61 – 2.50 (m, 2H), 2.43 (s, 3H), 1.59 – 1.45 (m, 4H), 1.39 – 1.18 (m, 4H), 0.87 (dt, *J* = 20.1, 7.3 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.16, 146.40, 144.02, 141.88, 135.99, 135.37, 132.76, 132.47, 131.30, 128.99, 128.89, 128.20, 127.26, 126.79, 126.71, 125.33, 125.27, 123.23, 122.65, 64.14, 35.51, 33.44, 30.72, 22.50, 19.20, 15.97, 14.04, 13.78. HRMS (EI-TOF) calcd for $C_{30}H_{34}O_2S^+$ ($[M]^+$): 458.2280, found: 458.2282.

(*R*)-(2*E*,4*Z*)-butyl 5-(2-((4-(tert-butyl)benzyl)thio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3qa)



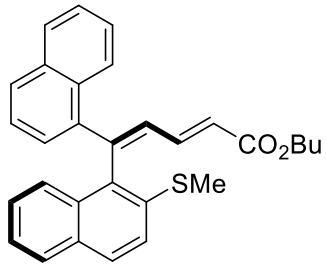
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(49.2 mg, 93%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 7.9 min (major), t = 6.8 min (minor), 89% ee. $[\alpha]_D^{20}$ = 40.4 (c = 0.983, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.82 (dd, *J* = 8.7, 2.5 Hz, 2H), 7.55 (dd, *J* = 8.6, 1.3 Hz, 2H), 7.44 – 7.38 (m, 1H), 7.33 (tt, *J* = 6.8, 1.4 Hz, 1H), 7.29 – 7.18 (m, 8H), 7.13 (d, *J* = 8.0 Hz, 2H), 6.85 (ddd, *J* = 15.2, 11.6, 1.2 Hz, 1H), 6.06 (d, *J* = 15.2 Hz, 1H), 4.06 (s, 2H), 4.01 (td, *J* = 6.6, 1.1 Hz, 2H), 1.57 – 1.45 (m, 2H), 1.27 (d, *J* = 1.2 Hz, 11H), 0.84 (td, *J* = 7.4, 1.1 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.05, 150.17, 146.68, 141.77, 139.05, 134.66, 134.24, 133.92, 132.61, 131.90, 128.89, 128.75, 128.71, 128.23, 127.71, 127.25, 126.96, 126.18, 125.76, 125.63, 125.50, 123.09, 64.21, 37.90, 34.57, 31.44, 30.75, 19.22, 13.80. HRMS (EI-TOF) calcd for $C_{36}H_{38}O_2S^+$ ($[M]^+$): 534.2593, found: 534.2593.

(*R*)-(2*E*,4*Z*)-butyl 5-(2-((3-chlorobenzyl)thio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ra)



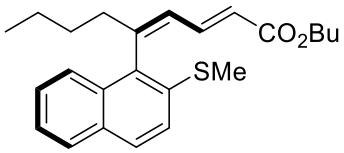
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(20.4 mg, 40%)。手性 HPLC 分离条件：a AD-H column (n-hexane/i-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 10.9 min (major), t = 9.3 min (minor), 90% ee. $[\alpha]_D^{20}$ = 56.0 (c = 1.093, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.64 (dd, *J* = 8.1, 1.5 Hz, 1H), 7.51 (dd, *J* = 7.7, 1.8 Hz, 1H), 7.45 (d, *J* = 8.7 Hz, 1H), 7.23 – 7.16 (m, 4H), 7.12 – 7.02 (m, 4H), 7.01 – 6.95 (m, 3H), 6.92 (dt, *J* = 7.9, 1.5 Hz, 1H), 6.77 (dt, *J* = 7.8, 1.4 Hz, 1H), 6.68 (t, *J* = 7.8 Hz, 1H), 6.15 (d, *J* = 15.1 Hz, 1H), 3.90 – 3.79 (m, 2H), 3.62 – 3.46 (m, 2H), 1.21 (dq, *J* = 8.6, 6.7 Hz, 2H), 1.07 – 0.93 (m, 2H), 0.62 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 166.32, 146.57, 141.40, 139.71, 139.41, 135.48, 134.49, 133.78, 133.05, 132.20, 129.87, 129.32, 129.06, 128.93, 128.87, 128.53, 128.51, 127.64, 127.51, 127.21, 127.19, 126.27, 126.04, 125.87, 123.95, 64.05, 37.30, 30.87, 19.30, 13.77. HRMS (EI-TOF) calcd for $C_{32}H_{29}ClO_2S^+$ ($[M]^+$): 512.1577, found: 512.1575.

(*R*)-(2*E*,4*Z*)-butyl 5-(2-(methylthio)naphthalen-1-yl)-5-(naphthalen-1-yl)penta-2,4-dienoate (4-3sa)



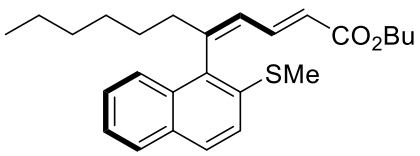
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 10/1 为展开剂)(37.0 mg, 82%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 6.4 min (major), t = 8.9 min (minor), 94% ee. $[\alpha]_D^{20}$ = 18.5 (c = 1.06, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.77 (d, *J* = 8.6 Hz, 1H), 7.93 – 7.88 (m, 2H), 7.85 (dd, *J* = 7.6, 1.8 Hz, 1H), 7.75 (dd, *J* = 7.9, 5.3 Hz, 2H), 7.65 (ddd, *J* = 8.5, 6.8, 1.5 Hz, 1H), 7.56 (ddd, *J* = 8.1, 6.8, 1.2 Hz, 1H), 7.50 (d, *J* = 8.7 Hz, 1H), 7.45 – 7.34 (m, 2H), 7.23 (t, *J* = 7.7 Hz, 1H), 7.15 – 7.06 (m, 2H), 7.00 (dd, *J* = 15.0, 11.6 Hz, 1H), 6.07 (d, *J* = 14.9 Hz, 1H), 4.05 (td, *J* = 6.6, 1.6 Hz, 2H), 2.41 (s, 3H), 1.54 (dt, *J* = 8.3, 6.7 Hz, 2H), 1.29 (h, *J* = 7.3 Hz, 2H), 0.88 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.13, 144.85, 141.62, 138.01, 136.27, 134.83, 134.60, 133.97, 132.97, 131.43, 131.14, 129.11, 128.96, 128.78, 128.29, 127.58, 126.71, 126.56, 126.15, 125.86, 125.36, 125.27, 125.10, 123.59, 123.19, 64.23, 30.72, 19.20, 16.13, 13.80. HRMS (EI-TOF) calcd for $C_{30}H_{28}O_2S^+$ ($[M]^+$): 452.1810, found: 452.1809.

(*R*)-(2*E*,4*Z*)-butyl 5-(2-(methylthio)naphthalen-1-yl)nona-2,4-dienoate (4-3ta)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(26.3 mg, 67%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 85/15, flow = 1.1 mL/min, 254 nm), t = 3.5 min (major), t = 6.2 min (minor), 93% ee. $[\alpha]_D^{20}$ = 131.1 (c = 1.125, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.81 (dd, *J* = 7.7, 2.9 Hz, 2H), 7.64 – 7.53 (m, 1H), 7.48 – 7.34 (m, 3H), 6.75 (dd, *J* = 15.2, 11.4 Hz, 1H), 6.57 (d, *J* = 11.5 Hz, 1H), 5.90 (d, *J* = 15.2 Hz, 1H), 3.99 (t, *J* = 6.6 Hz, 2H), 2.58 – 2.46 (m, 5H), 1.60 – 1.54 (m, 2H), 1.54 – 1.46 (m, 2H), 1.37 (h, *J* = 7.3 Hz, 2H), 1.26 (h, *J* = 7.4 Hz, 2H), 0.90 (t, *J* = 7.3 Hz, 3H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.37, 150.78, 141.90, 135.26, 133.57, 131.50, 131.42, 128.43, 128.31, 127.36, 126.97, 125.28, 124.95, 123.62, 120.98, 64.07, 38.04, 30.72, 29.76, 22.91, 19.19, 16.26, 14.10, 13.79. HRMS (EI-TOF) calcd for $C_{24}H_{30}O_2S^+$ ($[M]^+$): 382.1967, found: 382.1966.

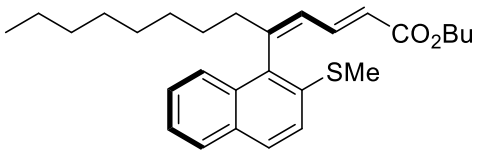
(*R*)-(2*E*,4*Z*)-butyl 5-(2-(methylthio)naphthalen-1-yl)undeca-2,4-dienoate (4-3ua)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(36.6 mg, 88%)。手性 HPLC 分离条件：a IB column (*n*-hexane/*i*-PrOH = 94/6, flow = 0.8 mL/min, 254 nm), t = 6.0 min (major), t = 6.6 min (minor), 95% ee. $[\alpha]_D^{20}$ = 121.0 (c = 1.003,

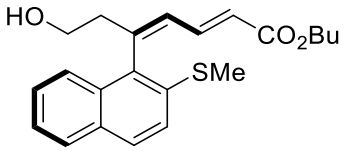
$CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.81 (dd, *J* = 7.7, 3.0 Hz, 2H), 7.64 – 7.51 (m, 1H), 7.48 – 7.35 (m, 3H), 6.76 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.57 (d, *J* = 11.5 Hz, 1H), 5.91 (d, *J* = 15.2 Hz, 1H), 3.99 (t, *J* = 6.6 Hz, 2H), 2.57 – 2.43 (m, 5H), 1.62 – 1.54 (m, 2H), 1.50 (dt, *J* = 8.2, 6.7 Hz, 2H), 1.34 (ddd, *J* = 13.3, 7.1, 3.9 Hz, 2H), 1.31 – 1.19 (m, 6H), 0.85 (dt, *J* = 11.4, 7.0 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.35, 150.83, 141.90, 135.33, 133.58, 131.52, 131.44, 128.42, 128.30, 127.35, 126.96, 125.28, 124.96, 123.67, 120.98, 64.06, 38.30, 31.83, 30.73, 29.46, 27.59, 22.73, 19.19, 16.28, 14.20, 13.77. HRMS (EI-TOF) calcd for $C_{26}H_{34}O_2S^+$ ($[M]^+$): 410.2280, found: 410.2278.

***(R)*-(2*E*,4*Z*)-butyl 5-(2-(methylthio)naphthalen-1-yl)trideca-2,4-dienoate (4-3va)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(32.0 mg, 73%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 3.7 min (major), t = 6.0 min (minor), 92% ee. $[\alpha]_D^{20}$ = 108.9 (c = 1.0, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 – 7.77 (m, 2H), 7.63 – 7.53 (m, 1H), 7.49 – 7.33 (m, 3H), 6.75 (dd, *J* = 15.2, 11.4 Hz, 1H), 6.61 – 6.44 (m, 1H), 5.90 (d, *J* = 15.2 Hz, 1H), 3.98 (t, *J* = 6.6 Hz, 2H), 2.57 – 2.41 (m, 5H), 1.61 – 1.54 (m, 2H), 1.50 (dt, *J* = 8.3, 6.7 Hz, 2H), 1.39 – 1.17 (m, 12H), 0.85 (dt, *J* = 12.0, 6.9 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.38, 150.85, 141.91, 135.34, 133.58, 131.52, 131.45, 128.43, 128.32, 127.36, 126.97, 125.29, 124.98, 123.67, 120.99, 64.08, 38.29, 31.97, 30.74, 29.80, 29.58, 29.39, 27.62, 22.77, 19.21, 16.30, 14.23, 13.79. HRMS (EI-TOF) calcd for $C_{28}H_{38}O_2S^+$ ($[M]^+$): 438.2593, found: 438.2590.

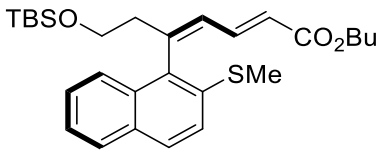
***(R)*-(2*E*,4*Z*)-butyl 7-hydroxy-5-(2-(methylthio)naphthalen-1-yl)hepta-2,4-dienoate (4-3wa)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 4/1 为展开剂)(10.9 mg, 27%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 70/30, flow = 1.1 mL/min, 254 nm), t = 8.1 min (major), t = 12.4 min (minor), 93% ee. $[\alpha]_D^{20}$ = 77.0 (c = 0.6, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.83 (dd, *J* = 9.1, 3.7 Hz, 2H), 7.67 – 7.56 (m, 1H), 7.51 – 7.39 (m, 3H), 6.79 (ddd, *J* = 14.9, 11.5, 1.0 Hz, 1H), 6.69 (dd, *J* = 11.5, 1.2 Hz, 1H), 5.96 (d, *J* = 15.0 Hz, 1H), 4.01 (tt, *J* = 6.7, 1.3 Hz, 2H), 3.72 – 3.51 (m, 2H), 2.89 (ddd, *J* = 14.1, 9.0, 4.9 Hz, 1H), 2.74 (dt, *J* = 14.4, 4.4 Hz, 1H), 2.54 (s, 3H), 1.57 – 1.47 (m, 2H), 1.28 (dq, *J* = 14.5, 7.5 Hz, 2H), 0.90 – 0.81 (m, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.24, 146.04, 141.15, 133.67, 133.51,

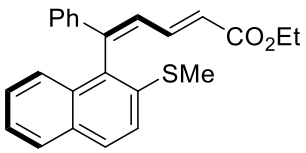
131.77, 131.36, 129.03, 128.51, 127.29, 125.69, 124.88, 123.47, 122.32, 64.27, 60.22, 42.82, 30.73, 19.22, 16.43, 13.81. HRMS (EI-TOF) calcd for $C_{22}H_{26}O_3S^+$ ([M]$^+$): 370.1603, found: 370.1601.

(*R*)-(2*E*,4*Z*)-butyl 7-((tert-butyldimethylsilyl)oxy)-5-(2-(methylthio)naphthalen-1-yl)hepta-2,4-dienoate (4-3xa)



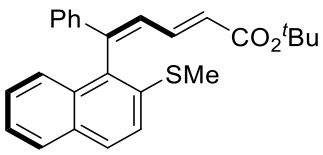
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(28.4 mg, 59%)。手性 HPLC 分离条件：a AS-H column (*n*-hexane/*i*-PrOH = 94/6, flow = 0.8 mL/min, 254 nm), t = 4.7 min (major), t = 5.3 min (minor), 90% ee. $[\alpha]_D^{20}$ = 72.7 (c = 1.15, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.80 (dd, *J* = 9.0, 4.9 Hz, 2H), 7.59 – 7.49 (m, 1H), 7.46 – 7.35 (m, 3H), 6.81 (d, *J* = 15.8 Hz, 1H), 6.05 (d, *J* = 15.8 Hz, 1H), 4.70 (d, *J* = 11.5 Hz, 1H), 4.60 (d, *J* = 11.5 Hz, 1H), 3.94 (t, *J* = 6.5 Hz, 2H), 2.49 (s, 3H), 2.25 (s, 3H), 1.50 – 1.38 (m, 2H), 1.17 (h, *J* = 7.5 Hz, 2H), 0.98 (s, 9H), 0.80 (t, *J* = 7.4 Hz, 3H), 0.20 (d, *J* = 2.9 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.65, 144.76, 142.78, 136.81, 135.64, 132.92, 131.48, 130.99, 128.34, 128.29, 127.12, 125.30, 124.58, 123.53, 118.10, 63.91, 58.47, 30.66, 26.01, 20.31, 19.16, 18.41, 16.06, 13.79, -4.95, -5.00. HRMS (EI-TOF) calcd for $C_{28}H_{40}O_3SiS^+$ ([M]$^+$): 484.2467, found: 484.2466.

(*R*)-(2*E*,4*Z*)-ethyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ab)



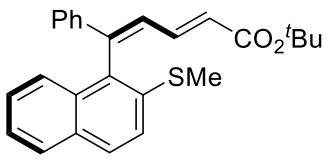
根据通用方法 A 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 =20/1 为展开剂)(34.1 mg, 92%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 6.6 min (major), t = 8.1 min (minor), 93% ee. $[\alpha]_D^{20}$ = 69.2 (c = 0.82, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.90 (d, *J* = 8.7 Hz, 1H), 7.85 – 7.80 (m, 1H), 7.56 – 7.46 (m, 2H), 7.42 – 7.33 (m, 2H), 7.33 – 7.28 (m, 2H), 7.28 – 7.22 (m, 3H), 7.21 (s, 1H), 6.84 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.08 (d, *J* = 15.2 Hz, 1H), 4.06 (q, *J* = 7.1 Hz, 2H), 2.43 (s, 3H), 1.17 (t, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.99, 146.31, 141.61, 138.71, 135.49, 132.59, 132.47, 131.34, 129.12, 128.87, 128.79, 128.27, 127.82, 127.33, 126.84, 125.38, 125.20, 123.33, 123.30, 60.29, 16.00, 14.32. HRMS (EI-TOF) calcd for $C_{24}H_{22}O_2S^+$ ([M]$^+$): 374.1341, found: 374.1340.

(*R*)-(2*E*,4*Z*)-tert-butyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ac)

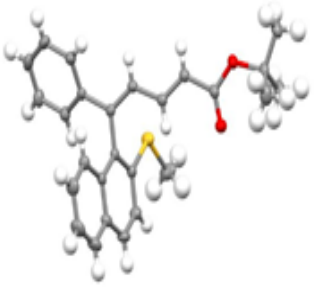


根据通用方法 A 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 20/1 为展开剂)(32.9 mg, 81%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 5.7 min (major), t = 4.6 min (minor), 94% ee. $[\alpha]_D^{20}$ = 94.9 (c = 1.035, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.88 (d, *J* = 8.7 Hz, 1H), 7.85 – 7.78 (m, 1H), 7.53 (dd, *J* = 8.5, 1.4 Hz, 1H), 7.48 (d, *J* = 8.8 Hz, 1H), 7.42 – 7.32 (m, 2H), 7.30 (ddq, *J* = 6.7, 3.8, 1.7 Hz, 2H), 7.26 – 7.24 (m, 3H), 7.23 – 7.18 (m, 1H), 6.77 (dd, *J* = 15.2, 11.6 Hz, 1H), 6.06 – 5.98 (m, 1H), 2.43 (s, 3H), 1.37 (s, 9H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.39, 145.76, 140.74, 138.81, 135.45, 132.67, 132.49, 131.35, 129.05, 128.78, 128.76, 128.26, 127.85, 127.30, 126.79, 125.34, 125.23, 123.26, 80.24, 28.23, 15.97. HRMS (EI-TOF) calcd for $C_{26}H_{26}O_2S^+$ ($[M]^+$): 402.1654, found: 402.1656.

X-ray data of 4-3ac



***(R)*4-3ac**



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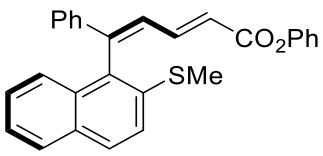
Cell:	a = 9.680 (3) b =8.318 (2) c = 13.550 (4)	
alpha = 90	beta = 92.130(15)	gamma = 90
Temperature: 170 K	Calculated	Reported
Volume	1090.3(5)	1090.3(6)
Space group	P 21	P 1 21 1
Hall group	P 2yb	P 2yb
Moiety formula	C_{26} H_{26} O_2 S	C_{26} H_{26} O_2 S
Sum formula	C_{26} H_{26} O_2 S	C_{26} H_{26} O_2 S
Mr	402.53	402.53
Dx, g cm^{-3}	1.226	1.226
Z	2	2
Mu (mm^{-1})	0.167	0.167

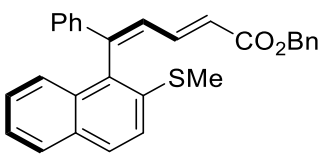
F000	428.0	428.0
F000'	428.42	
h,k,lmax	12,10,17	12,10,17
Nref	4819[2578]	4809
Tmin, Tmax	0.938,0.951	0.712,0.746
Tmin'	0.921	
Correction method = # Reported T	Limits: Tmin = 0.712	Tmax = 0.746
AbsCorr = MULTI-SCAN		
Data completeness	1.87/1.00	Theta(max) = 27.077
R (reflections)	0.0246(4714)	wR2(reflections)=0.0666(4809)
S = 1.048	Npar = 266	
Flack parameter	-0.030(15)	

_(R)_-(2_E_,4_Z_)-phenyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ad)



根据通用方法 A 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 20/1 为展开剂)(31.0 mg, 73%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 8.4 min (major), t = 9.1 min (minor), 97% ee. $[\alpha]_D^{20}$ = 65.0 (c = 0.773, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.92 (d, *J* = 8.8 Hz, 1H), 7.86 (dd, *J* = 7.6, 1.8 Hz, 1H), 7.57 (dd, *J* = 7.8, 1.7 Hz, 1H), 7.52 (d, *J* = 8.8 Hz, 1H), 7.45 – 7.34 (m, 5H), 7.33 – 7.29 (m, 5H), 7.21 – 7.13 (m, 1H), 7.07 – 6.97 (m, 3H), 6.30 (d, *J* = 15.1 Hz, 1H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 165.33, 150.83, 147.57, 143.52, 138.55, 135.51, 132.44, 132.34, 131.32, 129.33, 129.25, 129.14, 128.86, 128.33, 127.56, 127.41, 126.96, 125.65, 125.43, 125.12, 123.25, 122.18, 121.67, 15.98. HRMS (EI-TOF) calcd for $C_{28}H_{22}O_2S^+$ ([M]$^+$): 422.1341, found: 422.1341.

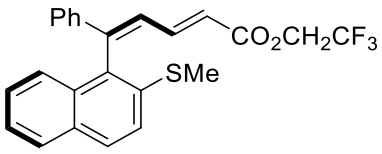
_(R)_-(2_E_,4_Z_)-benzyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ae)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(30.5 mg, 69%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 7.7 min (major), t = 11.8 min (minor), 97% ee. $[\alpha]_D^{20}$ = 86.2 (c = 0.91, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.90 (d, *J* = 8.7 Hz, 1H), 7.84 (dd, *J* = 8.0, 1.5 Hz, 1H), 7.53 (d, *J* = 8.6 Hz, 1H), 7.49 (d, *J* = 8.7 Hz, 1H), 7.39 (ddd, *J* = 8.1, 6.8, 1.4 Hz, 1H), 7.36 – 7.33 (m, 1H), 7.30

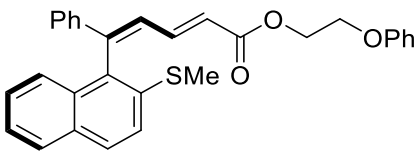
(tt, *J* = 5.3, 4.3, 1.9 Hz, 3H), 7.28 – 7.19 (m, 8H), 6.90 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.12 (d, *J* = 15.2 Hz, 1H), 5.05 (s, 2H), 2.42 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.75, 146.80, 142.34, 138.63, 136.24, 135.51, 132.52, 132.46, 131.32, 129.14, 128.96, 128.81, 128.55, 128.28, 128.12, 128.03, 127.61, 127.38, 126.88, 125.41, 125.17, 123.28, 122.70, 66.03, 15.97. HRMS (EI-TOF) calcd for $C_{29}H_{24}O_2S^+$ ([M]$^+$): 436.1497, found: 436.1496.

(*R*)-(2*E*,4*Z*)-2,2,2-trifluoroethyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3af)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(26.6 mg, 61%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 8.0 min (major), t = 10.7 min (minor), 92% ee. $[\alpha]_D^{20}$ = 80.7 (c = 1.085, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.94 (d, *J* = 8.7 Hz, 1H), 7.90 – 7.84 (m, 1H), 7.53 (d, *J* = 8.7 Hz, 2H), 7.43 (ddd, *J* = 8.1, 6.8, 1.4 Hz, 1H), 7.40 – 7.37 (m, 1H), 7.36 – 7.33 (m, 2H), 7.33 – 7.27 (m, 5H), 6.96 (dd, *J* = 15.2, 11.6 Hz, 1H), 6.21 – 6.11 (m, 1H), 4.42 (qd, *J* = 8.5, 4.8 Hz, 2H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 165.23, 148.24, 144.23, 138.45, 135.54, 132.43, 132.27, 131.34, 129.32, 129.27, 128.89, 128.34, 127.45, 127.23, 127.00, 125.48, 125.09, 123.30, 123.12 (q, J_{CF} = 277.8 Hz), 120.54, 60.22 (q, J_{CF} = 36.5 Hz), 16.00. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -73.77. HRMS (EI-TOF) calcd for $C_{24}H_{19}O_2F_3S^+$ ([M]$^+$): 428.1058, found: 428.1056.

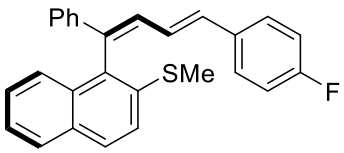
(*R*)-(2*E*,4*Z*)-2-phenoxyethyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ag)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =10/1 为展开剂)(36.7 mg, 77%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 80/20, flow =1.3 mL/min, 254 nm), t = 5.1 min (major), t = 7.3 min (minor), 95% ee. $[\alpha]_D^{20}$ = 73.3 (c = 1.06, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.88 (d, *J* = 8.7 Hz, 1H), 7.86 – 7.77 (m, 1H), 7.52 (dd, *J* = 8.5, 1.3 Hz, 1H), 7.48 (d, *J* = 8.7 Hz, 1H), 7.39 (ddd, *J* = 8.1, 6.8, 1.4 Hz, 1H), 7.36 – 7.33 (m, 1H), 7.33 – 7.28 (m, 2H), 7.28 – 7.20 (m, 7H), 6.97 – 6.87 (m, 2H), 6.87 – 6.79 (m, 2H), 6.13 (d, *J* = 15.2 Hz, 1H), 4.40 – 4.32 (m, 2H), 4.08 (t, *J* = 4.9 Hz, 2H), 2.42 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.85, 158.55, 146.86, 142.40, 138.63, 135.50, 132.49, 132.45, 131.32, 129.58, 129.17, 128.97, 128.81, 128.28, 127.65, 127.36, 126.88, 125.39, 125.16, 123.30,

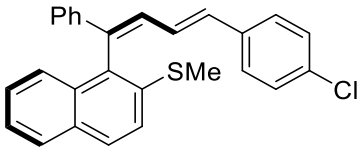
122.56, 121.20, 114.73, 65.91, 62.67, 15.98. HRMS (EI-TOF) calcd for $C_{30}H_{26}O_3S^+$ ([M]$^+$): 466.1603, found: 466.1601.

***(R)*-(1-((1*Z*,3*E*)-4-(4-fluorophenyl)-1-phenylbuta-1,3-dien-1-yl)naphthalen-2-yl)(methyl)sulfane (4-3ah)**



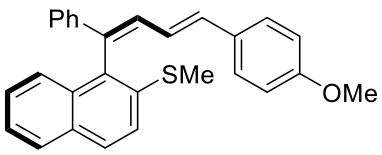
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(34.4 mg, 88%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 16.6 min (major), t = 7.9 min (minor), 92% ee. $[\alpha]_D^{20}$ = 140.6 (c = 0.66, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.95 – 7.86 (m, 1H), 7.74 – 7.64 (m, 2H), 7.46 – 7.40 (m, 2H), 7.32 – 7.27 (m, 2H), 7.19 – 7.15 (m, 2H), 7.10 – 6.97 (m, 3H), 6.74 – 6.66 (m, 2H), 6.55 – 6.50 (m, 2H), 6.49 – 6.39 (m, 2H), 1.92 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 162.59 (d, J_{CF} = 247.0 Hz), 140.27, 138.76, 136.81, 134.30, 134.28 (d, J_{CF} = 2.3 Hz), 133.78 (d, J_{CF} = 3.3 Hz), 133.31, 131.77, 131.06, 128.90, 128.55, 128.49, 128.41, 127.66, 126.72, 126.61 (d, J_{CF} = 2.5 Hz), 125.96, 125.62, 123.55, 115.54 (d, J_{CF} = 21.7 Hz), 15.28. ^{19}F NMR (376 MHz, Benzene-d_6) δ -113.95. HRMS (EI-TOF) calcd for $C_{27}H_{21}FO_2S^+$ ([M]$^+$): 396.1348, found: 396.1347.

***(R)*-(1-((1*Z*,3*E*)-4-(4-chlorophenyl)-1-phenylbuta-1,3-dien-1-yl)naphthalen-2-yl)(methyl)sulfane (4-3ai)**



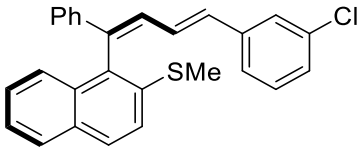
根据通用方法 A 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 =20/1 为展开剂)(37.8 mg, 90%)。手性 HPLC 分离条件：a AS-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 5.4 min (major), t = 6.8 min (minor), 87% ee. $[\alpha]_D^{20}$ = 178.1 (c = 1.077, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.91 – 7.84 (m, 1H), 7.74 – 7.66 (m, 2H), 7.45 – 7.39 (m, 2H), 7.29 (dd, *J* = 9.6, 4.9 Hz, 2H), 7.19 – 7.15 (m, 2H), 7.10 – 6.99 (m, 3H), 6.79 – 6.73 (m, 2H), 6.66 – 6.61 (m, 2H), 6.61 – 6.44 (m, 2H), 1.92 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 140.20, 139.33, 136.78, 136.05, 134.16, 133.28, 133.22, 131.76, 130.93, 128.94, 128.91, 128.82, 128.56, 127.92, 127.90, 127.68, 127.42, 126.75, 125.92, 125.64, 123.54, 15.28. HRMS (EI-TOF) calcd for $C_{27}H_{21}ClO_2S^+$ ([M]$^+$): 412.1053, found: 412.1054.

***(R)*-(1-((1*Z*,3*E*)-4-(4-methoxyphenyl)-1-phenylbuta-1,3-dien-1-yl)naphthalen-2-yl)(methyl)sulfane (4-3aj)**



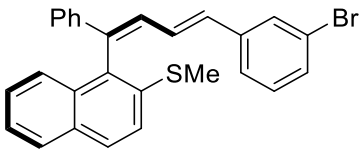
根据通用方法 A 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 =20/1 为展开剂)(27.6 mg, 68%)。手性 HPLC 分离条件：a AS-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 6.7 min (major), t = 7.7 min (minor), 91% ee. $[\alpha]_D^{20}$ = 205.9 (c = 0.76, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.99 – 7.90 (m, 1H), 7.74 – 7.66 (m, 2H), 7.47 – 7.42 (m, 2H), 7.37 (d, *J* = 10.5 Hz, 1H), 7.31 (d, *J* = 8.8 Hz, 1H), 7.18 – 7.15 (m, 2H), 7.08 (dd, *J* = 8.3, 6.4 Hz, 2H), 7.04 – 6.98 (m, 1H), 6.94 – 6.87 (m, 2H), 6.73 – 6.53 (m, 2H), 6.45 – 6.35 (m, 2H), 3.15 (s, 3H), 1.93 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 159.81, 140.53, 137.46, 136.87, 135.44, 134.62, 133.40, 131.52, 130.50, 128.87, 128.75, 128.49, 127.58, 127.52, 126.63, 126.13, 125.54, 124.93, 123.66, 114.27, 54.65, 15.33. HRMS (EI-TOF) calcd for $C_{28}H_{24}O_2S^+$ ($[M]^+$): 408.1548, found: 408.1549.

(*R*)-(1-((1*Z*,3*E*)-4-(3-chlorophenyl)-1-phenylbuta-1,3-dien-1-yl)naphthalen-2-yl)(methyl)sulfane (4-3ak)



根据通用方法 A 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 =20/1 为展开剂)(39.3 mg, 95%)。手性 HPLC 分离条件：a AS-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 4.1 min (major), t = 4.9 min (minor), 97% ee. $[\alpha]_D^{20}$ = 177.2 (c = 1.38, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.90 – 7.82 (m, 1H), 7.70 – 7.62 (m, 2H), 7.44 – 7.38 (m, 2H), 7.25 (d, *J* = 9.6 Hz, 2H), 7.15 – 7.12 (m, 2H), 7.09 – 6.96 (m, 4H), 6.83 – 6.74 (m, 1H), 6.70 – 6.57 (m, 2H), 6.48 – 6.39 (m, 2H), 1.90 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 140.12, 139.89, 139.58, 136.73, 134.70, 133.95, 133.89, 133.23, 131.72, 130.72, 129.87, 128.97, 128.91, 128.56, 128.2, 127.99, 127.65, 127.51, 127.35, 126.80, 125.85, 125.60, 124.18, 123.49, 15.26. HRMS (EI-TOF) calcd for $C_{27}H_{21}ClO_2S^+$ ($[M]^+$): 412.1053, found: 412.1054.

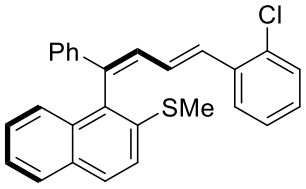
(*R*)-(1-((1*Z*,3*E*)-4-(3-bromophenyl)-1-phenylbuta-1,3-dien-1-yl)naphthalen-2-yl)(methyl)sulfane (4-3al)



根据通用方法 A 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 =20/1 为展开剂)(44.2 mg, 98%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 80/20, flow =1.2 mL/min, 254 nm), t = 24.8 min (major), t = 8.8 min (minor), 96% ee. $[\alpha]_D^{20}$ = 160.3 (c = 0.977, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.88 – 7.82 (m, 1H), 7.70 – 7.61 (m, 2H), 7.45 – 7.36 (m, 2H), 7.26 (s, 1H), 7.24 (d, *J* = 2.2 Hz, 1H), 7.20 (t, *J* = 1.8 Hz, 1H), 7.15 – 7.12 (m, 2H), 7.10 – 6.98

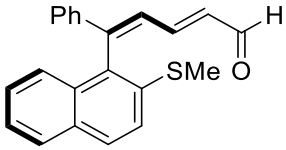
(m, 3H), 6.94 (ddd, *J* = 7.9, 2.0, 0.9 Hz, 1H), 6.69 (dt, *J* = 7.8, 1.2 Hz, 1H), 6.60 (dd, *J* = 15.5, 10.9 Hz, 1H), 6.44 – 6.31 (m, 2H), 1.90 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 140.11, 139.91, 139.87, 136.72, 133.94, 133.80, 133.23, 131.72, 130.70, 130.44, 130.39, 130.14, 128.97, 128.91, 128.55, 128.24, 128.00, 127.65, 126.80, 125.85, 125.60, 124.45, 123.48, 122.97, 15.26. HRMS (EI-TOF) calcd for $C_{27}H_{21}BrO_2S^+$ ([M]$^+$): 456.0547, found: 456.0546.

***(R)*-(1-((1*Z*,3*E*)-4-(2-chlorophenyl)-1-phenylbuta-1,3-dien-1-yl)naphthalen-2-yl)(methyl)sulfane(4-3am)**



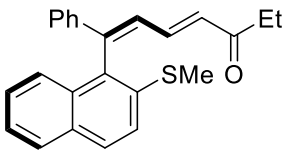
根据通用方法 A 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 =10/1 为展开剂)(29.1 mg, 70%)。手性 HPLC 分离条件：a IG column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 5.2 min (major), t = 5.7 min (minor), 93% ee. $[\alpha]_D^{20}$ = 141.5 (c = 0.867, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.88 – 7.80 (m, 1H), 7.70 – 7.62 (m, 2H), 7.39 (d, *J* = 15.5 Hz, 1H), 7.35 – 7.30 (m, 3H), 7.27 (d, *J* = 8.7 Hz, 1H), 7.15 – 7.12 (m, 2H), 7.07 – 6.96 (m, 4H), 6.88 (dd, *J* = 7.9, 1.6 Hz, 1H), 6.66 (dd, *J* = 15.5, 11.0 Hz, 1H), 6.51 (td, *J* = 7.6, 1.6 Hz, 1H), 6.32 (td, *J* = 7.6, 1.3 Hz, 1H), 1.90 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 140.03, 139.97, 136.77, 135.51, 134.13, 133.46, 133.29, 131.72, 130.95, 130.83, 129.84, 129.38, 128.89, 128.84, 128.48, 128.18, 127.96, 127.67, 126.92, 126.86, 126.69, 125.99, 125.60, 123.54, 15.30. HRMS (EI-TOF) calcd for $C_{27}H_{21}ClO_2S^+$ ([M]$^+$): 412.1053, found: 412.1054.

***(R)*-(2*E*,4*Z*)-5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienal (4-3an)**



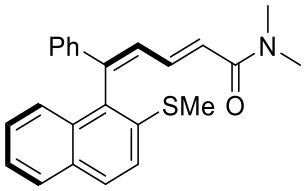
根据通用方法 A 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 10/1 为展开剂)(20.7 mg, 61%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 16.4 min (major), t = 20.2 min (minor), 77% ee. $[\alpha]_D^{20}$ = 60.5 (c = 0.86, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 9.26 (d, *J* = 8.1 Hz, 1H), 7.96 (d, *J* = 8.8 Hz, 1H), 7.91 – 7.84 (m, 1H), 7.54 (dd, *J* = 8.7, 2.2 Hz, 2H), 7.47 – 7.39 (m, 2H), 7.39 – 7.27 (m, 6H), 6.66 (dd, *J* = 15.2, 11.4 Hz, 1H), 6.33 (dd, *J* = 15.2, 8.0 Hz, 1H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 194.05, 148.94, 148.60, 138.17, 135.64, 133.20, 132.37, 132.03, 131.22, 129.52, 129.36, 128.95, 128.35, 127.66, 127.61, 127.09, 125.61, 125.05, 123.08, 15.93. HRMS (EI-TOF) calcd for $C_{22}H_{18}OS^+$ ([M]$^+$): 330.1078, found: 330.1076.

***(R)*-(4*E*,6*Z*)-7-(2-(methylthio)naphthalen-1-yl)-7-phenylhepta-4,6-dien-3-one (4-3ao)**



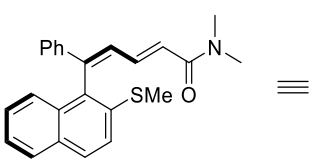
根据通用方法A经过制备级TLC分离得到白色泡沫(石油醚/乙酸乙酯 = 10/1 为展开剂)(21.5 mg, 59%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 10.6 min (major), t = 12.0 min (minor), 83% ee. $[\alpha]_D^{20}$ = 68.9 (c = 0.8067, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.93 (d, *J* = 8.8 Hz, 1H), 7.86 (dd, *J* = 7.9, 1.5 Hz, 1H), 7.57 – 7.49 (m, 2H), 7.44 – 7.35 (m, 2H), 7.34 – 7.31 (m, 2H), 7.30 – 7.26 (m, 3H), 7.23 (d, *J* = 11.3 Hz, 1H), 6.70 (dd, *J* = 15.5, 11.4 Hz, 1H), 6.36 (d, *J* = 15.4 Hz, 1H), 2.45 (s, 3H), 2.40 – 2.28 (m, 2H), 0.95 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 201.26, 147.06, 139.33, 138.67, 135.51, 132.50, 132.44, 131.27, 131.24, 129.18, 128.99, 128.84, 128.30, 128.28, 127.41, 126.83, 125.44, 125.18, 123.17, 33.78, 15.97, 8.18. HRMS (EI-TOF) calcd for $C_{24}H_{22}OS^+$ ($[M]^+$): 358.1391, found: 358.1392.

(*R*)-(2*E*,4*Z*)-*N*,*N*-dimethyl-5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienamide (4-3ap)

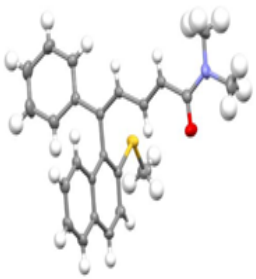


根据通用方法A经过制备级TLC分离得到白色泡沫(石油醚/乙酸乙酯 = 4/1 为展开剂)(20.6 mg, 54%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 70/30, flow =1.3 mL/min, 254 nm), t = 12.5 min (major), t = 20.0 min (minor), 94% ee. $[\alpha]_D^{20}$ = 82.2 (c = 0.62, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 (d, *J* = 8.7 Hz, 1H), 7.83 (dd, *J* = 7.9, 1.5 Hz, 1H), 7.56 (dd, *J* = 8.5, 1.4 Hz, 1H), 7.50 (d, *J* = 8.8 Hz, 1H), 7.42 – 7.37 (m, 1H), 7.33 (ddt, *J* = 9.9, 5.6, 2.5 Hz, 3H), 7.30 – 7.26 (m, 4H), 6.83 (dd, *J* = 14.7, 11.4 Hz, 1H), 6.55 (d, *J* = 14.7 Hz, 1H), 3.06 (s, 3H), 2.91 (s, 3H), 2.45 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.62, 144.67, 139.42, 139.03, 135.40, 132.87, 132.51, 131.41, 129.00, 128.73, 128.51, 128.40, 128.25, 127.21, 126.68, 125.30, 125.25, 123.35, 122.75, 37.43, 35.77, 16.00. HRMS (EI-TOF) calcd for $C_{24}H_{23}NOS^+$ ($[M]^+$): 373.1500, found: 373.1500.

X-ray data of (*R*)4-3ap

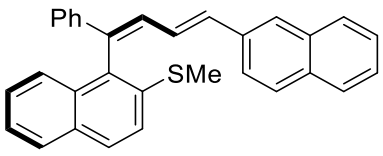


(*R*)4-3ap



Bond precision:	C-C = 0.0030 A	Wavelength = 1.54178
Cell:	a = 8.3648(11) b =11.1560(16) c = 21.208(3)	
alpha = 90	beta = 90	gamma = 90
Temperature: 170 K	Calculated	Reported
Volume	1979.1(5)	1979.1(5)
Space group	P 21 21 21	P 21 21 21
Hall group	P 2ac 2ab	P 2ac 2ab
Moiety formula	C_{24} H_{23} N O S	C_{24} H_{23} N O S
Sum formula	C_{24} H_{23} N O S	C_{24} H_{23} N O S
Mr	373.49	373.49
Dx, g cm^{-3}	1.253	1.254
Z	4	4
Mu (mm^{-1})	1.540	1.540
F000	792.0	792.0
F000’	795.29	
h,k,lmax	10,13,25	10,13,25
Nref	3630[2092]	3593
Tmin, Tmax	0.540,0.592	0.608,0.753
Tmin’	0.448	
Correction method = # Reported T	Limits: Tmin = 0.608	Tmax = 0.753
AbsCorr = MULTI-SCAN		
Data completeness	1.72/0.99	Theta(max) = 68.280
R (reflections)	0.0278(3588)	wR2(reflections)=0.0768(3593)
S = 1.079	Npar = 247	
Flack parameter	0.100(4)	

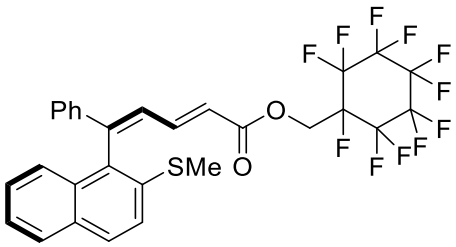
_(R)_-methyl(1-((1*Z*,3*E*)-4-(naphthalen-2-yl)-1-phenylbuta-1,3-dien-1-yl)naphthalen-2-yl)sulfane (4-3aq)



根据通用方法 A 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 =10/1 为展开剂)(38.4 mg, 90%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.3 mL/min,

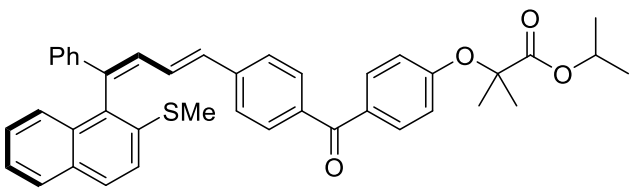
254 nm), t = 9.6 min (major), t = 8.9 min (minor), 95% ee. $[\alpha]_D^{20}$ = 165.7 (c = 0.8667, $CHCl_3$). ^{1}H NMR (400 MHz, Methylene Chloride-d_2) δ 7.99 (d, *J* = 8.7 Hz, 1H), 7.94 – 7.88 (m, 1H), 7.76 – 7.67 (m, 3H), 7.66 – 7.56 (m, 3H), 7.47 – 7.36 (m, 5H), 7.36 – 7.32 (m, 2H), 7.32 – 7.21 (m, 4H), 6.99 (d, *J* = 15.5 Hz, 1H), 6.48 (dd, *J* = 15.5, 11.0 Hz, 1H), 2.49 (s, 3H). ^{13}C NMR (101 MHz, Methylene Chloride-d_2) δ 140.12, 138.98, 136.52, 135.49, 135.33, 134.12, 133.77, 133.58, 133.10, 131.89, 131.08, 129.12, 129.11, 128.72, 128.54, 128.45, 128.15, 128.10, 127.58, 127.52, 127.18, 126.85, 126.68, 126.51, 125.79, 125.70, 123.95, 123.56, 16.02. HRMS (EI-TOF) calcd for $C_{31}H_{24}S^+$ ($[M]^+$): 428.1599, found: 428.1599.

(*R*)-(2*E*,4*Z*)-(perfluorocyclohexyl)methyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ar)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 10/1 为展开剂)(43.6 mg, 68%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 3.3 min (major), t = 3.5 min (minor), 92% ee. $[\alpha]_D^{20}$ = 58.0 (c = 0.98, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.93 (d, *J* = 8.8 Hz, 1H), 7.86 (d, *J* = 7.4 Hz, 1H), 7.51 (d, *J* = 8.7 Hz, 2H), 7.45 – 7.33 (m, 4H), 7.30 (dt, *J* = 5.2, 2.3 Hz, 3H), 7.25 (d, *J* = 4.6 Hz, 1H), 6.93 (dd, *J* = 15.3, 11.6 Hz, 1H), 6.09 (d, *J* = 15.2 Hz, 1H), 4.81 – 4.63 (m, 2H), 2.45 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 165.10, 148.59, 144.52, 138.35, 135.48, 132.43, 132.29, 131.36, 129.34, 129.28, 128.91, 128.31, 127.45, 127.03, 126.95, 125.46, 125.03, 123.23, 120.19, 56.35 (d, J_{CF} = 20.1 Hz), 15.93. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -118.64, -119.43, -122.45, -123.21, -123.76, -124.54, -132.21, -133.00, -139.22, -139.97, -141.49, -142.25, -188.99 (td, *J* = 22.8, 11.3 Hz). HRMS (EI-TOF) calcd for $C_{29}H_{19}F_{11}O_2S^+$ ($[M]^+$): 640.0930, found: 640.0932.

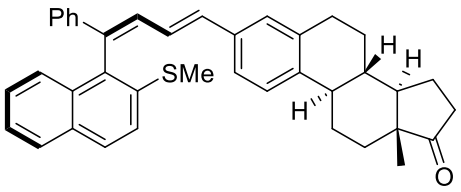
(*R*)-isopropyl 2-methyl-2-(4-(4-((1*E*,3*Z*)-4-(2-(methylthio)naphthalen-1-yl)-4-phenylbuta-1,3-dien-1-yl)benzoyl)phenoxy)propanoate (4-3as)



根据通用方法 A 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 3/1 为展开剂)(61.1 mg, 99%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 60/40, flow =1.3 mL/min, 254 nm), t = 14.9 min (major), t = 10.2 min (minor), 90% de. $[\alpha]_D^{20}$ = 134.4 (c = 1.038, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.93 – 7.85 (m, 1H), 7.72 (d, *J* =

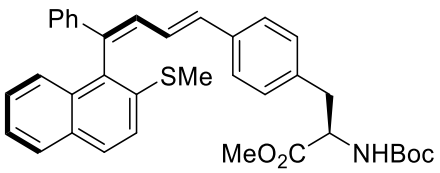
8.8 Hz, 1H), 7.70 – 7.66 (m, 1H), 7.66 – 7.59 (m, 2H), 7.45 – 7.40 (m, 2H), 7.40 – 7.34 (m, 2H), 7.35 – 7.26 (m, 2H), 7.19 – 7.15 (m, 2H), 7.10 – 6.96 (m, 3H), 6.92 – 6.77 (m, 4H), 6.73 (dd, *J* = 15.5, 10.8 Hz, 1H), 6.60 (d, *J* = 15.5 Hz, 1H), 4.96 (hept, *J* = 6.3 Hz, 1H), 1.92 (s, 3H), 1.52 (s, 6H), 0.88 (d, *J* = 6.3 Hz, 6H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 193.65, 172.95, 159.71, 140.86, 140.22, 140.09, 137.33, 136.81, 134.47, 134.07, 133.29, 132.23, 131.76, 131.50, 130.86, 130.43, 129.00, 128.97, 128.94, 128.56, 127.94, 127.71, 126.83, 126.47, 125.90, 125.66, 123.56, 117.23, 79.43, 69.07, 25.46, 25.42, 21.40, 15.31. HRMS (EI-TOF) calcd for $C_{41}H_{38}O_4S^+$ ([M]$^+$): 626.2491, found: 626.2491.

***(R)*-(8*S*,9*R*,13*R*,14*R*)-1,3-methyl-3-((1*E*,3*Z*)-4-(2-(methylthio)naphthalen-1-yl)-4-phenylbuta-1,3-dien-1-yl)-7,8,9,11,12,13,15,16-octahydro-6H-cyclopenta[a]phenanthren-17(14H)-one (4-3at)**



根据通用方法 A 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 3/1 为展开剂)(55.6 mg, 99%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 60/40, flow =1.3 mL/min, 254 nm), t = 14.8 min (major), t = 7.0 min (minor), 95% de. $[\alpha]_D^{20}$ = 274.3 (c = 0.78, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.99 – 7.90 (m, 1H), 7.73 – 7.62 (m, 2H), 7.48 – 7.39 (m, 3H), 7.29 (d, *J* = 8.7 Hz, 1H), 7.15 (d, *J* = 1.7 Hz, 2H), 7.14 (d, *J* = 1.7 Hz, 1H), 7.08 (dd, *J* = 8.3, 6.4 Hz, 2H), 7.05 – 6.99 (m, 1H), 6.95 (dd, *J* = 8.0, 1.9 Hz, 1H), 6.89 (d, *J* = 1.9 Hz, 1H), 6.84 – 6.74 (m, 3H), 2.32 (dd, *J* = 9.0, 4.3 Hz, 2H), 2.13 – 2.03 (m, 1H), 1.93 (s, 3H), 1.91 – 1.70 (m, 3H), 1.53 – 1.36 (m, 2H), 1.32 – 1.03 (m, 4H), 1.02 – 0.84 (m, 3H), 0.54 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 217.79, 140.43, 139.86, 138.31, 136.81, 136.63, 135.83, 135.30, 134.41, 133.35, 131.78, 131.43, 128.89, 128.83, 128.50, 127.68, 127.60, 127.47, 126.70, 126.31, 126.05, 125.87, 125.53, 124.60, 123.60, 50.30, 47.66, 44.57, 38.16, 35.57, 32.11, 29.24, 26.57, 25.84, 21.49, 15.33, 13.68. HRMS (EI-TOF) calcd for $C_{39}H_{38}OS^+$ ([M]$^+$): 554.2643, found: 554.2646.

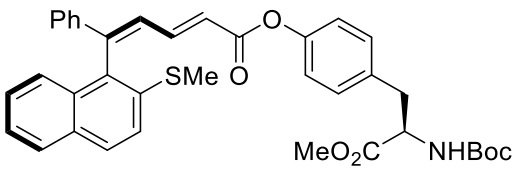
***(R)*-(*R*)-methyl 2-((tert-butoxycarbonyl)amino)-3-(4-((1*E*,3*Z*)-4-(2-(methylthio)naphthalen-1-yl)-4-phenylbuta-1,3-dien-1-yl)phenyl)propanoate (4-3au)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 3/1 为展开剂)(52.3 mg, 88%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 60/40, flow =1.3 mL/min, 254 nm), t = 22.1 min (major), t = 18.8 min (minor), 94% de. $[\alpha]_D^{20}$ = 162.6

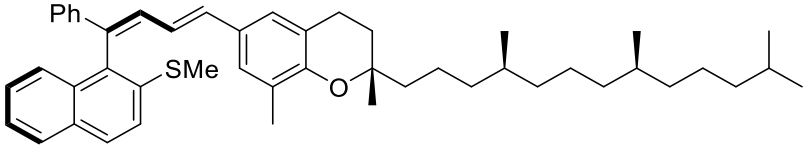
(c = 1.073, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.95 – 7.85 (m, 1H), 7.76 – 7.64 (m, 2H), 7.45 – 7.36 (m, 2H), 7.33 – 7.24 (m, 2H), 7.16 (m, 2H), 7.11 – 6.94 (m, 3H), 6.85 (d, *J* = 7.9 Hz, 2H), 6.70 – 6.57 (m, 4H), 4.88 (d, *J* = 8.4 Hz, 1H), 4.62 (dt, *J* = 8.6, 6.0 Hz, 1H), 3.12 (s, 3H), 2.87 – 2.55 (m, 2H), 1.91 (s, 3H), 1.36 (s, 9H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 172.13, 155.31, 140.32, 138.63, 136.79, 136.35, 135.94, 135.31, 134.33, 133.33, 131.77, 131.23, 129.68, 128.87, 128.84, 128.51, 127.74, 127.61, 127.06, 126.72, 126.66, 126.01, 125.56, 123.60, 79.50, 54.78, 51.53, 38.06, 28.36, 15.31. HRMS (ESI-TOF) calcd for $C_{36}H_{37}NO_4SNa^+$ ([M+Na]$^+$): 602.2336, found: 602.2338.

***(R)*-(2*E*,4*Z*)-4-((*R*)-2-((tert-butoxycarbonyl)amino)-3-methoxy-3-oxopropyl)phenyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3av)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =3/1 为展开剂)(61.1 mg, 95%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 60/40, flow =1.3 mL/min, 254 nm), t = 11.2 min (major), t = 8.0 min (minor), 95% de. $[\alpha]_D^{20}$ = 52.9 (c = 0.98, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 (d, *J* = 8.7 Hz, 1H), 7.83 (dd, *J* = 7.6, 1.7 Hz, 1H), 7.54 (dd, *J* = 8.0, 1.6 Hz, 1H), 7.49 (d, *J* = 8.8 Hz, 1H), 7.40 – 7.31 (m, 4H), 7.28 (q, *J* = 3.2, 2.6 Hz, 3H), 7.24 (s, 1H), 7.05 (d, *J* = 8.3 Hz, 2H), 6.99 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.95 – 6.90 (m, 2H), 6.25 (d, *J* = 15.2 Hz, 1H), 4.96 (d, *J* = 8.2 Hz, 1H), 4.53 (q, *J* = 6.6 Hz, 1H), 3.65 (s, 3H), 3.04 (td, *J* = 11.5, 9.1, 5.9 Hz, 2H), 2.44 (s, 3H), 1.40 (s, 9H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 172.25, 165.22, 155.13, 149.83, 147.61, 143.53, 138.47, 135.47, 133.38, 132.39, 132.27, 131.27, 130.13, 129.23, 129.12, 128.82, 128.29, 127.49, 127.37, 126.92, 125.39, 125.06, 123.21, 122.04, 121.70, 80.04, 54.44, 52.29, 37.73, 28.36, 15.94. HRMS (ESI-TOF) calcd for $C_{37}H_{37}NO_6SNa^+$ ([M+Na]$^+$): 646.2234, found: 646.2238.

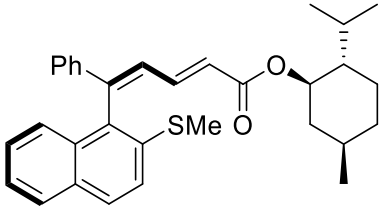
***(R)*-(*S*)-2,8-dimethyl-6-((1*E*,3*Z*)-4-(2-(methylthio)naphthalen-1-yl)-4-phenylbuta-1,3-dien-1-yl)-2-((4*S*,8*S*)-4,8,12-trimethyltridecyl)chroman (4-3aw)**



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(62.0 mg, 90%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.2 mL/min, 254 nm), t = 4.0 min (major), t = 2.8 min (minor), 91% de. $[\alpha]_D^{20}$ = 154.7 (c = 0.95, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.98 (dt, *J* = 6.4, 3.5 Hz, 1H), 7.72 – 7.62 (m, 2H),

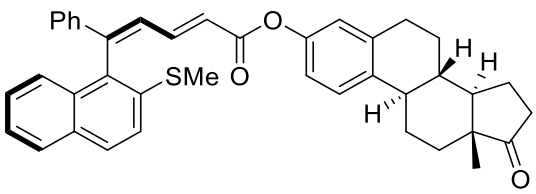
7.51 – 7.38 (m, 3H), 7.28 (d, *J* = 8.7 Hz, 1H), 7.16 – 7.13 (m, 2H), 7.08 (dd, *J* = 8.3, 6.5 Hz, 2H), 7.04 – 6.98 (m, 1H), 6.87 (s, 1H), 6.84 – 6.75 (m, 2H), 6.70 (dd, *J* = 15.4, 10.7 Hz, 1H), 2.11 (t, *J* = 6.7 Hz, 2H), 2.01 (s, 3H), 1.93 (s, 3H), 1.50 – 1.24 (m, 17H), 1.21 – 1.07 (m, 6H), 1.04 (s, 3H), 0.93 – 0.87 (m, 12H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 152.70, 140.67, 136.85, 136.68, 136.55, 134.63, 133.42, 132.00, 131.80, 128.96, 128.84, 128.71, 128.48, 127.94, 127.54, 127.36, 126.60, 126.40, 126.15, 125.93, 125.47, 124.02, 123.58, 120.62, 76.25, 40.49, 39.79, 37.94, 37.90, 37.86, 37.75, 33.27, 33.10, 31.34, 28.39, 25.32, 24.98, 24.17, 22.96, 22.87, 22.10, 21.36, 20.04, 19.89, 16.12, 15.29. HRMS (EI-TOF) calcd for $C_{48}H_{62}OS^+$ ([M]$^+$): 686.4521, found: 686.4519.

(*R*)-(2*E*,4*Z*)-(2*R*,5*R*)-2-isopropyl-5-methylcyclohexyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ax)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(43.4 mg, 89%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 22.2 min (major), t = 18.8 min (minor), 99% de. $[\alpha]_D^{20}$ = 23.6 (c = 0.933, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.94 – 7.81 (m, 2H), 7.58 – 7.44 (m, 2H), 7.42 – 7.33 (m, 2H), 7.33 – 7.28 (m, 2H), 7.28 – 7.24 (m, 3H), 7.22 (d, *J* = 11.5 Hz, 1H), 6.80 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.06 (d, *J* = 15.2 Hz, 1H), 4.55 (td, *J* = 10.8, 4.3 Hz, 1H), 2.43 (s, 3H), 1.96 – 1.86 (m, 1H), 1.62 (ddp, *J* = 19.9, 9.8, 3.8, 3.3 Hz, 4H), 1.41 (dddd, *J* = 15.2, 11.9, 6.6, 3.4 Hz, 1H), 1.26 (ddt, *J* = 14.6, 11.5, 3.2 Hz, 1H), 1.06 – 0.88 (m, 2H), 0.83 (d, *J* = 6.5 Hz, 4H), 0.76 (d, *J* = 7.0 Hz, 3H), 0.59 (d, *J* = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.55, 146.22, 141.46, 138.79, 135.39, 132.72, 132.50, 131.31, 129.06, 128.83, 128.77, 128.25, 127.72, 127.36, 126.84, 125.39, 125.15, 123.73, 123.38, 74.22, 47.08, 40.96, 34.37, 31.42, 26.39, 23.77, 22.10, 20.68, 16.56, 16.03. HRMS (EI-TOF) calcd for $C_{32}H_{36}O_2S^+$ ([M]$^+$): 484.2436, found: 484.2438.

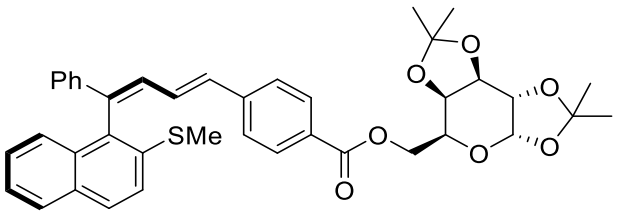
(*R*)-(2*E*,4*Z*)-(8*S*,9*R*,13*R*,14*R*)-13-methyl-17-oxo-7,8,9,11,12,13,14,15,16,17-decahydro-6H-cyclopenta[a]phenanthren-3-yl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-3ay)



根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 4/1 为展开剂)(58.0 mg, 99%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 60/40, flow =1.3 mL/min, 254 nm),

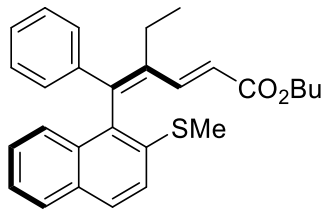
t = 8.8 min (major), t = 7.4 min (minor), 94% de. $[\alpha]_D^{20}$ = 126.6 (c = 0.952, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.71 – 7.63 (m, 1H), 7.61 – 7.44 (m, 3H), 7.32 (dt, *J* = 8.0, 3.4 Hz, 2H), 7.18 (d, *J* = 11.8 Hz, 1H), 7.13 – 7.08 (m, 3H), 7.04 – 6.97 (m, 3H), 6.89 (d, *J* = 8.5 Hz, 1H), 6.76 (dd, *J* = 8.5, 2.5 Hz, 1H), 6.64 (d, *J* = 2.6 Hz, 1H), 6.34 (d, *J* = 15.2 Hz, 1H), 2.45 (dd, *J* = 9.0, 4.3 Hz, 2H), 2.18 – 2.01 (m, 1H), 1.93 – 1.89 (m, 1H), 1.87 (s, 3H), 1.83 – 1.68 (m, 2H), 1.52 – 1.38 (m, 2H), 1.26 (td, *J* = 13.4, 12.8, 4.4 Hz, 2H), 1.13 – 0.85 (m, 5H), 0.55 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 217.91, 165.07, 149.43, 147.62, 143.23, 139.08, 137.64, 137.09, 136.32, 132.91, 132.69, 131.53, 129.35, 129.09, 128.96, 128.61, 127.95, 127.71, 127.37, 126.38, 125.54, 125.37, 123.38, 123.10, 122.14, 119.25, 50.25, 47.68, 44.20, 38.02, 35.61, 32.08, 29.44, 26.48, 25.86, 21.51, 15.28, 13.73. HRMS (EI-TOF) calcd for $C_{40}H_{38}O_3S^+$ ($[M]^+$): 598.2542, found: 598.2545.

(*R*)-((3a*S*,5*S*,5a*R*,8a*R*,8b*S*)-2,2,7,7-tetramethyltetrahydro-3aH-bis([1,3]dioxolo)[4,5-b:4',5'-d]pyran-5-yl)methyl 4-((1*E*,3*Z*)-4-(2-(methylthio)naphthalen-1-yl)-4-phenylbuta-1,3-dien-1-yl)benzoate (4-3az)



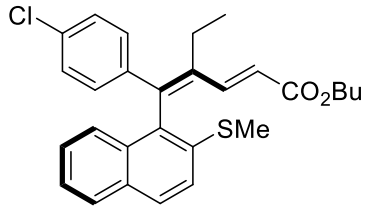
根据通用方法 A 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 10/1 为展开剂)(65.1 mg, 99%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.1 mL/min, 254 nm), t = 11.1 min (major), t = 12.9 min (minor), 93% de. $[\alpha]_D^{20}$ = 80.6 (c = 0.988, $CHCl_3$). ^{1}H NMR (400 MHz, Benzene-d_6) δ 7.89 – 7.84 (m, 1H), 7.83 – 7.76 (m, 2H), 7.75 – 7.64 (m, 2H), 7.44 – 7.37 (m, 2H), 7.33 – 7.22 (m, 2H), 7.20 – 7.16 (m, 1H), 7.10 – 6.97 (m, 3H), 6.81 (d, *J* = 8.3 Hz, 2H), 6.67 (dd, *J* = 15.5, 10.9 Hz, 1H), 6.52 (d, *J* = 15.5 Hz, 1H), 5.47 (d, *J* = 5.0 Hz, 1H), 4.71 – 4.55 (m, 2H), 4.45 (dd, *J* = 7.9, 2.4 Hz, 1H), 4.30 (ddd, *J* = 7.0, 4.8, 1.9 Hz, 1H), 4.14 (dd, *J* = 5.0, 2.4 Hz, 1H), 3.93 (dd, *J* = 7.9, 1.9 Hz, 1H), 1.92 (s, 3H), 1.40 (d, *J* = 6.4 Hz, 6H), 1.11 (s, 3H), 1.00 (s, 3H). ^{13}C NMR (101 MHz, Benzene-d_6) δ 166.15, 141.84, 140.22, 140.12, 136.77, 134.53, 134.08, 133.27, 131.77, 130.89, 130.32, 129.33, 129.04, 129.00, 128.92, 128.56, 127.94, 127.68, 126.83, 126.62, 125.90, 125.66, 123.60, 109.59, 108.63, 96.82, 71.51, 71.31, 70.98, 66.55, 64.24, 26.19 (d, *J* = 2.5 Hz), 24.93, 24.47, 15.34. HRMS (EI-TOF) calcd for $C_{40}H_{40}O_7S^+$ ($[M]^+$): 664.2495, found: 664.2495.

(*R*)-(2*E*,4*Z*)-butyl 4-((2-(methylthio)naphthalen-1-yl)(phenyl)methylene)hex-2-enoate (4-5aa)



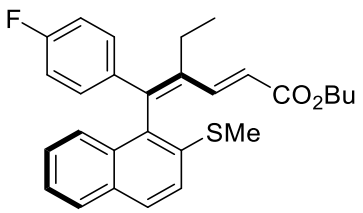
根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(40.5 mg, 94%)。手性 HPLC 分离条件：a AS-H column (*n*-hexane/*i*-PrOH = 94/6, flow =0.8 mL/min, 254 nm), t = 8.2 min (major), t = 9.8 min (minor), 95% ee. $[\alpha]_D^{20}$ = 52.3 (c = 0.917, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.78 (td, *J* = 12.7, 10.5, 6.7 Hz, 3H), 7.46 – 7.37 (m, 5H), 7.28 (d, *J* = 1.7 Hz, 1H), 7.26 – 7.18 (m, 2H), 6.96 (d, *J* = 15.9 Hz, 1H), 6.06 (d, *J* = 15.9 Hz, 1H), 3.97 (t, *J* = 6.4 Hz, 2H), 2.71 (q, *J* = 7.5 Hz, 2H), 2.44 (d, *J* = 1.4 Hz, 3H), 1.47 (p, *J* = 6.7 Hz, 2H), 1.30 (t, *J* = 7.4 Hz, 3H), 1.18 (q, *J* = 7.5 Hz, 2H), 0.82 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.44, 144.13, 143.71, 139.89, 139.83, 135.95, 135.18, 132.34, 131.46, 129.49, 128.67, 128.28, 127.90, 127.57, 127.15, 125.32, 125.14, 123.39, 119.20, 64.05, 30.64, 22.12, 19.15, 15.98, 14.42, 13.78. HRMS (EI-TOF) calcd for $C_{28}H_{30}O_2S^+$ ($[M]^+$): 430.1967, found: 430.1965.

(*R*)-(2*E*,4*Z*)-butyl 4-((4-chlorophenyl)(2-(methylthio)naphthalen-1-yl)methylene)hex-2-enoate (4-5ba)



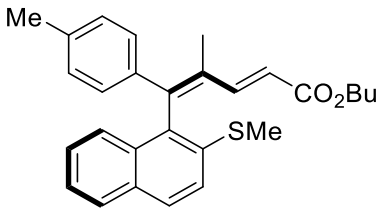
根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(20.4 mg, 43%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 4.1 min (major), t = 4.6 min (minor), 90% ee. $[\alpha]_D^{20}$ = 11.5 (c = 0.773, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 – 7.78 (m, 2H), 7.72 – 7.63 (m, 1H), 7.40 (ddt, *J* = 10.0, 6.8, 3.9 Hz, 3H), 7.35 – 7.29 (m, 2H), 7.24 – 7.20 (m, 2H), 6.91 (d, *J* = 15.9 Hz, 1H), 6.05 (d, *J* = 15.9 Hz, 1H), 3.96 (t, *J* = 6.5 Hz, 2H), 2.67 (q, *J* = 7.4 Hz, 2H), 2.45 (s, 3H), 1.46 (dq, *J* = 8.8, 6.7 Hz, 2H), 1.28 (t, *J* = 7.5 Hz, 3H), 1.16 (dt, *J* = 14.8, 7.4 Hz, 2H), 0.81 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.34, 143.35, 142.71, 140.45, 138.25, 135.37, 135.27, 133.41, 132.23, 131.47, 130.86, 128.89, 128.42, 128.18, 127.34, 125.25, 125.03, 123.28, 119.64, 64.14, 30.65, 22.14, 19.16, 15.92, 14.40, 13.80. HRMS (EI-TOF) calcd for $C_{28}H_{29}ClO_2S^+$ ($[M]^+$): 464.1577, found: 464.1579.

(*R*)-(2*E*,4*Z*)-butyl 4-((4-fluorophenyl)(2-(methylthio)naphthalen-1-yl)methylene)hex-2-enoate (4-5ca)



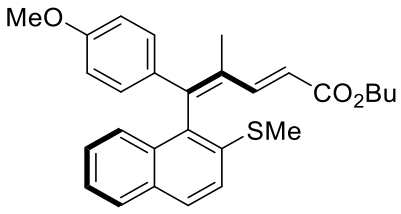
根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(29.6 mg, 65%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow =1.0 mL/min, 254 nm), t = 4.6 min (major), t = 5.6 min (minor), 90% ee. $[\alpha]_D^{20}$ = 33.9 (c = 0.9, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.85 – 7.76 (m, 2H), 7.71 (dd, *J* = 8.1, 1.5 Hz, 1H), 7.46 – 7.32 (m, 5H), 6.98 – 6.88 (m, 3H), 6.05 (d, *J* = 15.9 Hz, 1H), 3.96 (t, *J* = 6.5 Hz, 2H), 2.68 (q, *J* = 7.4 Hz, 2H), 2.44 (s, 3H), 1.46 (dq, *J* = 8.5, 6.5 Hz, 2H), 1.29 (t, *J* = 7.5 Hz, 3H), 1.17 (h, *J* = 7.4 Hz, 2H), 0.81 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.38, 162.06 (d, J_{CF} = 247.8 Hz), 143.47, 142.91, 140.10, 135.77 (d, J_{CF} = 3.4 Hz), 135.68, 135.16, 132.22, 131.47, 131.24 (d, J_{CF} = 7.9 Hz), 128.81, 128.39, 127.29, 125.16 (d, J_{CF} = 13.4 Hz), 123.31, 119.41, 114.93 (d, J_{CF} = 21.3 Hz), 64.10, 30.65, 22.11, 19.16, 15.92, 14.37, 13.79. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -114.06. HRMS (EI-TOF) calcd for $C_{28}H_{29}FO_2S^+$ ($[M]^+$): 448.1872, found: 448.1873.

(*R*)-(2*E*,4*Z*)-butyl 4-methyl-5-(2-(methylthio)naphthalen-1-yl)-5-(p-tolyl)penta-2,4-dienoate (4-5da)



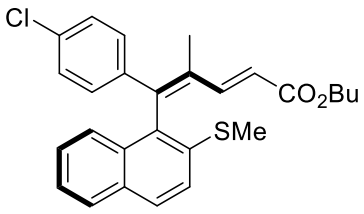
根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 =20/1 为展开剂)(39.4 mg, 91%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 94/6, flow = 0.8 mL/min, 254 nm), t = 7.9 min (major), t = 8.5 min (minor), 95% ee. $[\alpha]_D^{20}$ = 61.2 (c = 0.88, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 – 7.81 (m, 2H), 7.77 – 7.68 (m, 1H), 7.43 (ddd, *J* = 11.0, 9.4, 6.9 Hz, 3H), 7.28 (t, *J* = 6.1 Hz, 2H), 7.14 – 7.04 (m, 3H), 6.07 (d, *J* = 15.6 Hz, 1H), 4.02 (t, *J* = 6.5 Hz, 2H), 2.48 (s, 3H), 2.33 (s, 3H), 2.29 (s, 3H), 1.52 (dq, *J* = 8.5, 6.4 Hz, 2H), 1.25 (q, *J* = 7.5 Hz, 2H), 0.87 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.40, 145.31, 144.83, 137.49, 136.74, 135.87, 135.32, 133.28, 132.51, 131.39, 130.10, 128.64, 128.58, 128.22, 127.12, 125.38, 125.10, 123.11, 119.08, 64.00, 30.66, 21.35, 19.16, 15.99, 15.88, 13.77. HRMS (EI-TOF) calcd for $C_{28}H_{30}O_2S^+$ ($[M]^+$): 430.1967, found: 430.1969.

(*R*)-(2*E*,4*Z*)-butyl 5-(4-methoxyphenyl)-4-methyl-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-5ea)



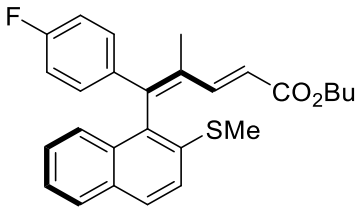
根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(37.8 mg, 85%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 94/6, flow = 0.8 mL/min, 254 nm), t = 11.1 min (major), t = 12.2 min (minor), 93% ee. $[\alpha]_D^{20}$ = 47.3 (c = 0.96, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.81 (t, *J* = 9.3 Hz, 2H), 7.71 – 7.59 (m, 1H), 7.46 – 7.34 (m, 3H), 7.26 – 7.22 (m, 2H), 7.04 (dd, *J* = 15.6, 1.2 Hz, 1H), 6.84 – 6.70 (m, 2H), 6.01 (dd, *J* = 15.6, 1.2 Hz, 1H), 3.97 (t, *J* = 6.5 Hz, 2H), 3.75 (d, *J* = 1.2 Hz, 3H), 2.44 (d, *J* = 1.2 Hz, 3H), 2.26 (s, 3H), 1.48 (p, *J* = 6.7 Hz, 2H), 1.20 (h, *J* = 7.1 Hz, 2H), 0.86 – 0.76 (m, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.44, 158.98, 145.38, 144.52, 135.94, 135.30, 132.78, 132.49, 132.04, 131.54, 131.38, 128.64, 128.22, 127.13, 125.35, 125.12, 123.11, 118.82, 113.26, 63.98, 55.25, 30.66, 19.16, 16.01, 15.87, 13.77. HRMS (EI-TOF) calcd for $C_{28}H_{30}O_3S^+$ ($[M]^+$): 446.1916, found: 446.1919.

(*R*)-(2*E*,4*Z*)-butyl 5-(4-chlorophenyl)-4-methyl-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-5fa)



根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(38.5 mg, 84%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 4.8 min (major), t = 5.6 min (minor), 93% ee. $[\alpha]_D^{20}$ = 32.9 (c = 1.073, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.86 – 7.75 (m, 2H), 7.67 – 7.60 (m, 1H), 7.47 – 7.37 (m, 3H), 7.27 (d, *J* = 8.0 Hz, 2H), 7.22 (d, *J* = 8.6 Hz, 2H), 7.03 (d, *J* = 15.6 Hz, 1H), 6.05 (d, *J* = 15.6 Hz, 1H), 3.98 (t, *J* = 6.5 Hz, 2H), 2.45 (s, 3H), 2.23 (s, 3H), 1.52 – 1.43 (m, 2H), 1.20 (p, *J* = 7.4 Hz, 2H), 0.83 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.23, 144.80, 143.38, 138.10, 135.50, 135.24, 134.28, 133.43, 132.38, 131.51, 131.43, 128.95, 128.37, 128.09, 127.34, 125.26, 125.07, 123.15, 119.86, 64.12, 30.65, 19.16, 15.96, 15.86, 13.77. HRMS (EI-TOF) calcd for $C_{27}H_{27}ClO_2S^+$ ($[M]^+$): 450.1420, found: 450.1419.

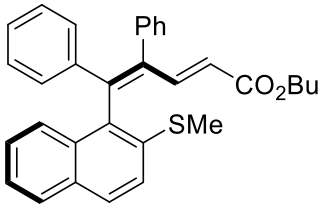
(*R*)-(2*E*,4*Z*)-butyl 5-(4-fluorophenyl)-4-methyl-5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate (4-5ga)



根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(31.3 mg, 71%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 4.9 min (major), t = 6.0 min (minor), 93% ee. $[\alpha]_D^{20}$ =

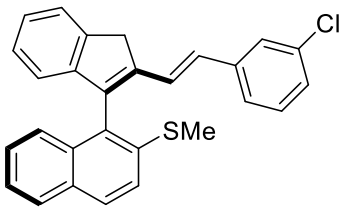
57.2 (c = 1.155, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.82 (t, *J* = 9.5 Hz, 2H), 7.69 – 7.60 (m, 1H), 7.46 – 7.35 (m, 3H), 7.33 – 7.27 (m, 2H), 7.03 (d, *J* = 15.7 Hz, 1H), 6.95 (t, *J* = 8.7 Hz, 2H), 6.04 (d, *J* = 15.6 Hz, 1H), 3.98 (t, *J* = 6.5 Hz, 2H), 2.44 (s, 3H), 2.23 (s, 3H), 1.48 (dq, *J* = 8.5, 6.6 Hz, 2H), 1.20 (h, *J* = 7.4 Hz, 2H), 0.82 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.30, 162.03 (d, J_{CF} = 247.8 Hz), 144.94, 143.58, 135.63 (d, J_{CF} = 3.5 Hz), 135.52, 135.40, 133.88, 132.37, 131.94 (d, J_{CF} = 8.1 Hz), 131.44, 128.88, 128.36, 127.30, 125.19 (d, J_{CF} = 10.3 Hz), 123.18, 119.62, 114.87 (d, J_{CF} = 21.3 Hz), 64.10, 30.66, 19.17, 15.95, 15.87, 13.78. ^{19}F NMR (376 MHz, Chloroform-*d*) δ -114.05. HRMS (EI-TOF) calcd for $C_{27}H_{27}FO_2S^+$ ($[M]^+$): 434.1716, found: 434.1719.

***(R)*-(2*E*,4*E*)-butyl 5-(2-(methylthio)naphthalen-1-yl)-4,5-diphenylpenta-2,4-dienoate (4-5ha)**



根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(37.9 mg, 77%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 5.1 min (major), t = 5.7 min (minor), 90% ee. $[\alpha]_D^{20}$ = 207.9 (c = 0.94, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.89 (d, *J* = 8.8 Hz, 1H), 7.87 – 7.75 (m, 2H), 7.52 (d, *J* = 8.7 Hz, 1H), 7.42 (td, *J* = 6.1, 5.5, 3.2 Hz, 2H), 7.39 – 7.28 (m, 5H), 7.19 (d, *J* = 15.5 Hz, 1H), 6.99 (tdd, *J* = 8.3, 5.1, 2.5 Hz, 5H), 5.63 (d, *J* = 15.5 Hz, 1H), 3.94 (t, *J* = 6.5 Hz, 2H), 2.52 (s, 3H), 1.44 (dq, *J* = 8.5, 6.6 Hz, 2H), 1.17 (h, *J* = 7.4 Hz, 2H), 0.81 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.39, 145.38, 144.78, 140.20, 139.20, 138.68, 136.04, 135.24, 132.35, 131.51, 130.96, 130.56, 129.07, 128.57, 128.35, 127.55, 127.51, 127.35, 125.31, 125.21, 123.32, 122.53, 64.05, 30.63, 19.13, 15.96, 13.76. HRMS (EI-TOF) calcd for $C_{32}H_{30}O_2S^+$ ($[M]^+$): 478.1967, found: 478.1968.

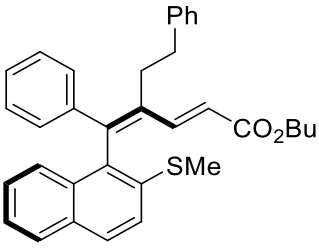
***(R)*-(*E*)-(1-(2-(3-chlorostyryl)-1H-inden-3-yl)naphthalen-2-yl)(methyl)sulfane (4-5ik)**



根据通用方法 B 在 60 ºC 下使用 **L13** 为手性配体经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 20/1 为展开剂)(23.8 mg, 56%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 96/4, flow = 0.8 mL/min, 254 nm), t = 7.9 min (major), t = 8.5 min (minor), 87% ee. $[\alpha]_D^{20}$ = 108.6 (c = 0.715, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.97 (d, *J* = 8.8 Hz, 1H), 7.90 (dd, *J* = 8.2, 1.3 Hz, 1H), 7.58 (dd, *J* = 8.1, 4.8 Hz, 2H), 7.51 (d, *J* = 8.4 Hz, 1H), 7.44 (ddd, *J* = 8.1, 6.6, 1.3 Hz, 1H), 7.34 (ddd, *J* = 8.2, 6.7, 1.4 Hz, 1H), 7.26 – 7.21 (m, 2H), 7.18 – 7.07 (m, 4H), 6.83 (d, *J* = 16.1 Hz, 1H), 6.77 – 6.64 (m, 2H),

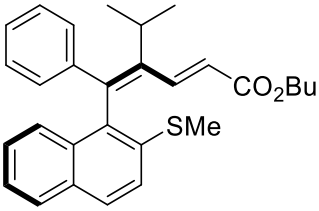
4.00 (s, 2H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 145.92, 143.71, 142.31, 140.82, 139.39, 136.29, 134.52, 132.73, 131.34, 129.79, 129.04, 128.98, 128.88, 128.24, 127.42, 127.01, 126.80, 126.34, 125.93, 125.54, 125.35, 124.87, 124.78, 123.91, 123.36, 120.74, 37.76, 16.16. HRMS (EI-TOF) calcd for $C_{32}H_{30}O_2S^+$ ([M]$^+$): 424.1053, found: 424.1050.

(*R*)-(2*E*,4*Z*)-butyl 4-((2-(methylthio)naphthalen-1-yl)(phenyl)methylene)-6-phenylhex-2-enoate (4-5ja)



根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(23.1 mg, 47%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.0 mL/min, 254 nm), t = 5.2 min (major), t = 7.0 min (minor), 91% ee. $[\alpha]_D^{20}$ = 25.4 (c = 0.98, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.80 (dd, *J* = 9.2, 4.9 Hz, 2H), 7.67 – 7.61 (m, 1H), 7.44 – 7.40 (m, 2H), 7.39 – 7.36 (m, 2H), 7.33 – 7.28 (m, 2H), 7.26 – 7.20 (m, 3H), 7.16 – 7.12 (m, 2H), 7.03 (d, *J* = 15.9 Hz, 1H), 6.15 (d, *J* = 15.9 Hz, 1H), 4.00 (t, *J* = 6.5 Hz, 2H), 3.00 (d, *J* = 2.1 Hz, 4H), 2.45 (s, 3H), 1.53 – 1.43 (m, 2H), 1.19 (dt, *J* = 14.7, 7.4 Hz, 2H), 0.84 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.38, 145.43, 143.83, 141.66, 139.68, 137.63, 135.87, 135.11, 132.16, 131.48, 129.52, 128.73, 128.59, 128.49, 128.28, 127.93, 127.69, 127.19, 126.22, 125.42, 125.18, 123.46, 119.28, 64.16, 35.40, 30.93, 30.66, 19.17, 16.05, 13.81. HRMS (EI-TOF) calcd for $C_{34}H_{34}O_2S^+$ ([M]$^+$): 506.2280, found: 506.2279.

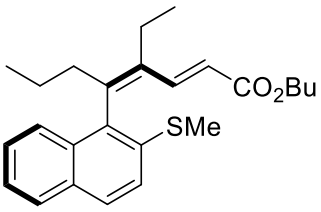
(*R*)-(2*E*,4*Z*)-butyl 5-methyl-4-((2-(methylthio)naphthalen-1-yl)(phenyl)methylene)hex-2-enoate (4-5ka)



根据通用方法 B 经过制备级 TLC 分离得到白色固体(石油醚/乙酸乙酯 = 20/1 为展开剂)(18.5 mg, 41%)。手性 HPLC 分离条件：a OD-H+IB column (*n*-hexane/*i*-PrOH = 99/1, flow = 0.5 mL/min, 254 nm), t = 17.0 min (major), t = 17.9 min (minor), 82% ee. $[\alpha]_D^{20}$ = 61.8 (c = 0.753, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.81 (d, *J* = 8.3 Hz, 1H), 7.76 (d, *J* = 8.6 Hz, 2H), 7.46 – 7.41 (m, 1H), 7.38 (dd, *J* = 8.5, 1.8 Hz, 4H), 7.26 – 7.22 (m, 2H), 7.21 – 7.16 (m, 1H), 7.01 (d, *J* = 16.4 Hz, 1H), 5.99 (d, *J* = 16.4 Hz, 1H), 3.92 (t, *J* = 6.5 Hz, 2H), 3.46 (p, *J* = 7.1 Hz, 1H), 2.46 (s, 3H), 1.47 – 1.38 (m, 2H), 1.35 (d, *J* = 7.1 Hz, 6H), 1.12 (dt, *J* = 14.7, 7.5 Hz, 2H), 0.80 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.18, 143.77, 142.48, 142.02, 140.13, 136.74, 134.83, 132.05, 131.47, 129.56, 128.45, 128.31, 127.92, 127.41,

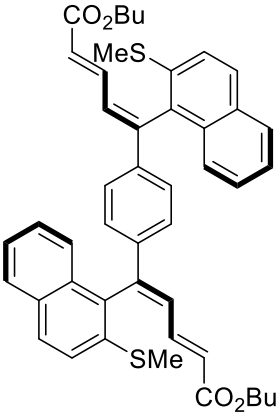
127.15, 125.15, 125.09, 123.28, 121.03, 64.01, 30.62, 30.41, 21.87, 21.44, 19.13, 15.92, 13.81. HRMS (EI-TOF) calcd for $C_{29}H_{32}O_2S^+$ ([M]$^+$): 444.2123, found: 444.2125.

***(R)*-(2*E*,4*Z*)-butyl 4-ethyl-5-(2-(methylthio)naphthalen-1-yl)octa-2,4-dienoate (4-5la)**



根据通用方法 B 经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(22.1 mg, 56%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 90/10, flow = 1.1 mL/min, 254 nm), t = 3.6 min (major), t = 6.0 min (minor), 85% ee. $[\alpha]_D^{20}$ = 124.0 (c = 1.0, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.79 (dd, *J* = 9.1, 3.2 Hz, 2H), 7.58 – 7.51 (m, 1H), 7.44 – 7.34 (m, 3H), 6.83 (d, *J* = 15.8 Hz, 1H), 5.89 (d, *J* = 15.8 Hz, 1H), 3.93 (t, *J* = 6.5 Hz, 2H), 2.66 – 2.52 (m, 4H), 2.48 (s, 3H), 1.48 – 1.40 (m, 2H), 1.35 (dt, *J* = 10.1, 7.0 Hz, 2H), 1.26 (t, *J* = 7.5 Hz, 3H), 1.15 (h, *J* = 7.4 Hz, 2H), 0.85 (t, *J* = 7.3 Hz, 3H), 0.79 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.65, 146.03, 143.99, 137.89, 136.21, 134.41, 132.18, 131.38, 128.28, 128.14, 126.74, 125.33, 125.13, 123.46, 117.01, 63.90, 37.27, 30.68, 21.94, 21.07, 19.16, 16.12, 14.96, 13.77, 13.71. HRMS (EI-TOF) calcd for $C_{25}H_{32}O_2S^+$ ([M]$^+$): 396.2123, found: 396.2122.

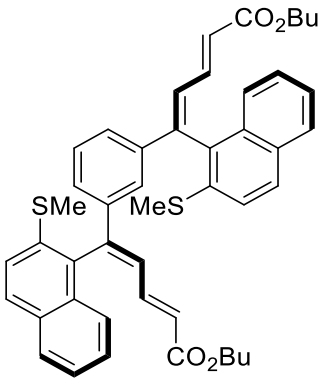
***(R),(R)*-(2*E*,2'*E*,4*Z*,4'*Z*)-dibutyl 5,5'-(1,4-phenylene)bis(5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate) (4-7aa)**



根据通用方法 C 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 10/1 为展开剂)(24.2 mg, 66%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 85/15, flow = 1.2 mL/min, 254 nm), t = 16.3 min (major), t = 25.0 min (minor), 99% ee, 94:6 dr. $[\alpha]_D^{20}$ = 33.5 (c = 0.85, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.87 (d, *J* = 8.8 Hz, 2H), 7.84 – 7.78 (m, 2H), 7.46 (t, *J* = 8.7 Hz, 4H), 7.35 (dddd, *J* = 22.0, 8.1, 6.7, 1.4 Hz, 4H), 7.20 (d, *J* = 4.9 Hz, 6H), 6.81 (dd, *J* = 15.2, 11.5 Hz, 2H), 6.07 (d, *J* = 15.1 Hz, 2H), 4.00 (t, *J* = 6.6 Hz, 4H), 2.42 (s, 6H), 1.51 (dt, *J* = 8.4, 6.6 Hz, 4H), 1.26 (q, *J* = 7.6 Hz, 4H), 0.85 (t, *J* = 7.4 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.01, 145.66, 141.53, 138.91, 135.45, 132.34, 132.15, 131.27, 129.13, 128.25, 128.05, 127.32, 127.11, 125.36, 125.13, 123.46, 123.12, 64.22, 30.69, 19.19, 15.91, 13.77. HRMS (EI-TOF) calcd for $C_{46}H_{46}O_4S_2^+$ ([M]$^+$): 726.2838, found: 726.2836.

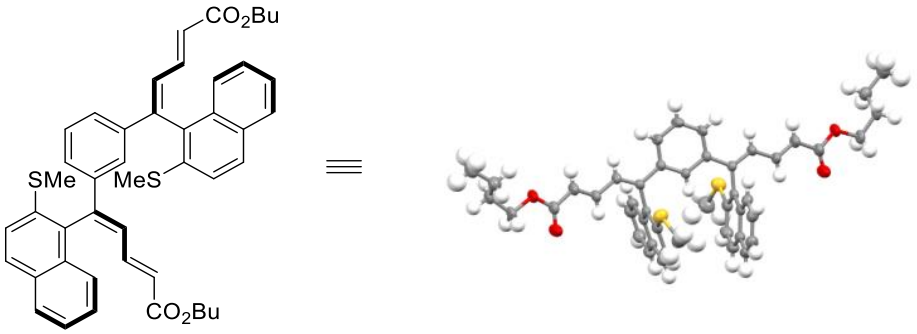
***(R),(R)*-(2*E*,2'*E*,4*Z*,4'*Z*)-dibutyl 5,5'-(1,3-phenylene)bis(5-(2-(methylthio)naphthalen-1-**

yl)penta-2,4-dienoate) (4-7ba)



根据通用方法 C 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 10/1 为展开剂)(25.5 mg, 69%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 85/15, flow = 1.2 mL/min, 254 nm), t = 6.2 min (major), t = 14.0 min (minor), 99% ee, 97:3 dr. $[\alpha]_D^{20}$ = 116.2 (c = 1.375, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.76 (dd, *J* = 14.2, 8.4 Hz, 4H), 7.50 – 7.32 (m, 6H), 7.28 (dd, *J* = 4.6, 3.3 Hz, 2H), 7.26 – 7.23 (m, 1H), 7.21 – 7.07 (m, 4H), 6.82 – 6.56 (m, 3H), 6.03 (d, *J* = 15.2 Hz, 2H), 3.98 (t, *J* = 6.6 Hz, 4H), 2.07 (s, 6H), 1.50 (dq, *J* = 8.4, 6.7 Hz, 4H), 1.26 (dd, *J* = 8.4, 6.6 Hz, 4H), 0.83 (t, *J* = 7.4 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.03, 145.89, 141.57, 138.74, 135.29, 132.22, 132.11, 131.15, 129.04, 128.88, 128.16, 127.61, 127.13, 126.48, 126.40, 125.21, 125.04, 123.33, 123.17, 64.23, 30.70, 19.19, 15.76, 13.77. HRMS (EI-TOF) calcd for $C_{46}H_{46}O_4S_2^+$ ($[M]^+$): 726.2838, found: 726.2837.

X-ray data of (*R*,*R*)-4-7ba

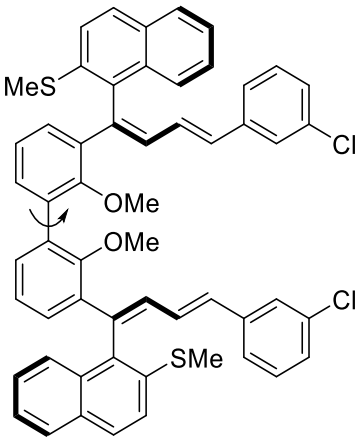


(*R*,*R*)-4-7ba

Bond precision:	C-C = 0.0065 A	Wavelength = 0.71073
Cell:	a = 21.7400(12) b =15.7298(9) c = 15.8082(8)	
alpha = 90	beta = 132.803(1)	gamma = 90
Temperature: 170 K	Calculated	Reported
Volume	3966.3(4)	3966.2(4)
Space group	C 2	C 1 2 1
Hall group	C 2y	C 2y
Moiety formula	C_{46} H_{46} O_4 S_2	C_{46} H_{46} O_4 S_2
Sum formula	C_{46} H_{46} O_4 S_2	C_{46} H_{46} O_4 S_2

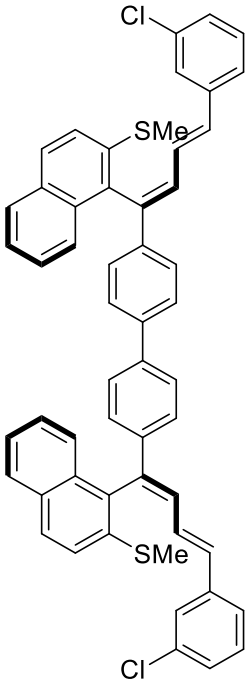
Mr	726.95	726.95
Dx, g cm^{-3}	1.217	1.217
Z	4	4
Mu (mm^{-1})	0.177	0.177
F000	1544.0	1544.0
F000’	1545.61	
h,k,lmax	27,19,19	27,19,19
Nref	8174[4242]	8147
Tmin, Tmax	0.967,0.982	0.686,0.745
Tmin’	0.945	
Correction method = # Reported T	Limits: Tmin = 0.686	Tmax = 0.745
AbsCorr = MULTI-SCAN		
Data completeness	1.92/1.00	Theta(max) = 26.429
R (reflections)	0.0479(6919)	wR2(reflections)=0.1403(8147)
S = 1.043	Npar = 475	
Flack parameter	0.03(2)	

***(R),(R)*-(((1*Z*,1'*Z*,3*E*,3'*E*)-(2,2'-dimethoxy-[1,1'-biphenyl]-3,3'-diyl)bis(4-(3-chlorophenyl)buta-1,3-diene-1,1-diyl))bis(naphthalene-2,1-diyl))bis(methylsulfane) (4-7ck)**



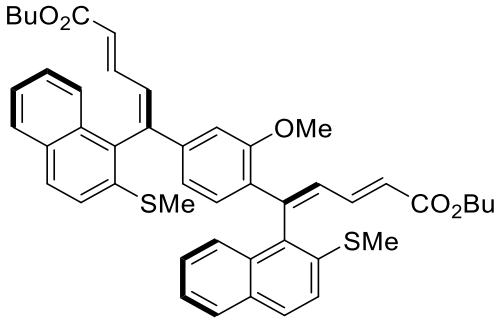
根据通用方法 C 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 =10/1 为展开剂)(35.6 mg, 79%)。手性 HPLC 分离条件：a IA column (*n*-hexane/*i*-PrOH = 92/8, flow = 1.0 mL/min, 254 nm), t = 9.4 min (major), t = 7.0 min (minor), 93% ee, 92:8 dr. $[\alpha]_D^{20}$ = 85.3 (c = 1.335, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.94 (d, *J* = 8.7 Hz, 2H), 7.91 – 7.76 (m, 6H), 7.56 (d, *J* = 8.7 Hz, 2H), 7.43 (qd, *J* = 7.2, 3.4 Hz, 4H), 7.32 - 7.21 (m, 2H), 7.12 – 7.04 (m, 6H), 6.99 (t, *J* = 4.2 Hz, 2H), 6.91 (t, *J* = 7.7 Hz, 2H), 6.77 (dd, *J* = 7.9, 1.8 Hz, 2H), 6.70 (d, *J* = 15.5 Hz, 2H), 6.31 (dd, *J* = 15.5, 11.2 Hz, 2H), 3.56 (s, 6H), 2.47 (s, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 156.40, 139.46, 136.34, 135.57, 135.21, 134.53, 134.41, 133.27, 133.04, 131.41, 131.14, 129.87, 129.69, 128.94, 128.66, 128.22, 127.41, 127.25, 126.46, 125.94, 125.37, 124.84, 123.75, 123.71, 123.63, 123.57, 59.68, 16.20. HRMS (ESI-TOF) calcd for $C_{56}H_{44}Cl_2O_2S_2$+Na ($[M+Na]^+$): 905.2052, found: 905.2056.

***(R),(R)*-4,4'-bis((1*Z*,3*E*)-4-(3-chlorophenyl)-1-(2-(methylthio)naphthalen-1-yl)buta-1,3-dien-1-yl)-1,1'-biphenyl (4-7dk)**



根据通用方法 C 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 10/1 为展开剂)(25.8 mg, 62%)。手性 HPLC 分离条件：a IF column (*n*-hexane/*i*-PrOH = 40/60, flow = 1.2 mL/min, 254 nm), t = 38.7 min (major), t = 30.7 min (minor), 98% ee, 94:6 dr. $[\alpha]_D^{20}$ = 82.1 (c = 1.2, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.96 (d, *J* = 8.8 Hz, 2H), 7.91 – 7.86 (m, 2H), 7.68 – 7.63 (m, 2H), 7.56 (d, *J* = 8.8 Hz, 2H), 7.49 – 7.45 (m, 4H), 7.41 (dtd, *J* = 14.8, 6.8, 1.5 Hz, 4H), 7.36 – 7.32 (m, 6H), 7.13 (d, *J* = 1.9 Hz, 2H), 7.09 (dd, *J* = 5.1, 1.1 Hz, 4H), 7.02 (td, *J* = 4.0, 3.3, 1.6 Hz, 2H), 6.72 (d, *J* = 15.5 Hz, 2H), 6.32 (dd, *J* = 15.5, 11.0 Hz, 2H), 2.47 (s, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 139.86, 139.25, 138.96, 138.30, 135.75, 134.43, 133.48, 133.09, 132.59, 131.31, 130.05, 129.72, 128.84, 128.27, 127.91, 127.54, 127.32, 127.13, 126.64, 126.43, 125.45, 125.36, 124.91, 123.04, 15.88. HRMS (EI-TOF) calcd for $C_{54}H_{40}Cl_2S_2^+$ ($[M]^+$): 822.1948, found: 822.1946.

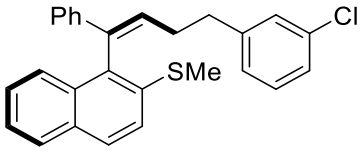
***(R),(R)*-(2*E*,2'*E*,4*Z*,4'*Z*)-dibutyl 5,5'-(2-methoxy-1,4-phenylene)bis(5-(2-(methylthio)naphthalen-1-yl)penta-2,4-dienoate) (4-7ea)**



根据通用方法 C 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 10/1 为展开剂)(28.1 mg, 74%)。手性 HPLC 分离条件：two IC columns (*n*-hexane/*i*-PrOH = 80/20, flow = 1.2 mL/min, 254 nm), t = 21.9 min (major), t = 25.6 min (minor), 95% ee, 93:7 dr. $[\alpha]_D^{20}$ = 67.5 (c = 1.04, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.81 (ddd, *J* = 18.3, 10.9, 8.3 Hz, 4H), 7.61 (d, *J* = 11.8 Hz, 1H), 7.54 (dd, *J* = 8.0, 1.6 Hz, 1H), 7.50 – 7.40 (m, 3H), 7.34 (dddd, *J* = 14.6, 8.7, 4.0, 2.2 Hz, 4H), 7.19 (d, *J* = 11.5 Hz, 1H), 7.05 (d, *J* = 1.8 Hz, 1H), 6.79 (ddd, *J* = 14.7, 11.6, 2.7 Hz, 2H), 6.63 – 6.42 (m, 2H), 6.04 (dd, *J* = 25.0, 15.2 Hz, 2H), 3.99 (q, *J* = 6.4 Hz, 4H), 3.85 (s, 3H), 2.41 (s, 6H), 1.56 – 1.45 (m, 4H), 1.30 – 1.22 (m, 4H), 0.84 (td, *J* = 7.4, 2.5 Hz, 6H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.21, 167.00, 158.39, 145.84, 142.59, 142.50, 141.48, 139.50, 135.44, 135.39, 133.82, 132.62, 132.52, 132.37, 132.14, 131.24, 131.22, 130.98, 129.14, 128.83, 128.22, 128.11, 128.07, 127.30,

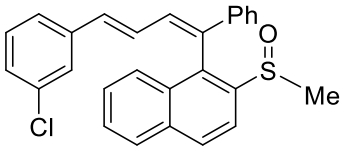
127.18, 125.37, 125.24, 125.16, 123.48, 123.07, 122.88, 119.74, 109.38, 64.23, 64.06, 55.65, 30.70, 30.69, 19.19, 15.95, 15.92, 13.79. HRMS (EI-TOF) calcd for $C_{47}H_{48}O_5S_2^+$ ([M]$^+$): 756.2943, found: 756.2947.

(*R*)-(*Z*)-(1-(4-(3-chlorophenyl)-1-phenylbut-1-en-1-yl)naphthalen-2-yl)(methyl)sulfane(4-8)



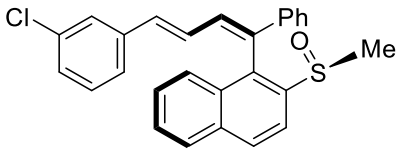
经过制备级 TLC 分离得到黄色液体(石油醚/乙酸乙酯 = 20/1 为展开剂)(34.1 mg, 83%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 96/4, flow = 0.8 mL/min, 254 nm), t = 7.6 min (major), t = 8.2 min (minor), 93% ee. $[\alpha]_D^{20}$ = 38.9 (c = 1.11, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.88 (ddd, *J* = 12.1, 8.5, 2.0 Hz, 2H), 7.67 (d, *J* = 8.3 Hz, 1H), 7.51 (dd, *J* = 8.8, 1.9 Hz, 1H), 7.48 – 7.35 (m, 2H), 7.29 (d, *J* = 1.9 Hz, 1H), 7.27 (d, *J* = 1.8 Hz, 1H), 7.26 – 7.20 (m, 3H), 7.17 – 7.11 (m, 2H), 7.06 (s, 1H), 6.95 (tt, *J* = 3.8, 2.0 Hz, 1H), 6.57 (td, *J* = 7.2, 1.9 Hz, 1H), 2.81 – 2.64 (m, 2H), 2.50 (d, *J* = 1.9 Hz, 3H), 2.32 – 2.19 (m, 1H), 2.12 (dtd, *J* = 13.0, 6.9, 3.2 Hz, 1H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 143.93, 139.91, 137.70, 135.18, 134.10, 133.95, 132.26, 131.28, 131.21, 129.58, 128.64, 128.50, 128.32, 128.18, 127.26, 127.07, 126.77, 126.20, 126.09, 125.20, 125.17, 122.88, 35.00, 31.45, 15.69. HRMS (EI-TOF) calcd for $C_{27}H_{23}ClS^+$ ([M]$^+$): 414.1209, found: 414.1211.

1-((1*Z*,3*E*)-4-(3-chlorophenyl)-1-phenylbuta-1,3-dien-1-yl)-2-(methylsulfinyl)naphthalene(*rac*-4-9a)



^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.25 – 8.20 (m, 2.38H), 8.01 (d, *J* = 8.2 Hz, 1.32H), 7.84 (d, *J* = 8.4 Hz, 1.31H), 7.62 (m, 1.34H), 7.50 (m, 1.39H), 7.35 (d, *J* = 11.0 Hz, 1.32H), 7.28 (m, 2.69H), 7.25 (s, 1.39H), 7.18 (dd, *J* = 7.7, 2.0 Hz, 2.4H), 7.12 – 7.08 (m, 3.93H), 7.00 – 6.95(m, 1.37H), 6.75 (d, *J* = 15.5 Hz, 1.3H), 6.32 (dd, *J* = 15.4, 11.0 Hz, 1H), 6.07 (dd, *J* = 15.4, 11.0 Hz, 0.24H) 2.67 (s, 1.0H), 2.24 (s, 3H). The dr value was determined by ^{1}H NMR (3:1 dr).

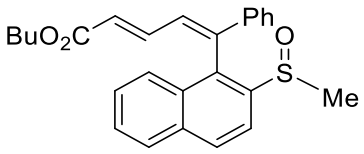
(*R*)-1-((1*Z*,3*E*)-4-(3-chlorophenyl)-1-phenylbuta-1,3-dien-1-yl)-2-((*S*)-methylsulfinyl)naphthalene (4-9a)



根据通用方法 E 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 2/1 为展开剂)(33.4 mg, 77%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 70/30, flow = 1.1 mL/min, 254 nm), t = 19.3 min (major), t = 17.5 min (minor), 96% ee, 14:1 dr. $[\alpha]_D^{20}$ = -61.1 (c

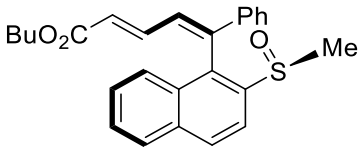
= 0.93, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.27 – 8.17 (m, 2H), 8.01 (d, *J* = 8.4 Hz, 1H), 7.84 (d, *J* = 8.5 Hz, 1H), 7.62 (ddd, *J* = 8.1, 6.7, 1.3 Hz, 1H), 7.50 (ddd, *J* = 8.3, 6.7, 1.4 Hz, 1H), 7.35 (d, *J* = 11.0 Hz, 1H), 7.28 (m, 1H), 7.24 (m, 2H), 7.18 (dd, *J* = 7.8, 2.0 Hz, 2H), 7.13 – 7.06 (m, 3H), 7.00 (dt, *J* = 6.1, 2.2 Hz, 1H), 6.75 (d, *J* = 15.5 Hz, 1H), 6.32 (dd, *J* = 15.4, 11.1 Hz, 1H), 2.23 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 141.76, 140.24, 138.58, 135.47, 135.11, 134.89, 134.80, 134.51, 131.96, 130.60, 130.60, 129.80, 129.06, 129.06, 128.73, 128.28, 128.09, 128.06, 128.04, 126.86, 126.80, 126.35, 124.90, 119.45, 42.31. HRMS (EI-TOF) calcd for $C_{27}H_{21}ClOS^+$ ([M]$^+$): 428.1002, found: 428.1003.

(2*E*,4*Z*)-butyl 5-(2-(methylsulfinyl)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (*rac*-4-9b)



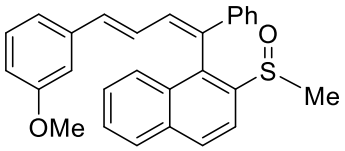
^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.19 (m, 3.06H), 7.98 (dd, *J* = 8.4, 4.6 Hz, 1.57H), 7.74 (dd, *J* = 11.5, 8.2 Hz, 1.52H), 7.64 – 7.56 (m, 1.57H), 7.53 – 7.46 (m, 1.49H), 7.33 – 7.25 (m, 7.54H), 7.19 (dd, *J* = 4.9, 1.7 Hz, 1.61H), 6.78 (dd, *J* = 15.2, 11.6 Hz, 1H), 6.11 (dd, *J* = 15.2, 2.0 Hz, 1.49H), 4.06 – 3.93 (m, 3.12H), 2.66 (s, 1.77H), 2.17 (s, 3H), 1.56 – 1.43 (m, 3.19H), 1.26 – 1.18 (m, 3.32H), 0.83 (dt, *J* = 10.7, 7.4 Hz, 4.81H). The dr value was determined by ^{1}H NMR (1.7:1 dr)

***(R)*-(2*E*,4*Z*)-butyl 5-(2-((*S*)-methylsulfinyl)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-9b)**



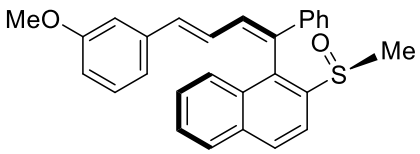
根据通用方法 E 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 2/1 为展开剂)(38.2 mg, 93%)。手性 HPLC 分离条件：a IC column (*n*-hexane/*i*-PrOH = 60/40, flow = 1.1 mL/min, 254 nm), t = 31.3 min (major), t = 27.9 min (minor), 93% ee, 6:1 dr. $[\alpha]_D^{20}$ = -89.6 (c = 0.97, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.18 (s, 2H), 7.98 (dt, *J* = 8.2, 0.9 Hz, 1H), 7.76 (d, *J* = 8.6 Hz, 1H), 7.61 (ddd, *J* = 8.1, 6.8, 1.2 Hz, 1H), 7.54 – 7.46 (m, 1H), 7.28 (dq, *J* = 4.3, 2.3 Hz, 4H), 7.23 – 7.16 (m, 2H), 6.78 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.10 (d, *J* = 15.1 Hz, 1H), 4.04 – 3.93 (m, 2H), 2.17 (s, 3H), 1.55 – 1.43 (m, 2H), 1.26 – 1.15 (m, 3H), 0.81 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.36, 142.30, 141.74, 140.07, 139.65, 134.74, 133.86, 131.76, 130.83, 129.30, 129.17, 128.72, 128.27, 128.16, 128.10, 126.87, 126.47, 124.88, 119.35, 64.37, 42.30, 30.60, 19.13, 13.74. HRMS (EI-TOF) calcd for $C_{26}H_{26}O_3S^+$ ([M]$^+$): 418.1603, found: 418.1605.

1-((1*Z*,3*E*)-4-(3-methoxyphenyl)-1-phenylbuta-1,3-dien-1-yl)-2-(methylsulfinyl)naphthalene (*rac*-4-9c)



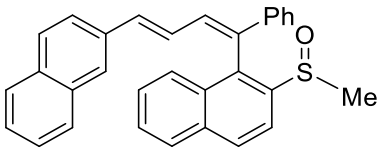
^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.20 (q, *J* = 8.6 Hz, 2.55H), 8.00 (d, *J* = 8.2 Hz, 1.26H), 7.85 (d, *J* = 8.5 Hz, 1.2H), 7.61 (t, *J* = 7.7 Hz, 1.28H), 7.49 (t, *J* = 7.7 Hz, 1.31H), 7.35 (d, *J* = 10.7 Hz, 1.29H), 7.31 - 7.21 (m, 4.04H), 7.23 – 7.13 (m, 2.59H), 7.09 (t, *J* = 8.1 Hz, 1.29H), 6.72 (ddd, *J* = 37.2, 28.4, 15.6 Hz, 5.3H), 6.30 (dd, *J* = 15.4, 11.0 Hz, 1H), 3.70 (d, *J* = 2.8 Hz, 3.97H), 2.66 (s, 0.92H), 2.22 (s, 3H). The dr value was determined by ^{1}H NMR (3:1 dr).

***(R)*-1-((1*Z*,3*E*)-4-(3-methoxyphenyl)-1-phenylbuta-1,3-dien-1-yl)-2-((*S*)-methylsulfinyl)naphthalene (4-9c)**



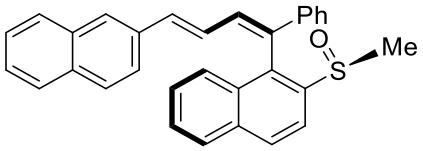
根据通用方法 E 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 2/1 为展开剂)(35.2 mg, 84%)。手性 HPLC 分离条件：a IB column (*n*-hexane/*i*-PrOH = 65/35, flow = 1.0 mL/min, 254 nm), t = 6.9 min (major), t = 8.9 min (minor), 91% ee, 10:1 dr. $[\alpha]_D^{20}$ = -34.8 (c = 0.69, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.25 – 8.17 (m, 2H), 8.00 (d, *J* = 8.2 Hz, 1H), 7.86 (d, *J* = 8.5 Hz, 1H), 7.61 (ddd, *J* = 8.2, 6.7, 1.2 Hz, 1H), 7.49 (ddd, *J* = 8.2, 6.8, 1.3 Hz, 1H), 7.35 (d, *J* = 11.0 Hz, 1H), 7.27 – 7.23 (m, 3H), 7.18 (dd, *J* = 7.9, 1.7 Hz, 2H), 7.08 (t, *J* = 8.0 Hz, 1H), 6.83 – 6.63 (m, 4H), 6.31 (dd, *J* = 15.4, 11.1 Hz, 1H), 3.70 (s, 3H), 2.23 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 159.70, 141.82, 140.49, 138.18, 136.60, 135.09, 134.77, 134.55, 132.01, 131.04, 130.42, 129.55, 129.02, 128.64, 128.05, 127.99, 127.95, 126.88, 126.29, 126.04, 119.57, 119.44, 113.68, 112.47, 55.30, 42.32. HRMS (EI-TOF) calcd for $C_{28}H_{24}O_2S^+$ ($[M]^+$): 424.1497, found: 424.1495.

2-(methylsulfinyl)-1-((1*Z*,3*E*)-4-(naphthalen-2-yl)-1-phenylbuta-1,3-dien-1-yl)naphthalene (*rac*-4-9d)



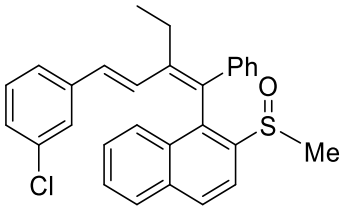
^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.24 (q, *J* = 8.9, 7.8 Hz, 2.44H), 8.02 (d, *J* = 8.3 Hz, 1.29H), 7.89 (d, *J* = 8.5 Hz, 1.34H), 7.74 – 7.66 (m, 2.53H), 7.60 (dd, *J* = 10.8, 6.9 Hz, 4.04H), 7.50 (t, *J* = 7.7 Hz, 1.4H), 7.45 – 7.36 (m, 3.96H), 7.27 (d, *J* = 7.0 Hz, 4.15H), 7.24 – 7.12 (m, 3.87H), 7.04 – 6.94 (m, 1.21H), 6.45 (dd, *J* = 15.5, 11.0 Hz, 1H), 2.68 (s, 0.79H), 2.25 (s, 3H). The dr value was determined by ^{1}H NMR (3.8:1 dr).

***(R)*-2-((*S*)-methylsulfinyl)-1-((1*Z*,3*E*)-4-(naphthalen-2-yl)-1-phenylbuta-1,3-dien-1-yl)naphthalene (4-9d)**



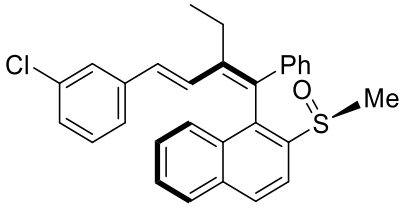
根据通用方法 E 经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 2/1 为展开剂)(41.2 mg, 93%)。手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 50/50, flow = 1.1 mL/min, 254 nm), t = 9.8 min (major), t = 10.9 min (minor), 95% ee, 13.6:1 dr. $[\alpha]_D^{20}$ = -34.9 (c = 0.993, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.25 (q, *J* = 8.8 Hz, 2H), 8.02 (dd, *J* = 8.3, 1.2 Hz, 1H), 7.89 (dd, *J* = 8.4, 1.2 Hz, 1H), 7.70 (ddd, *J* = 7.9, 6.5, 2.4 Hz, 2H), 7.65 – 7.56 (m, 3H), 7.50 (ddd, *J* = 8.3, 6.8, 1.3 Hz, 1H), 7.45 – 7.36 (m, 3H), 7.30 – 7.25 (m, 3H), 7.21 (ddd, *J* = 7.9, 6.6, 1.7 Hz, 3H), 7.00 (d, *J* = 15.4 Hz, 1H), 6.46 (dd, *J* = 15.4, 11.0 Hz, 1H), 2.25 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 141.81, 140.48, 136.91, 135.18, 134.81, 134.40, 134.29, 133.51, 133.29, 132.06, 131.21, 130.45, 129.03, 128.66, 128.23, 128.15, 128.05, 128.04, 127.99, 127.73, 127.31, 126.91, 126.37, 126.29, 126.21, 125.94, 123.68, 119.48, 42.32. HRMS (EI-TOF) calcd for $C_{31}H_{24}OS^+$ ($[M]^+$): 444.1548, found: 444.1548.

1-((1*Z*,3*E*)-4-(3-chlorophenyl)-2-ethyl-1-phenylbuta-1,3-dien-1-yl)-2-(methylsulfinyl)naphthalene (*rac*-4-9e)



^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.16 – 8.08 (m, 2.44H), 8.04 (dd, *J* = 8.4, 1.4 Hz, 1.2H), 7.98 – 7.93 (m, 1.25H), 7.63 – 7.54 (m, 2.43H), 7.27 – 7.26 (m, 1.46H), 7.26 – 7.24 (m, 1H), 7.24 – 7.17 (m, 3.23H), 7.06 – 6.97 (m, 2.46H), 6.95 (t, *J* = 1.8 Hz, 0.25H), 6.91 (t, *J* = 1.8 Hz, 1H), 6.76 (dd, *J* = 7.5, 1.6 Hz, 1.26H), 6.65 (d, *J* = 16.1 Hz, 1.24H), 6.28 (d, *J* = 16.1 Hz, 1H), 6.14 (d, *J* = 16.1 Hz, 0.25H), 2.91 – 2.75 (m, 2.38H), 2.67 (s, 0.66H), 1.84 (s, 3H), 1.39 (t, *J* = 7.4 Hz, 3H). The dr value was determined by ^{1}H NMR (4.5:1 dr).

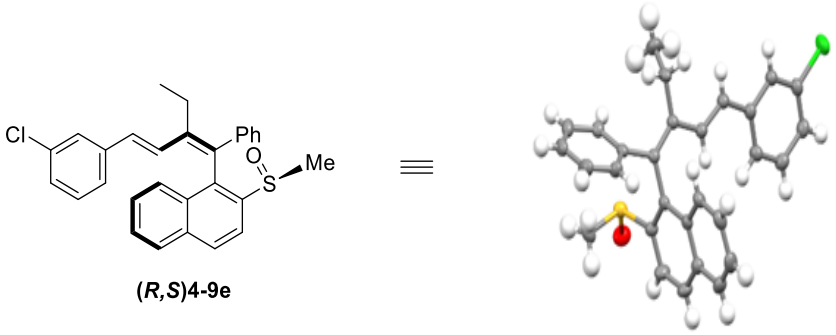
***(R)*-1-((1*Z*,3*E*)-4-(3-chlorophenyl)-2-ethyl-1-phenylbuta-1,3-dien-1-yl)-2-((*S*)-methylsulfinyl)naphthalene (4-9e)**



根据通用方法 E 经过制备级 TLC 分离得到黄色固体(石油醚/乙酸乙酯 = 2/1 为展开剂)(43.4 mg, 95%)。手性 HPLC 分离条件：two AD-H columns (*n*-hexane/*i*-PrOH = 85/15, flow = 1.1 mL/min, 254 nm), t = 10.0 min (major), t = 13.2 min (minor), 96% ee, 18.7:1 dr. $[\alpha]_D^{20}$ = -495.8 (c = 0.923, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.10 (s, 2H), 8.04 (dd, *J* = 8.4, 1.5 Hz, 1H), 7.96 (dd, *J* = 8.0, 1.4 Hz, 1H), 7.64 – 7.54 (m,

2H), 7.27 (d, *J* = 1.8 Hz, 1H), 7.26 – 7.24 (m, 1H), 7.24 – 7.16 (m, 3H), 7.06 – 6.96 (m, 2H), 6.91 (t, *J* = 1.8 Hz, 1H), 6.76 (dt, *J* = 7.5, 1.6 Hz, 1H), 6.66 (d, *J* = 16.2 Hz, 1H), 6.28 (d, *J* = 16.2 Hz, 1H), 2.94 – 2.75 (m, 2H), 2.67 (s, 0.16H), 1.85 (s, 3H), 1.39 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 141.86, 141.64, 141.53, 139.17, 138.30, 134.94, 134.39, 134.30, 132.05, 130.30, 129.67, 129.33, 129.25, 129.00, 128.74, 128.54, 128.17, 127.92, 127.63, 127.53, 127.22, 126.92, 124.33, 119.47, 41.91, 22.26, 14.95. HRMS (EI-TOF) calcd for $C_{29}H_{25}ClOS^+$ ([M]$^+$): 456.1315, found: 456.1316.

X-ray data of *(R,S)*4-9e

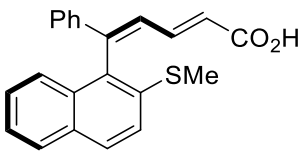


***(R,S)*4-9e**

Bond precision:	C-C = 0.0034 A	Wavelength = 0.71073
Cell:	a = 9.2032(5) b = 15.5569(7) c = 9.4429(5)	
alpha = 90	beta = 116.395(2)	gamma = 90
Temperature: 170 K	Calculated	Reported
Volume	1211.03(11)	1211.03(11)
Space group	P 21	P 1 21 1
Hall group	P 2yb	P 2yb
Moiety formula	C_{29} H_{25} Cl O S	C_{29} H_{25} Cl O S
Sum formula	C_{29} H_{25} Cl O S	C_{29} H_{25} Cl O S
Mr	457.00	457.00
Dx, g cm^{-3}	1.253	1.253
Z	2	2
Mu (mm^{-1})	0.263	0.263
F000	480.0	480.0
F000’	480.71	
h,k,lmax	11,19,11	11,19,11

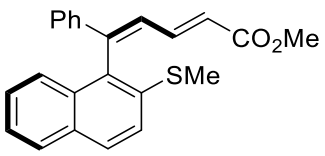
Nref	5019[2606]	4976
Tmin, Tmax	0.921,0.951	0.708,0.745
Tmin'	0.895	
Correction method = # Reported T	Limits: Tmin = 0.708	Tmax = 0.745
AbsCorr = MULTI-SCAN		
Data completeness	1.91/0.99	Theta(max) = 26.488
R (reflections)	0.0256(4790)	wR2(reflections)=0.0642(4976)
S = 1.053	Npar = 291	
Flack parameter	-0.029(13)	

***(R)*-(2*E*,4*Z*)-5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoic acid (4-10a)**



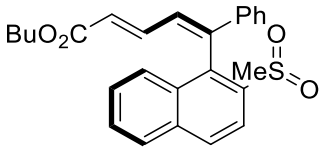
经过制备级 TLC 分离得到黄色泡沫(二氯甲烷/甲醇 = 10/1 为展开剂)(43.1 mg, 92% yield, 92% ee)。$[\alpha]_D^{20} = 67.8$ (c = 1.142, $CHCl_3$). 对映体比率由化合物 **4-10b** 推测给出。^{1}H NMR (400 MHz, DMSO-d_6) δ 12.23 (s, 1H), δ 8.07 (d, *J* = 8.8 Hz, 1H), 8.00 – 7.94 (m, 1H), 7.66 (d, *J* = 8.8 Hz, 1H), 7.50 (d, *J* = 11.4 Hz, 1H), 7.48 – 7.43 (m, 1H), 7.40 (d, *J* = 3.6 Hz, 2H), 7.30 (s, 5H), 6.54 (dd, *J* = 15.1, 11.5 Hz, 1H), 6.16 (d, *J* = 15.2 Hz, 1H), 2.47 (s, 3H). ^{13}C NMR (101 MHz, DMSO-d_6) δ 167.39, 144.84, 140.79, 137.85, 135.57, 131.57, 131.26, 130.61, 129.66, 128.93, 128.78, 128.75, 128.36, 127.45, 126.38, 125.26, 124.93, 124.25, 122.98, 14.67. HRMS (EI-TOF) calcd for $C_{22}H_{18}O_2S^+$ ($[M]^+$): 346.1028, found: 346.1028.

***(R)*-(2*E*,4*Z*)-methyl 5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-10b)**



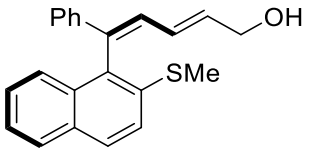
经过制备级 TLC 分离得到黄色泡沫(石油醚/乙酸乙酯 = 10/1 为展开剂)(32.9 mg, 90%)。手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 85/15, flow = 1.1 mL/min, 254 nm), t = 4.4 min (major), t = 5.4 min (minor), 92% ee. $[\alpha]_D^{20} = 81.2$ (c = 0.97, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.95 (d, *J* = 8.7 Hz, 1H), 7.91 – 7.85 (m, 1H), 7.56 (dd, *J* = 11.5, 8.5 Hz, 2H), 7.47 – 7.42 (m, 1H), 7.42 – 7.38 (m, 1H), 7.35 (dd, *J* = 7.0, 3.3 Hz, 2H), 7.32 – 7.28 (m, 4H), 6.88 (dd, *J* = 15.2, 11.5 Hz, 1H), 6.13 (d, *J* = 15.2 Hz, 1H), 3.64 (s, 3H), 2.48 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 167.38, 146.46, 141.78, 138.64, 135.51, 132.51, 132.46, 131.32, 129.14, 128.93, 128.81, 128.28, 127.79, 127.37, 126.85, 125.41, 125.18, 123.27, 122.89, 51.54, 15.99. HRMS (EI-TOF) calcd for $C_{23}H_{20}O_2S^+$ ($[M]^+$): 360.1184, found: 360.1184.

(*R*)-(2*E*,4*Z*)-butyl 5-(2-(methylsulfonyl)naphthalen-1-yl)-5-phenylpenta-2,4-dienoate (4-11)



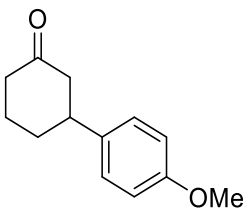
手性 HPLC 分离条件：a AD-H column (*n*-hexane/*i*-PrOH = 70/30, flow = 1.2 mL/min, 254 nm), t = 8.2 min (major), t = 9.7 min (minor). $[\alpha]_D^{20}$ = 40.6 (c = 1.08, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 8.20 (d, *J* = 8.8 Hz, 1H), 8.12 – 8.04 (m, 2H), 8.00 – 7.94 (m, 2H), 7.89 (d, *J* = 8.6 Hz, 1H), 7.65 (ddd, *J* = 8.1, 6.8, 1.2 Hz, 1H), 7.57 (dd, *J* = 8.1, 1.9 Hz, 1H), 7.51 (ddd, *J* = 8.3, 6.8, 1.3 Hz, 1H), 7.41 (t, *J* = 7.9 Hz, 1H), 7.31 (d, *J* = 11.7 Hz, 1H), 7.25 (s, 1H), 6.68 (dd, *J* = 15.2, 11.7 Hz, 1H), 6.09 (d, *J* = 15.2 Hz, 1H), 3.98 (t, *J* = 6.6 Hz, 2H), 2.73 (s, 3H), 1.50 (dq, *J* = 8.4, 6.7 Hz, 2H), 1.24 (dt, *J* = 9.2, 6.5 Hz, 2H), 0.82 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 166.77, 144.49, 140.86, 139.43, 136.46, 133.89, 132.31, 130.35, 130.05, 129.95, 129.38, 129.15, 128.82, 128.58, 128.52, 128.41, 127.60, 127.42, 127.15, 124.63, 123.89, 64.44, 44.26, 30.64, 19.17, 13.75. HRMS (EI-TOF) calcd for $C_{26}H_{26}O_4S^+$ ($[M]^+$): 434.1552, found: 434.1552.

(*R*)-(2*E*,4*Z*)-5-(2-(methylthio)naphthalen-1-yl)-5-phenylpenta-2,4-dien-1-ol (4-12)



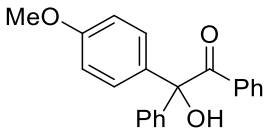
手性 HPLC 分离条件：a OD-H column (*n*-hexane/*i*-PrOH = 70/30, flow = 1.2 mL/min, 254 nm), t = 4.0 min (major), t = 5.2 min (minor). $[\alpha]_D^{20}$ = 52.1 (c = 1.0, $CHCl_3$). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.95 – 7.81 (m, 2H), 7.62 (dd, *J* = 8.0, 1.6 Hz, 1H), 7.48 (d, *J* = 8.8 Hz, 1H), 7.37 (dqd, *J* = 8.3, 6.8, 1.6 Hz, 2H), 7.29 – 7.26 (m, 2H), 7.25 – 7.18 (m, 3H), 7.13 (d, *J* = 10.9 Hz, 1H), 6.04 (dt, *J* = 15.3, 6.0 Hz, 1H), 5.76 (ddt, *J* = 15.3, 11.0, 1.5 Hz, 1H), 3.97 (dt, *J* = 6.1, 1.8 Hz, 2H), 2.43 (s, 3H), 1.75 – 1.52 (br, 1H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 139.32, 138.30, 135.46, 135.05, 133.39, 132.49, 131.24, 129.47, 128.87, 128.62, 128.58, 128.18, 127.71, 127.19, 126.24, 125.43, 125.24, 122.95, 63.41, 15.76. HRMS (EI-TOF) calcd for $C_{22}H_{20}OS^+$ ($[M]^+$): 332.1235, found: 332.1234.

3-(4-methoxyphenyl)cyclohexanone(4-15)



4-15 是已知化合物[21a]。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.14 (d, *J* = 8.7 Hz, 2H), 6.86 (d, *J* = 8.7 Hz, 2H), 3.79 (s, 3H), 2.96 (m, 1H), 2.61 – 2.29 (m, 4H), 2.13 (m, 1H), 2.08 – 2.01 (m, 1H), 1.84 – 1.74 (m, 2H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 211.36, 158.37, 136.68, 127.59, 114.12, 55.38, 49.34, 44.08, 41.28, 33.11, 25.59.

2-hydroxy-2-(4-methoxyphenyl)-1,2-diphenylethanone(4-17)



4-17 是已知化合物[21c]。^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.73 (dt, *J* = 8.5, 1.4 Hz, 2H), 7.49 – 7.39 (m, 3H), 7.37 – 7.30 (m, 5H), 7.28 (t, *J* = 8.4 Hz, 2H), 6.87 (d, *J* = 8.1 Hz, 2H), 5.01 (s, 1H), 3.80 (s, 3H). ^{13}C NMR (101 MHz, Chloroform-*d*) δ 201.03, 159.37, 142.21, 135.24, 134.09, 132.99, 130.93, 129.72, 128.45, 128.35, 128.21, 128.17, 113.80, 84.80, 55.36.

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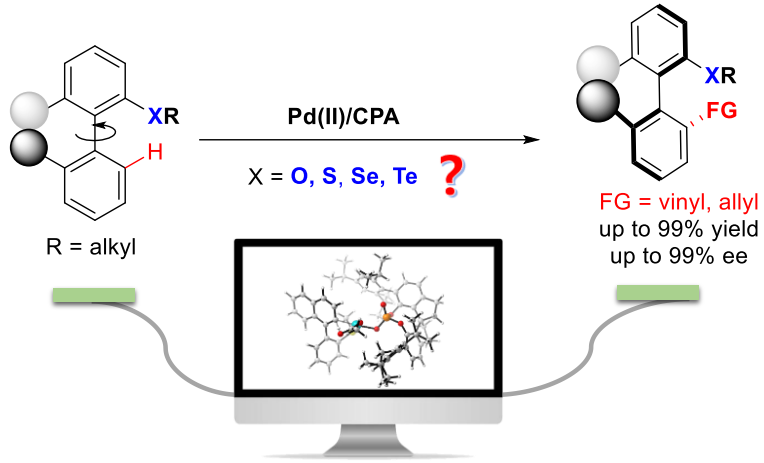
总结与展望

全文总结

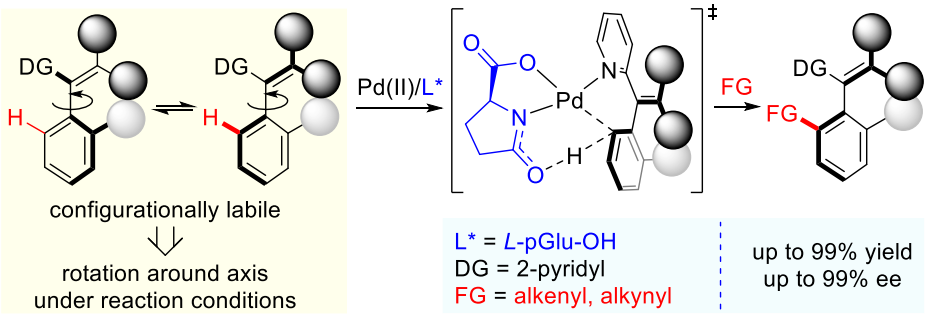
本论文围绕钯催化不对称碳氢键活化构建轴手性化合物展开研究，分别实现了钯催化硫醚导向不对称碳氢键烯基化和烯丙基化反应构建轴手性联芳和钯催化不对称芳烃和烯烃碳氢键官能团化反应构建含开链式烯烃结构的轴手性烯基芳烃化合物。具体总结如下：

1. 钯催化硫醚导向不对称碳氢键官能团化构建轴手性联芳



我们通过 DFT 计算了解氧族原子在钯催化不对称碳氢键活化反应中的导向能力，选择硫醚为反应的导向基团，在手性磷酸的作用下，成功实现对轴手性联芳化合物的催化不对称合成。该反应的底物适用范围非常广阔，许多天然产物和活性分子衍生的烯基化试剂均可以在反应中得到很好的反应结果。反应还可以兼容一些拥有双导向能力基团的联芳底物。此外，该策略被成功应用于构建含双立体轴元素的轴手性联芳骨架中。

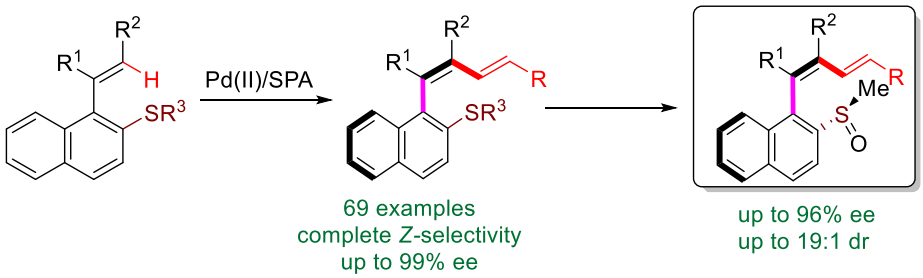
2. 钯催化吡啶导向不对称芳烃碳氢键官能团化构建轴手性烯基芳烃



我们首次利用钯催化不对称碳氢键烯基化反应构建含开链式烯烃结构单元的轴手性烯基芳烃。我们以吡啶作为导向基，廉价易得的 *L*-焦谷氨酸为手性配体，通过钯催化不对称芳烃碳氢键烯基化和炔基化反应以优秀的产率和对映体选择性高效地构建了一系列烯

基芳烃非联芳阻转手性化合物。同时，我们在机理研究中发现了一个非常规的配体减速效应，并且利用 DFT 计算对烯基化反应的机理进行了深一步的探究。

3. 钯催化硫醚导向不对称烯烃碳氢键烯基化反应构建含共轭烯烃结构的轴手性烯基芳烃



- **axially chiral styrenes with conjugated dienes**
- **more challenging asymmetric alkenyl C–H activation**
- **construction of diaxially chiral styrenes**
- **olefin ligands with axial chirality and *S*-stereogenic center**

我们利用钯/手性螺环磷酸催化体系，以硫醚为导向基，实现了不对称烯烃碳氢键烯基化反应。反应能够以优秀的产率，出色的对映体选择性和完全的 *Z* 构型选择性得到含有共轭烯烃结构单元的轴手性烯基芳烃化合物。该反应的底物适用性非常好，高效合成了许多三取代和四取代烯烃结构的轴手性烯基芳烃化合物。同时该策略可以以良好的产率和优秀的对映体选择性以及非对映体选择性直接构建含多个立体轴要素的轴手性烯基芳烃化合物。更重要的是，含硫醚结构的轴手性烯基芳烃产物可以被进一步氧化成手性亚砜化合物，作为新型的手性亚砜烯烃配体应用到铑催化不对称共轭加成反应中。

展望

虽然我们在钯催化不对称碳氢键活化构建轴手性联芳和轴手性烯基芳烃化合物方面取得了一些阶段性的成果。但是在轴手性的研究邻域中仍然存在着许多值得我们进行深一步的探索内容，比如：

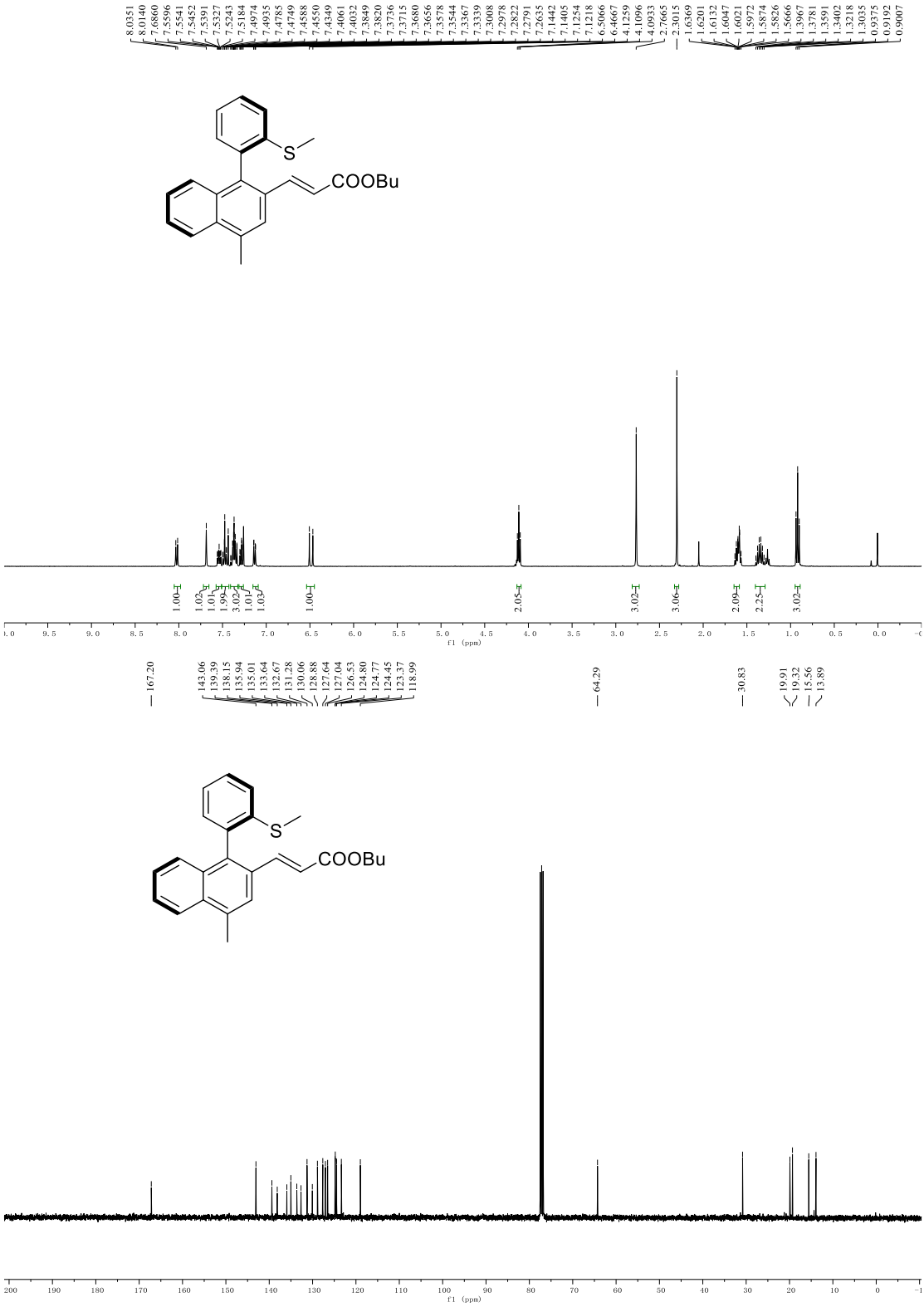
1）目前通过钯催化不对称碳氢键活化反应构建联芳和非联芳阻转手性化合物的方式主要集中于对含有前手性轴的底物进行动态动力学拆分。使用简单易得的底物，通过直接构筑手性轴的方式来实现联芳和非联芳阻转手性化合物的不对称构建是更加经济和具有实用价值的。

2）目前钯催化不对称碳氢键活化合成阻转手性化合物的方式主要局限于碳碳键的形成，通过不对称碳杂键的形成往阻转手性化合物中引入功能性的杂原子将对产生的轴手性化合物赋予更大的应用前景。

3）联芳和烯基芳烃阻转手性化合物仅仅是轴手性化合物中的冰山一角，这个邻域中还拥有着许多结构特异，构象多变且具有强大应用价值的轴手性类型。这些更具有合成挑战性的阻转手性化合物急需科学家们进行探索研究。

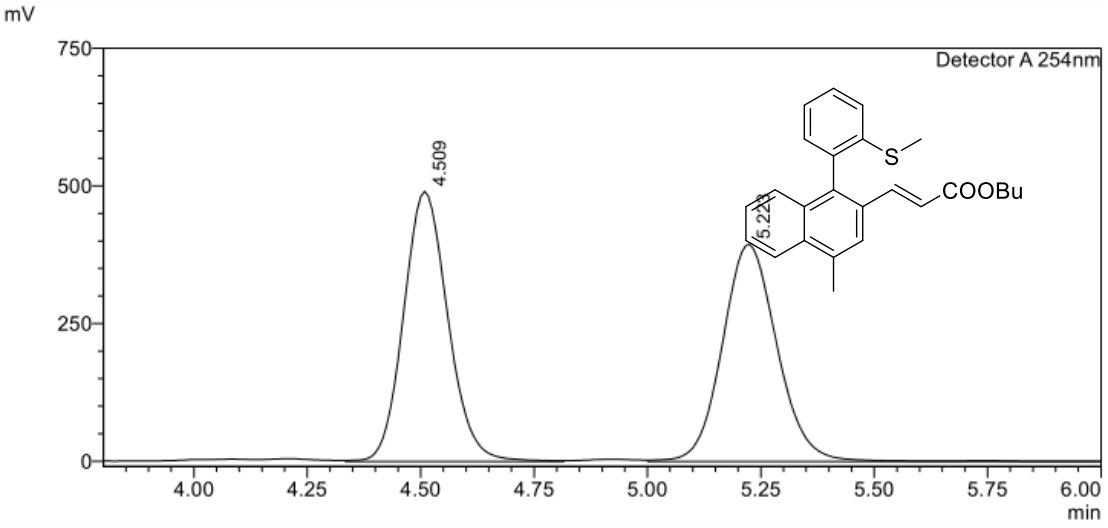
谱图节选

第二章部分：**2-10**



2-10: IC, Hex/^{i}PrOH = 85/15, rate = 1.2 mL/min, 254 nm

<Chromatogram>

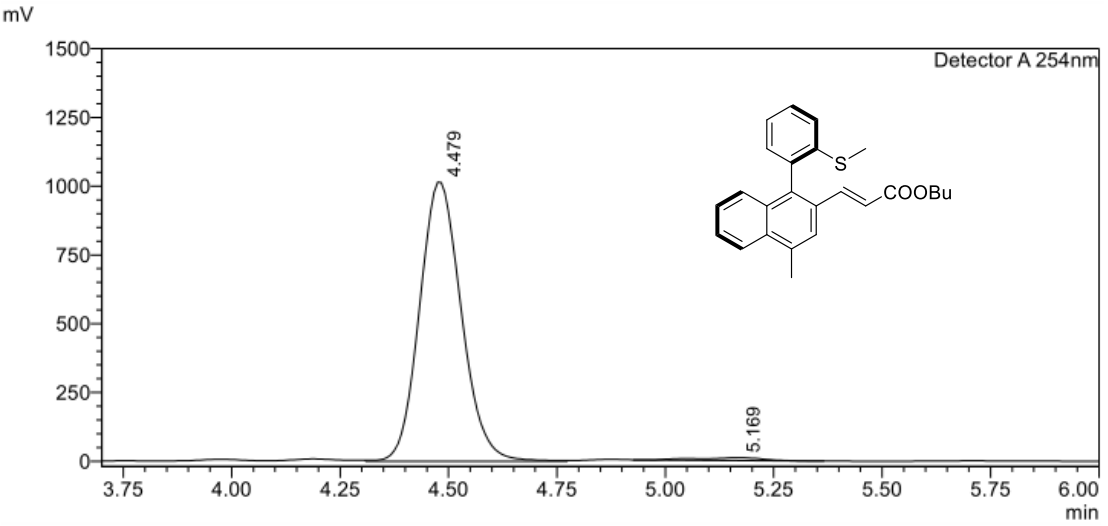


<Peak Table>

Detector A 254nm

Peak#	Ret. Time	Area	Height	Conc.	Unit	Mark	Name
1	4.509	3339796	490537	50.140			
2	5.223	3321133	394242	49.860			
Total		6660929	884780				

<Chromatogram>

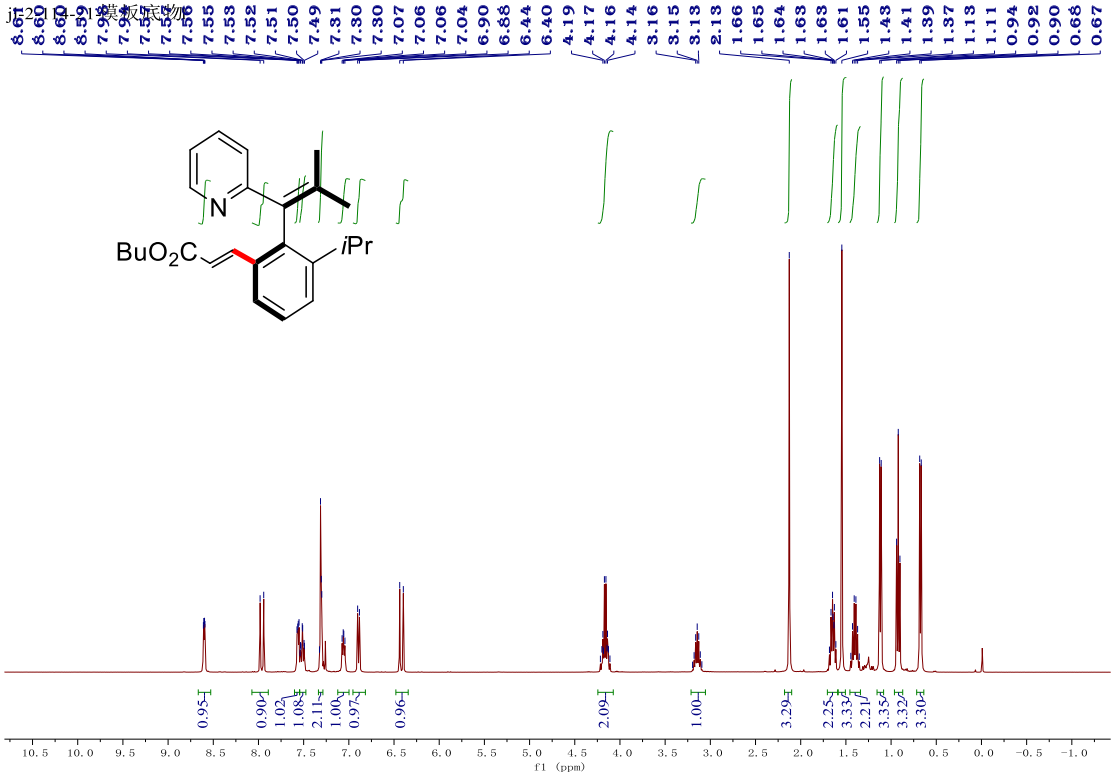


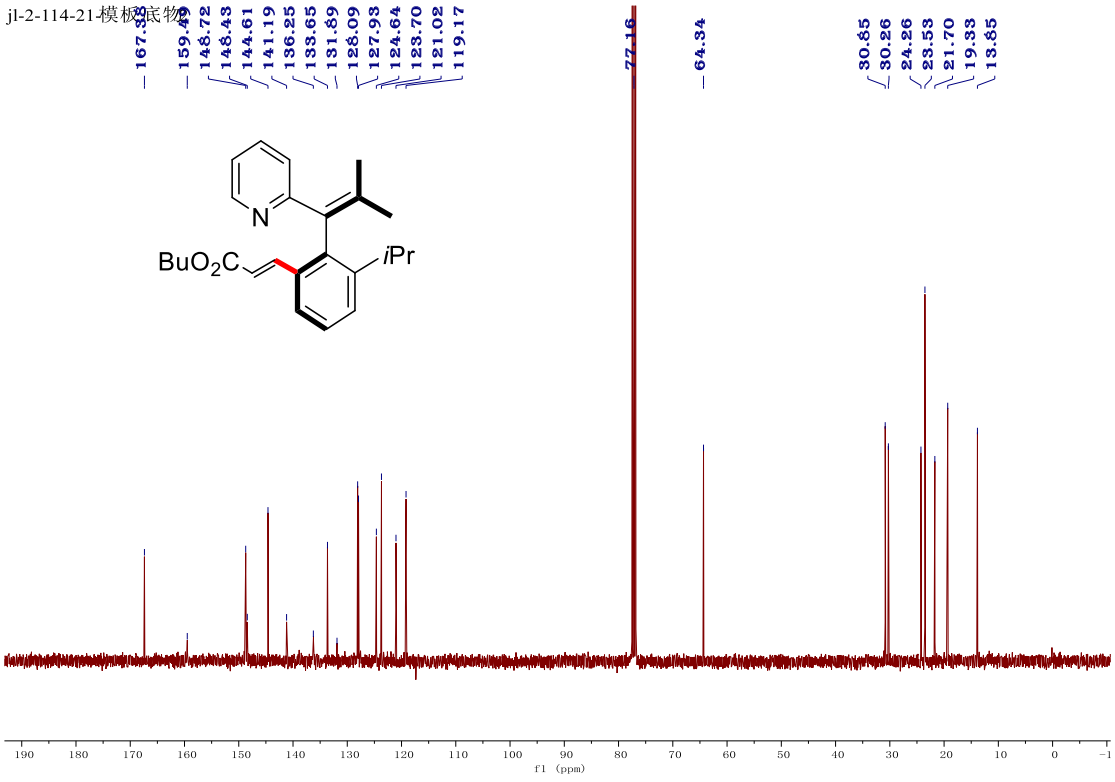
<Peak Table>

Detector A 254nm

Peak#	Ret. Time	Area	Height	Conc.	Unit	Mark	Name
1	4.479	6809938	1015456	98.373			
2	5.169	112635	10556	1.627		M	
Total		6922574	1026012				

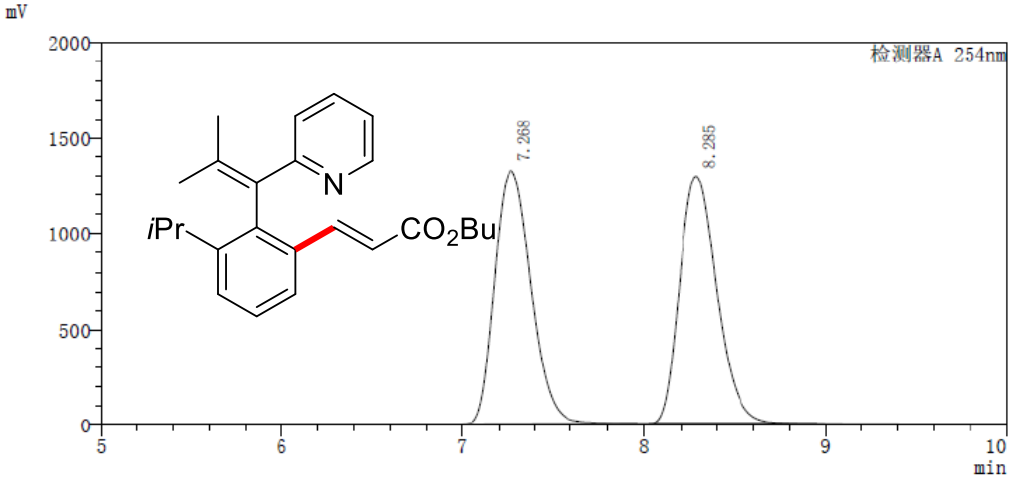
第三章部分：**3-3aa**


jl-2-114-21-模板底物2
8.61 8.60 8.59 7.96 7.95 7.55 7.53 7.52 7.51 7.50 7.49 7.31 7.30 7.30 7.07 7.06 7.06 7.04 6.90 6.88 6.44 6.40 4.19 4.17 4.16 4.14 3.16 3.15 3.13 2.13 1.66 1.65 1.64 1.63 1.63 1.61 1.55 1.43 1.41 1.39 1.37 1.13 1.11 0.94 0.92 0.90 0.68 0.67
N
BuO2C
iPr
0.95 0.90 1.02 1.08 2.11 1.00 0.97 0.96 2.09 1.00 3.29 2.25 3.33 2.21 3.35 3.32 3.30
f1 (ppm)


jl-2-114-21-模板底物2
167.32 159.43 148.72 148.43 144.61 141.19 136.25 133.65 131.89 128.09 127.93 124.64 123.70 121.02 119.17
77.16
64.34
30.85 30.26 24.26 23.53 21.70 19.33 13.85
N
BuO2C
iPr
f1 (ppm)

3-3aa: AD-H, Hex/^{i}PrOH = 97/3, rate = 0.5 mL/min, 254 nm

<Chromatogram>

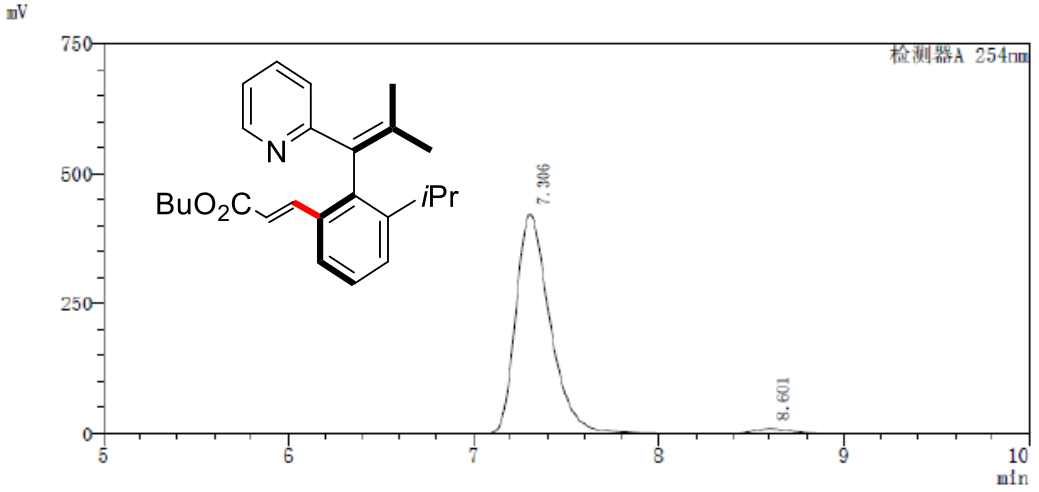


<Peak Table>

Detector A 254nm

Peak	Ret. Time	Area	Height	Conc.	Unit	Mark	Name
1	7.268	18827794	1327637	50.270		M	
2	8.285	18625422	1295478	49.730		M	
Total		37453216	2623116				

<Chromatogram>

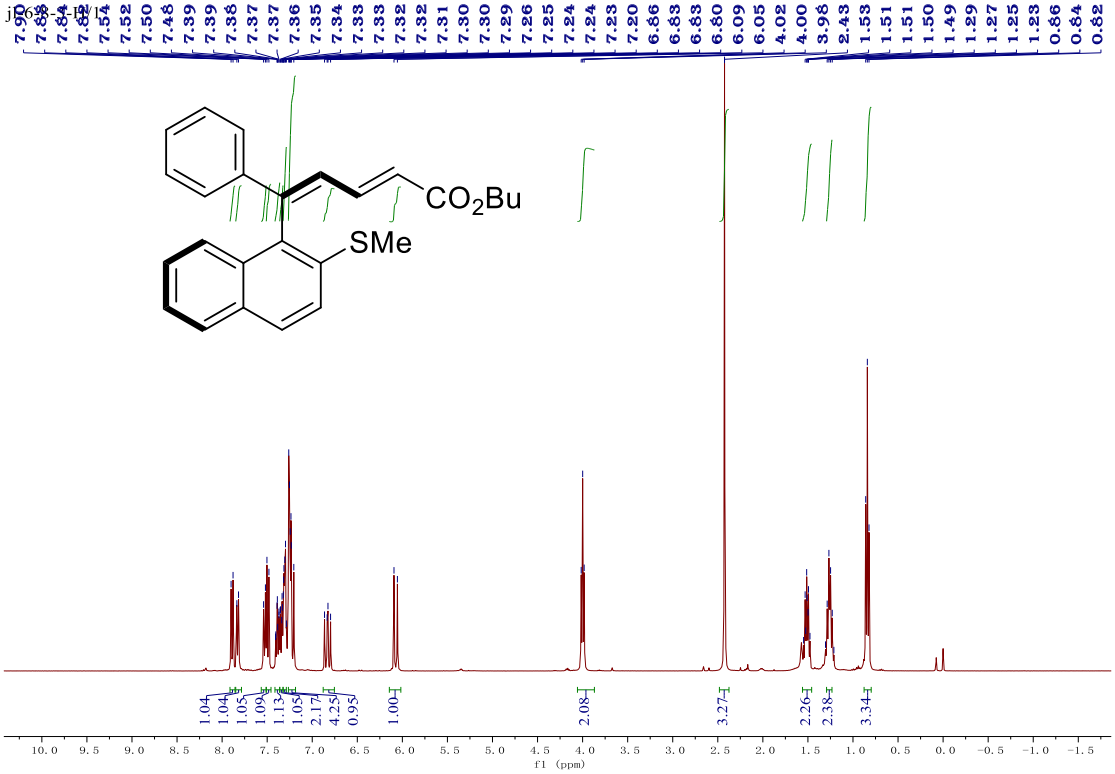


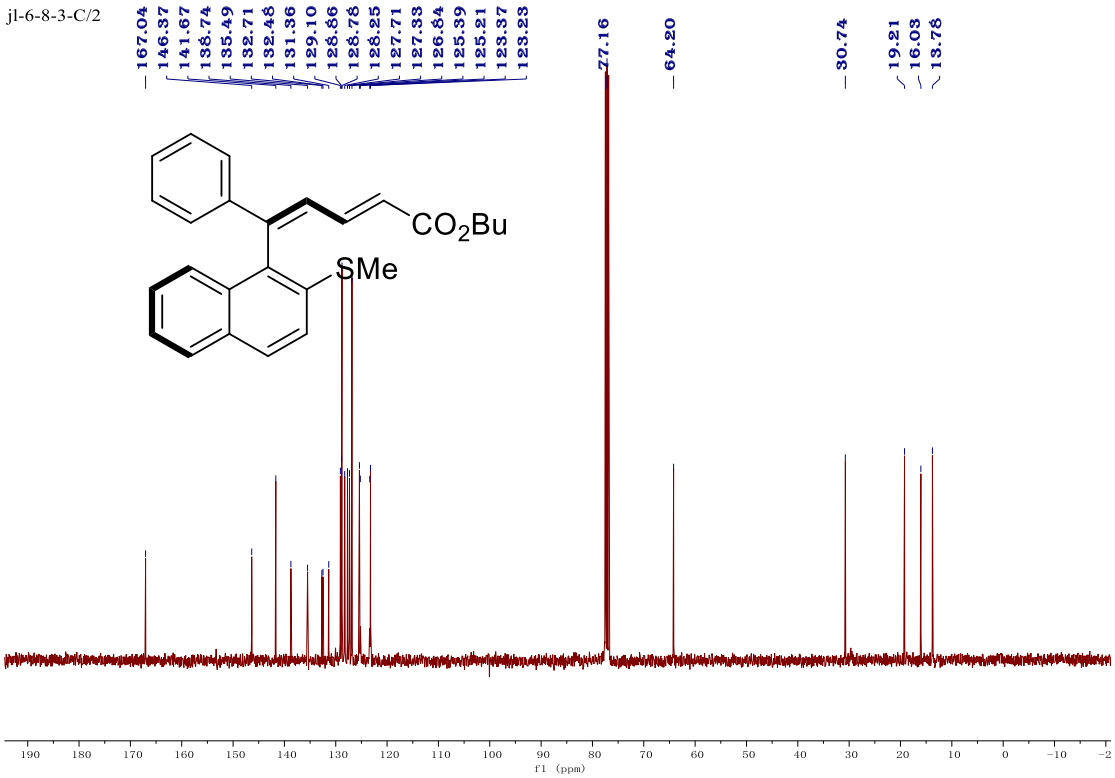
<Peak Table>

Detector A 254nm

Peak	Ret. Time	Area	Height	Conc.	Unit	Mark	Name
1	7.306	5440856	421443	97.391		M	
2	8.601	145755	10531	2.609		M	
Total		5586612	431974				

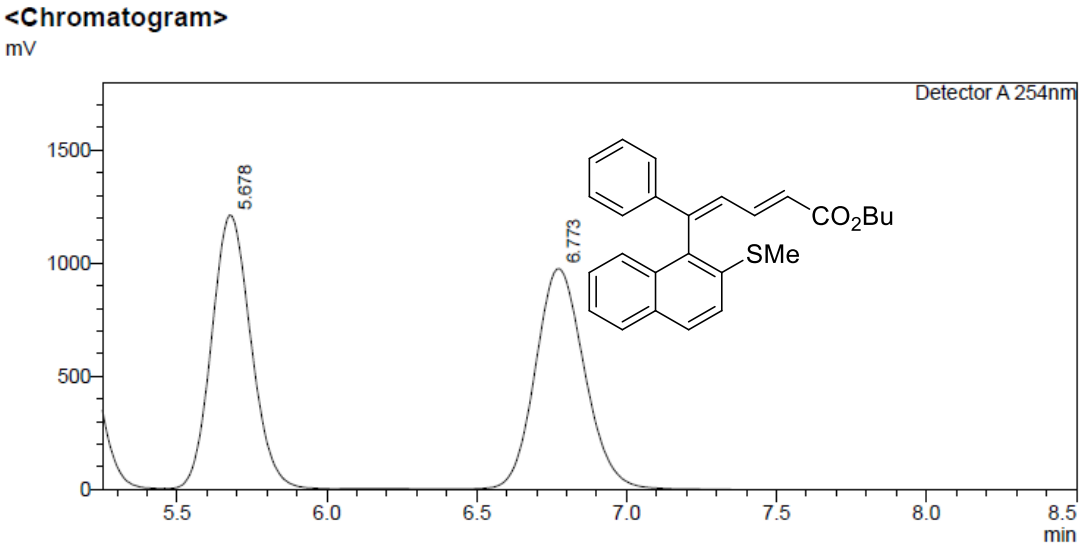
第四章部分：**4-3aa**


jl-6-8-3-H/1
7.90 7.88 7.54 7.52 7.50 7.48 7.39 7.39 7.38 7.37 7.37 7.36 7.35 7.34 7.33 7.33 7.32 7.32 7.31 7.30 7.30 7.29 7.26 7.25 7.24 7.24 7.23 7.20 6.86 6.83 6.83 6.80 6.09 6.05 4.02 4.00 3.98 2.43 1.53 1.51 1.51 1.50 1.49 1.29 1.27 1.25 1.23 0.86 0.84 0.82
CO2Bu
SMe
1.04 1.04 1.05 1.09 1.13 1.05 2.17 4.25 0.95 1.00 2.08 3.27 2.26 2.38 3.34
f1 (ppm)


jl-6-8-3-C/2
167.04 146.37 141.67 138.74 135.49 132.71 132.48 131.36 129.10 128.86 128.78 128.25 127.71 127.33 126.84 125.39 125.21 123.37 123.23
77.16
64.20
30.74
19.21 16.03 13.78
CO2Bu
SMe
f1 (ppm)

4-3aa: IC, Hexane/^{i}PrOH = 90/10, rate = 1.1 mL/min, 254nm

<Chromatogram>

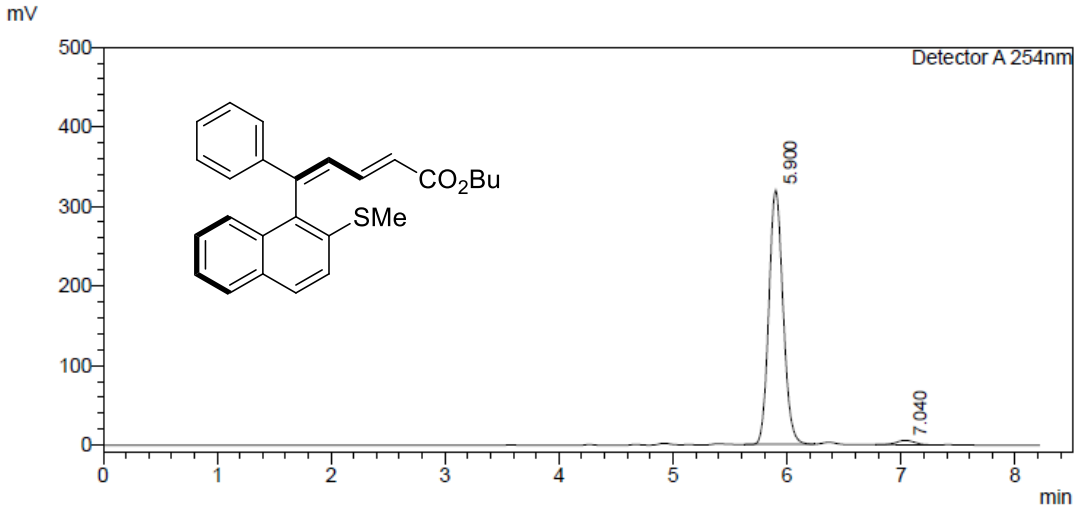


<Peak Table>

Detector A 254nm

Peak#	Ret. Time	Area	Height	Conc.	Unit	Mark	Name
1	5.678	11233789	1213938	50.026			
2	6.773	11222046	977618	49.974		V	
Total		22455835	2191555				

<Chromatogram>



<Peak Table>

Detector A 254nm

Peak#	Ret. Time	Area	Height	Conc.	Unit	Mark	Name
1	5.900	2762593	319325	97.829		M	
2	7.040	61294	5550	2.171		M	
Total		2823887	324874				

作者攻读博士期间发表的论文

1. Liao, G.; Zhang, T.; **Jin, L.;** Wang, B.-J.; Xu, C.-K.; Lan, Y.;* Zhao, Y.;* Shi, B.-F.* Experimental and Computational Studies on the Directing Ability of Chalcogenoethers in Palladium-Catalyzed Atroposelective C–H Olefination and Allylation. *Angew. Chem. Int. Ed.* **2022**, *61*, e202115221. (Liao, G.; Zhang, T.和 **Jin, L.**为共同一作) (博士论文第二章)
2. **Jin, L.;** Yao, Q.-J.; Xie, P.-P.; Li, Y.; Zhan, B.-B.; Han, Y.-Q.; Hong, X.;* Shi, B.-F.* Atroposelective Synthesis of Axially Chiral Styrenes via an Asymmetric C–H Functionalization Strategy. *Chem*. **2020**, *6*, 497. (**Jin, L.;** Yao, Q.-J.和 Xie, P.-P.为共同一作) (博士论文第三章)
3. **Jin, L.;** Zhang, P.; Li, Y.; Yu, X.; Shi, B.-F.* Atroposelective Synthesis of Conjugated Diene-Based Axially Chiral Styrenes via Pd(II)-Catalyzed Thioether-Directed Alkenyl C−H Olefination. *J. Am. Chem. Soc.* **2021**, *143*, 12335. (博士论文第四章)
4. Zhan, B.-B.; Fan, J.; **Jin, L.;** Shi, B.-F.***** Divergent Synthesis of Silicon-Containing Peptides via Pd-Catalyzed Post-Assembly γ–C(sp^3)–H Silylation. *ACS Catal.* **2019**, *9*, 3298.
5. Song, H.; Li, Y.; Yao, Q.-J.; **Jin, L.;** Liu, L.; Liu, Y.-H.; Shi, B.-F.* Synthesis of Axially Chiral Styrenes via Pd-Catalyzed Asymmetric C–H Olefination Enabled by an Amino Amide Transient Directing Group. *Angew. Chem. Int. Ed.* **2020**, *59*, 6576.
6. Zhan, B.-B.; Jia, Z.-S.; Luo, J.; **Jin, L.;** Lin, X.-F.; Shi, B.-F.* Palladium-Catalyzed Directed Atroposelective C–H Allylation via β–H Elimination: 1,1-Disubstituted Alkenes as Allyl Surrogates. *Org. Lett*. **2020**, *22*, 9693.
7. Zhan, B.-B.; **Jin, L.;** Shi, B.-F.* Palladium-Catalyzed Enantioselective C–H Functionalization via C–H Palladation. *Trends in Chem.* **2022**, *4*, 220.

致谢

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金良

2022 年 4 月 紫金港

金良的博士答辩决议

论文围绕钯催化不对称碳氢键活化构建轴手性联芳和烯基芳烃展开研究，发展了新型的不对称碳氢键官能化反应，具有重要学术价值。论文主要内容及创新点如下：

1. 基于 DFT 理论计算探究硫族元素在钯催化不对称碳氢键活化反应中的导向能力，选择硫醚为导向基团，在手性磷酸的作用下，以优异的产率和对映选择性合成了一系列轴手性联芳化合物。

2. 以 *L*-焦谷氨酸为手性配体，发展了钯催化不对称芳烃碳氢键烯基化和炔基化反应，以优秀的产率和对映体选择性高效地构建了一系列含开链式烯烃结构的轴手性烯基芳烃化合物。

3. 发展了钯/手性螺环磷酸催化体系，实现了不对称烯烃碳氢键烯基化反应，构建了一系列含有 *Z* 构型共轭烯烃结构的轴手性烯基芳烃化合物。

论文选题新颖，文献综述全面，撰写规范，行文条理清晰，内容充实，工作量饱满，数据翔实，结论可靠，创新性强，体现出作者掌握了本学科扎实的理论基础和系统深入的专业知识，具备了独立从事科学研究工作的能力，是一篇优秀的博士论文。答辩过程中表述清晰，回答问题正确。

经答辩委员会无记名投票表决，5 票同意，0 票反对，0 票弃权，同意通过金良的博士论文答辩，同意毕业，建议授予理学博士学位。

王彩云

2022.6.9