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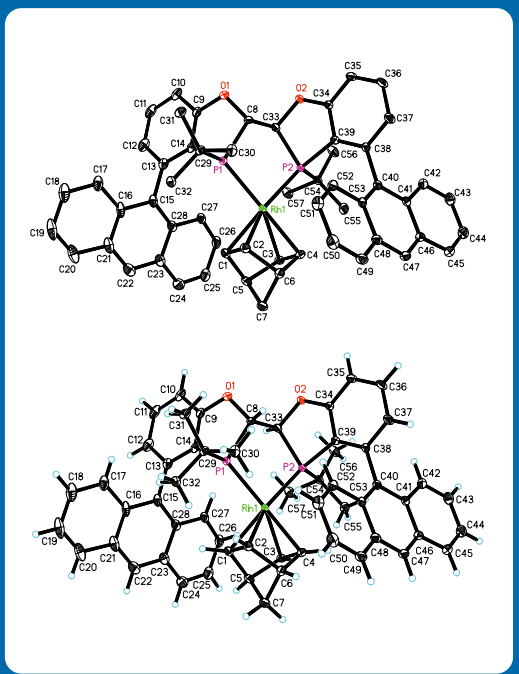

CONTENTS

Research Article

Development of Novel P-chiral Phosphorus Ligands for Efficient Transition-Metal Catalyzed Reactions

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Abstract: We have developed four categories of air-stable and operationally convenient phosphorus ligands on the basis of a benzooxaphosphole backbone. The bulky biaryl monophosphorus ligands BI-DIME and AntPhos are efficient for sterically hindered aryl-aryl cross-couplings; two new P,P=O ligands are developed and applicable for sterically hindered aryl-isopropyl cross-couplings; several P-chiral monophosphorus ligands are highly efficient for asymmetric aryl-aryl cross-couplings and various chiral cyclizations; a structurally unique P-chiral bisphosphorus ligand WingPhos is versatile for asymmetric hydrogenation as well as asymmetric addition of arylboron reagents to aryl ketones. The high reactivity, chemoselectivity, as well as enantioselectivity achieved with these phosphorus ligands have allowed practical applications in construction of various therapeutic agents and natural products.

Keywords: P-chiral phosphorus ligand, cross-coupling, reductive cyclization, dearomative cyclization, natural products

1. Introduction

Over past several decades, the development of efficient transition-metal catalyzed reactions has become one of the most active area in organic chemistry and transition-metal catalysis has made significant impacts on almost every chemical fields including natural product synthesis, medicinal chemistry, material chemistry, fine and agrochemical industry, chemical biology, and etc.[1] Numerous efficient transition-metal catalysts have been developed, which have not only greatly improved synthetic efficiency, but also provided opportunities to explore new research fields and ideal synthetic chemistry. Significant efforts have been taken recently in developing highly efficient, cost-effective, and environmentally benign catalytic reactions. Consequently, a few practical processes in particular asymmetric hydrogenations and cross-couplings[2] are developed and operated at industrial scales with excellent chemo-, regio-, and enantioselectivities at extremely high substrate/catalyst ratios (over 1,000,000). It is without any doubt that transition-metal catalyzed transformations will continue to play increasingly important roles in construction of new molecules, and bring incredible benefits to our life and society.

In transition metal catalysis, the catalyst generally consists with a transition metal and one or several ligands. In search for a new and efficient catalyst for a specific reaction, the judicial choice of a transition metal is naturally of utmost importance. However, the electronic and steric properties of ligands can significantly influence the reactivity and selectivity of the reaction. Since Wilkinson and co-workers discovered $RhCl(PPh_3)_3$ as the catalyst for alkene hydrogenation, phosphorus ligands have received great attention.[3] Up today, thousands of various phosphorus ligands have been designed and developed and a few of them have proven to be very useful and have become indispensable tools in asymmetric hydrogenation and other related areas.[4] It is fair to say that the development of phosphorus ligands has promoted the progress of transition metal catalysis. Conversely, the number of well-designed phosphorus ligands will continue to grow rapidly and more efficient catalytic processes are expected to be discovered in the future.

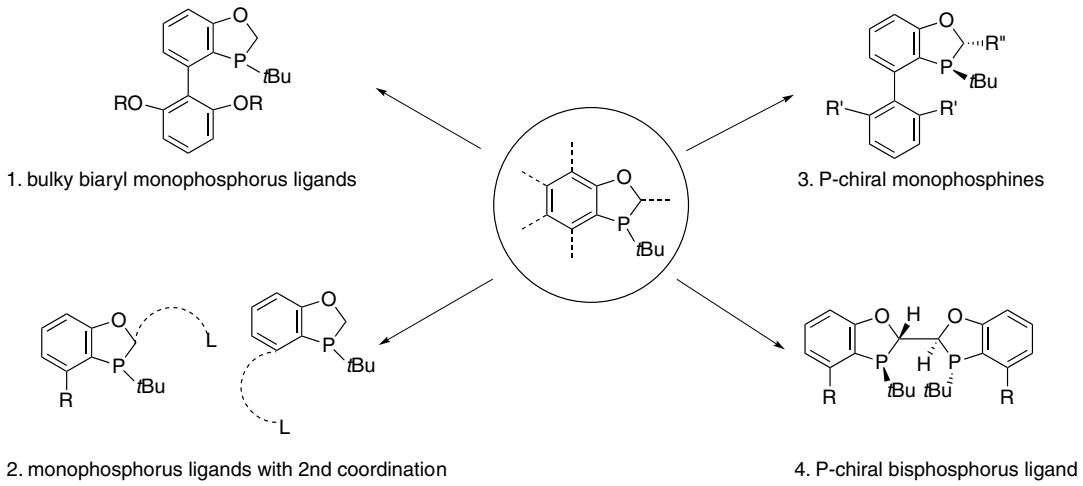
Ligands dictate the electronic and steric properties of the transition metal catalyst. As a result, they have often played significant role for the reactivity and selectivity of the catalytic reaction. An excellent catalyst often features a well-defined and predictable conformation, which requires its ligating ligands to possess an unambiguous, fixed, and rigid structural conformation. Therefore, the rational design and development of a ligand with a stable configuration and a rigid structure is often a very effective way for the development of efficient catalytic reaction.

Our research group has embarked a program on exploring efficient and practical catalytic reactions by inventing novel and highly-efficient phosphorus ligands in recent years. We designed and developed a series of phosphorus ligands based on a benzoheterophosphole as the backbone structure[5] with the following features: 1) The 5-membered bisdihydrobenzooxaphosphole ring system makes such ligands conformationally rigid, which help predict the conformation of its metal complex in a real reaction; 2) The physical properties of such ligands were improved as air-stable solid by the introduction of the benzene ring, leading to great operational convenience; 3) Ease of changing the substituents on various locations of such structure allows systematic variation of its steric and electronic properties; 4) The capability of introducing P-chirality in its structure allows such ligands applicable for asymmetric catalysis.

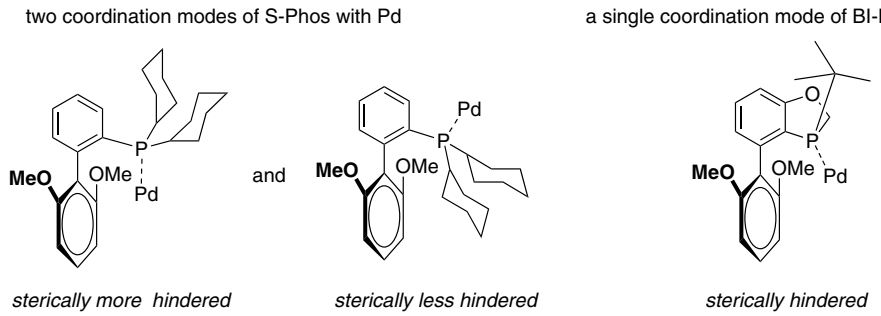
Thus, we have developed four categories of ligands for various purposes (Scheme 1): 1) bulky biaryl monophosphorus ligands that have enabled sterically hindered aryl-aryl cross-couplings; 2) monophosphorus ligands with 2nd coordination that have provided greater functional group tolerance or enabled sterically hindered aryl-isopropyl cross-couplings; 3) P-chiral monophosphorus ligands that have enabled efficient asymmetric aryl-aryl cross-couplings or asymmetric cyclizations; 4) P-chiral bisphosphorus ligands that are applied successfully in asymmetric hydrogenations and asymmetric additions of arylboronic reagents. In this article, we outline some of our recent progress in exploring the application of those novel phosphorus ligands in transition metal catalysis.

2. Sterically Hindered Aryl-Aryl Suzuki-Miyaura Cross-Couplings

In the past several decades, transition-metal catalyzed cross-couplings have received significant attention.[6] Today, it has become one of most powerful method for constructing carbon-carbon bonds for the synthesis of various chemical compounds such as drugs, pesticides and materials. In particular, significant progresses have been achieved on Suzuki-Miyaura cross-couplings thanks to the stable and environmentally benign properties of organoboron reagents. The last twenty years have witnessed the even-broader substrate scope of Suzuki-Miyaura cross-couplings with excellent functional group compatibility at low catalyst loading (<0.1 mol%). Despite the significant advances, there have been only few reports on sterically hindered Suzuki-Miyaura couplings between di-*ortho*-substituted aryl halides and di-*ortho*-substituted arylboronic acids. Biaryl monophosphorus ligands such as S-Phos, X-Phos, and others developed from Buchwald's group have shown good reactivity on some sterically hindered substrates.[7] However, the exact capabilities of steric tolerance and functional group compatibilities are unknown. It has been proven that a single electron-rich and steric bulky monophosphorus ligand is beneficial to palladium catalyzed cross-couplings.[8] Electron-rich phosphorus ligands increase the oxidation power of transition metals and hence facilitate reactions where the oxidative addition step is rate-limiting; while the steric hindrance of the monophosphorus ligand allows to form a single-ligand-coordinated palladium species, which is believed to be active for the transmetallation step as well as reductive elimination. On the basis of these principles, we have developed a conformationally rigid monophosphorus ligand BI-DIME for steric hindered Suzuki-Miyaura coupling reactions. Structurally, BI-DIME eliminates any conformational ambiguity caused by rotation of the C–P bond as observed in Buchwald's S-Phos system (Scheme 2). The sterically more hindered nature of BI-DIME has provided great advantages in Suzuki-Miyaura couplings of sterically hindered arylboronic acids.[9]



Scheme 1. Four categories of ligands developed in our Lab

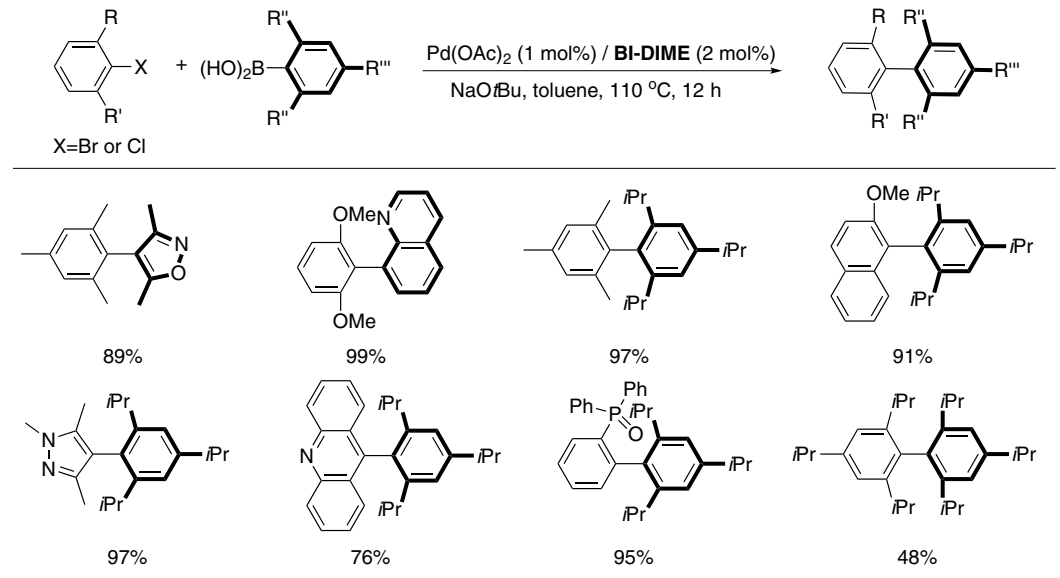


Scheme 2. Comparison of SPhos and BI-DIME

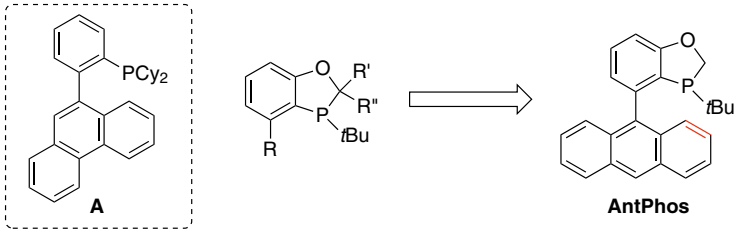
With BI-DIME as ligand, a series of *ortho*-disubstituted arylboronic acids were successfully coupled with *ortho*-disubstituted aryl bromides to form corresponding tetra-*ortho*-substituted biaryls in excellent yields under strong basic conditions (NaO*t*Bu as base). Tetra-*ortho*-substituted biaryls bearing secondary alkyl *ortho*-substituents such as isopropyl groups were synthesized for the first time through cross-coupling reactions (Scheme 3). Substituents such as methyl, methoxy and phosphine oxide were well tolerable, heteroaryls such as pyrazole, quinolone and acridine were also compatible. At 2.5 mol% Pd loading, a tetra-*ortho*-isopropyl substituted biaryl was also successfully formed for the first time in moderate yield by Suzuki-Miyaura coupling. Sterically hindered aryl chlorides could also be employed. The Pd-BI-DIME/NaO*t*Bu system has significantly expanded the scope and utility of sterically hindered aryl-aryl cross-couplings. Mechanistic studies revealed that the NaO*t*Bu might have accelerated the dissociation of the inactive Pd(II) dimer species to form the active Pd(II) monomer species during the reaction, which might have significantly improved the rate of the transmetallation step.

Construction of the functionalized tetra-*ortho*-substituted biaryls is very important for the synthesis of biaryl natural products and ligands.[10] Many of important functional groups such as aldehyde, ester, ketone and nitro are not tolerable to the strong basic conditions with NaO*t*Bu as base. Furthermore, the protodeboronation of the functionalized arylboronic acids is greatly accelerated under strong basic conditions. Only a mild base such as K_3PO_4 can be employed for those substrates and BI-DIME was not effective. For this, a more reactive and functional group compatible phosphorus ligand was needed. In 2002, Buchwald reported a biaryl monophosphine ligand **A** bearing with a phenanthrene moiety, which provided excellent yields for a series of tetra-*ortho*-substituted biaryls with K_3PO_4 as the base.[11] Interestingly, a π coordination of the phenanthrene moiety with the palladium center was observed in its complex. Inspired by this work, we designed and synthesized a new ligand AntPhos with an anthryl group in its framework (Scheme 4).[12] Gratifyingly, various functionalized substrates were coupled efficiently by AntPhos as ligand with K_3PO_4 as base. Functionalities such as aldehyde, ketone, phosphate, cyano, fluoro, and trifluoromethyl group were all well tolerated. This catalytic system provides an effective method for the synthesis of a series of sterically hindered, functionalized biaryls (Scheme 5).

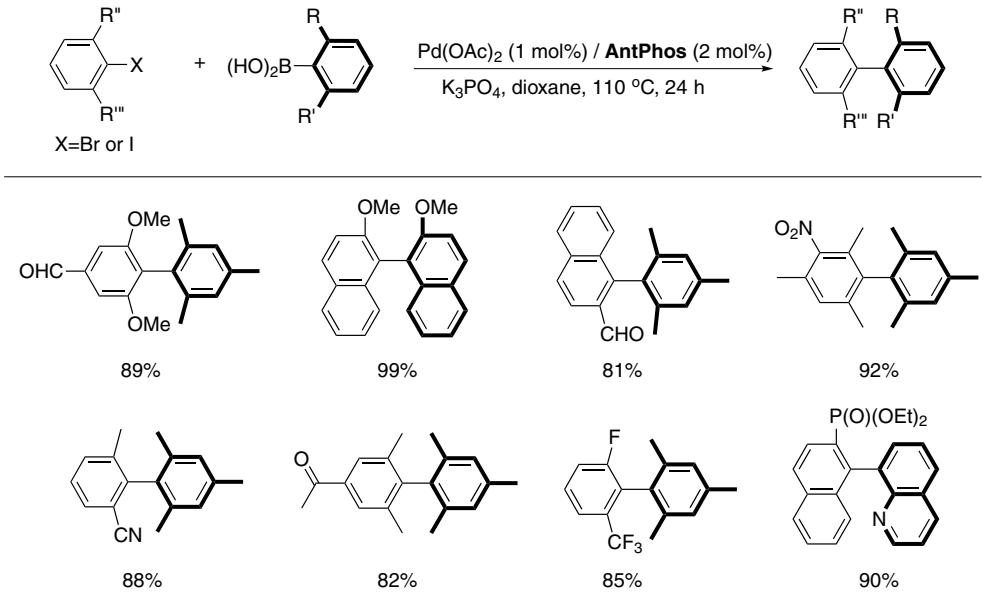
The X-ray crystal structure of [Pd(0)((*R*)-AntPhos)$_2$] revealed an interesting π-coordination between the Pd center and the anthracene ring at 1,2 positions (Scheme 6). We believe that this coordination may not only contribute to stabilize the [Pd(0)((*R*)-AntPhos)] complex, but also help inhibit the dimerization of its Pd(II) complex and increase the stability of its monomeric palladium(II) complex, which well explains its good activity in functionalized sterically hindered cross-couplings.



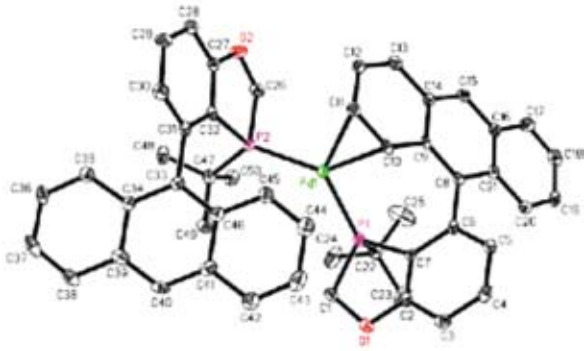
Scheme 3. Substrates scope of sterically hindered Suzuki-Miyaura Coupling with BI-DIME as ligand



Scheme 4. Design of AntPhos



Scheme 5. Substrates scope of functionalized sterically-hindered cross-coupling by AntPhos as ligand



Scheme 6. X-ray structure of [Pd(0)((*R*)-AntPhos)$_2$]

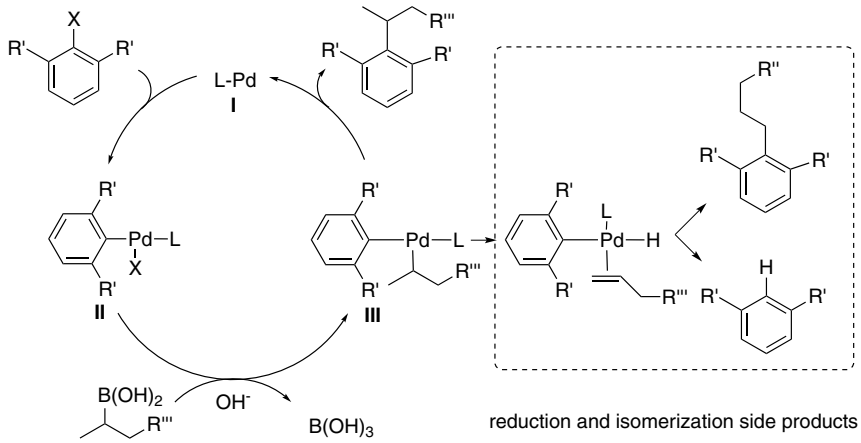
3. Sterically Hindered Aryl-Alkyl Suzuki-Miyaura Cross-Couplings

The transition-metal catalyzed cross-couplings between aryl halides and alkylmetallic reagents have become an important method for the construction of substituted aryls.[13] In particular, aryl-alkyl Suzuki-Miyaura cross-couplings have received much attention thanks to the readily availability of aryl halides as well as the good stability of alkylboronic acids. However, few efficient catalytic systems were reported due to several challenging innate issues: a) the sp^3-hybridized alkylboronic acids are much bulkier and slower for transmetallation in contrast to the sp^2-hybridized arylboronic acids; b) the presence of β-hydrogen in alkylboronic acid allows the β-hydride elimination pathway, leading to the reduction of aryl halides and the formation of the regio-isomer during cross-coupling. These issues become more prominent in cross-couplings between sterically hindered aryl halides and secondary alkylboron reagents (Scheme 7). Biscoe and co-workers reported a highly selective aryl-isopropyl Suzuki-Miyaura coupling of non-hindered substrates,[14] but isomerization and low yields were particularly observed in aryl-isopropyl Suzuki-Miyaura couplings of *ortho*-substituted aryl halides.[15] An efficient method leading to high yields and selectivities was yet to be developed for the Suzuki-Miyaura coupling between di-*ortho*-substituted aryl halides and acyclic secondary alkylboronic acids. Such method would be highly desirable for late-stage introduction of alkyl groups to aromatic molecules.

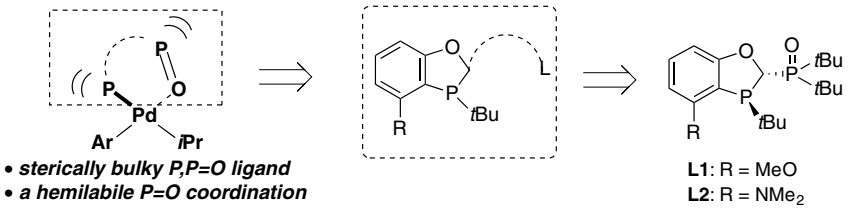
We envisioned that the introduction of a hemilabile coordination by installing a P=O group adjacent to a bulky phosphorus ligand would be beneficial to steric hindered aryl acyclic secondary alkyl coupling. Our proposal was: a) the hemilabile coordination can block an empty coordination site of the palladium center to help inhibit β-hydride elimination; b) the bulky conformation of the ligand could promote facile reductive elimination step. After intensive design and synthesis, we were pleased to develope two novel bulky P,P=O ligands **L1** and **L2** on the basis of 2,3-dihydrobenzo[*d*]-[1,3]oxaphosphole framework (Scheme 8).[16] Both of them were easily prepared within 5 steps in gram scales.

With **L1** as the ligand, a series of mono or di-*ortho*-substituted aryl bromides were coupled with acyclic secondary

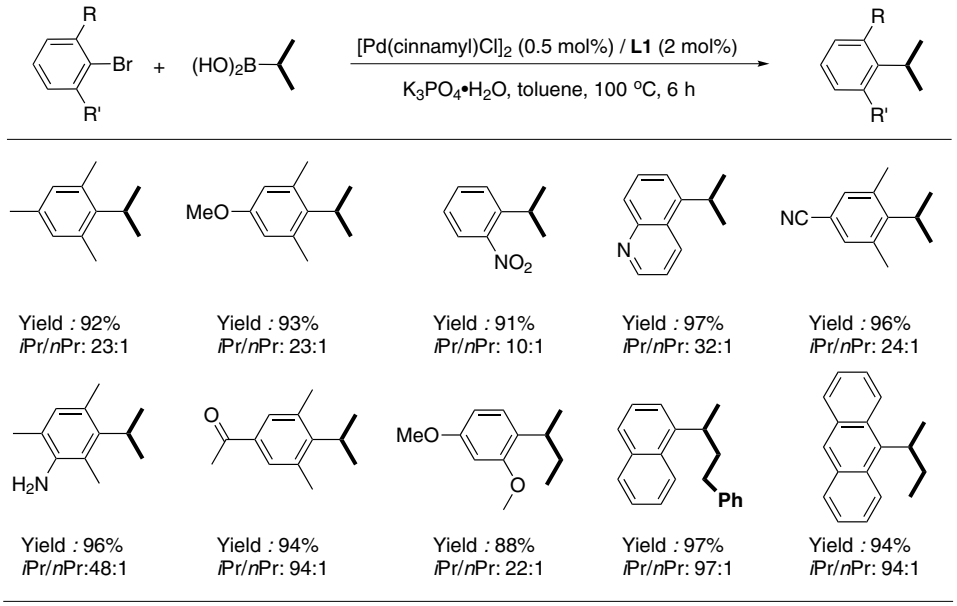
alkylboronic acids in excellent yields and selectivities under 1 mol% palladium loading (Scheme 9). Noteworthy was the excellent functional group compatibility, where methoxy, nitrile, cyano, ketone, amine and quinoline moieties were well tolerated. This method offered advantages over traditional Negishi and Kumada aryl alkyl cross-couplings.



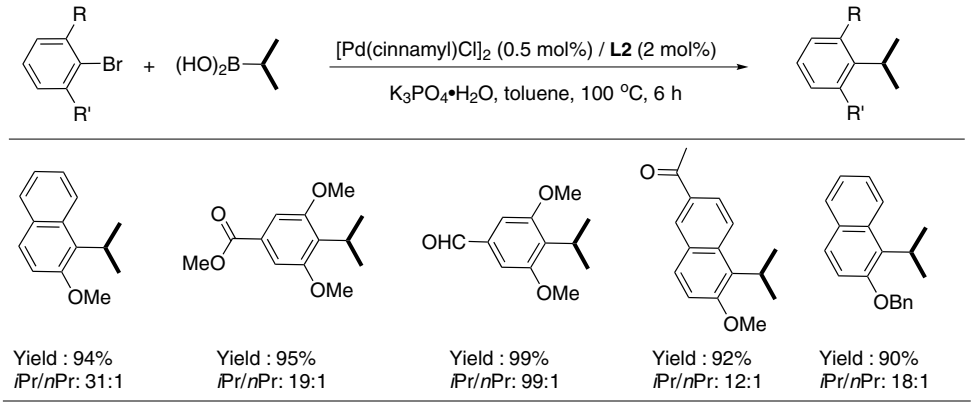
Scheme 7. Reduction and isomerization in Suzuki-Miyaura cross-couplings



Scheme 8. The design of steric bulky P,P=O ligand



Scheme 9. Substrate scope of sterically hindered aryl secondary alkyl cross-coupling

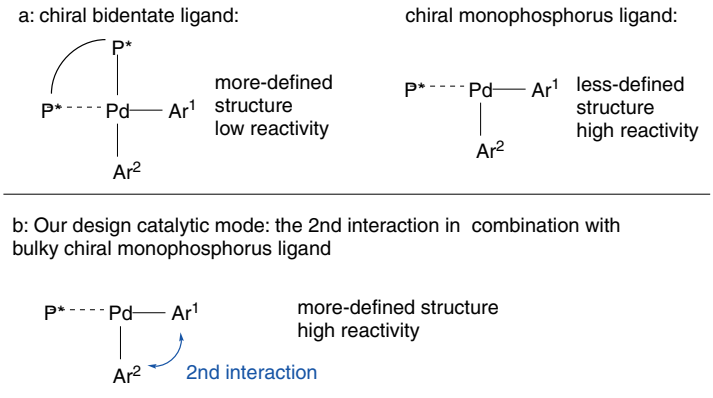


Scheme 10. Substrate scope of sterically hindered aryl secondary alkyl cross-coupling

Since the isopropyl *ortho*-alkoxy di-*ortho*-substituted arene moieties exist in numerous bioactive natural products,[17] a highly efficient cross-coupling between *ortho*-alkoxy di-*ortho*-substituted aryl halides and isopropylboronic acids is yet to be accomplished. Although ligand **L1** provided only moderate yield and poor *i*Pr/*n*Pr selectivity, we were pleased to find the ligand **L2** led to excellent yields and *i*Pr/*n*Pr selectivities for those challenging transformations. A series of isopropyl *ortho*-alkoxy di-*ortho*-substituted arenes were efficiently synthesized in high yields and selectivities. Various functionalities such as aldehyde, ketone and ester were all tolerable (Scheme 10). This protocol was successfully employed in the late-stage modification of estrone at gram scale and applied in a new synthetic route toward gossypol by introduction of the isopropyl group by cross-coupling,[16] demonstrating the power of this methodology.

4. Asymmetric Suzuki-Miyaura Cross-Coupling

Chiral biaryl structures exist in numerous biological interesting natural products as well as serve as privileged frameworks for efficient ligands. As one of the most direct and effective method, the development of cross-couplings for construction those chiral biaryls have received much attention during the past several years.[18] Although much study on asymmetric cross-couplings including Kumada, Negishi, Suzuki-Miyaura have been reported in high yields and stereoselectivities,[19] most current methods focus on the development of unfunctionalized substrates with little synthetic interest. We sought to explore an efficient catalytic system that would be compatible to various functional groups and be applicable to the synthesis of chiral biaryl natural products. Our previous study has proven that the steric bulky and conformationally rigid monophosphorus ligands could promote the reactivity of sterically hindered aryl-aryl couplings. The presence of P-chirality in BI-DIME and related ligands encouraged us to investigate asymmetric Suzuki-Miyaura cross-coupling with these chiral ligands. There remains a significant challenge to achieve high enantioselectivity for cross-coupling with a chiral monophosphorus ligand. Unlike bidentate phosphorus ligands, chiral monophosphorus ligands allow more space at the palladium center, resulting in a less-defined Pd structure and more difficulty in enantiocontrol (Scheme 11a). To provide a solution to this problem, we designed a new catalytic mode by introducing a secondary interaction between the two



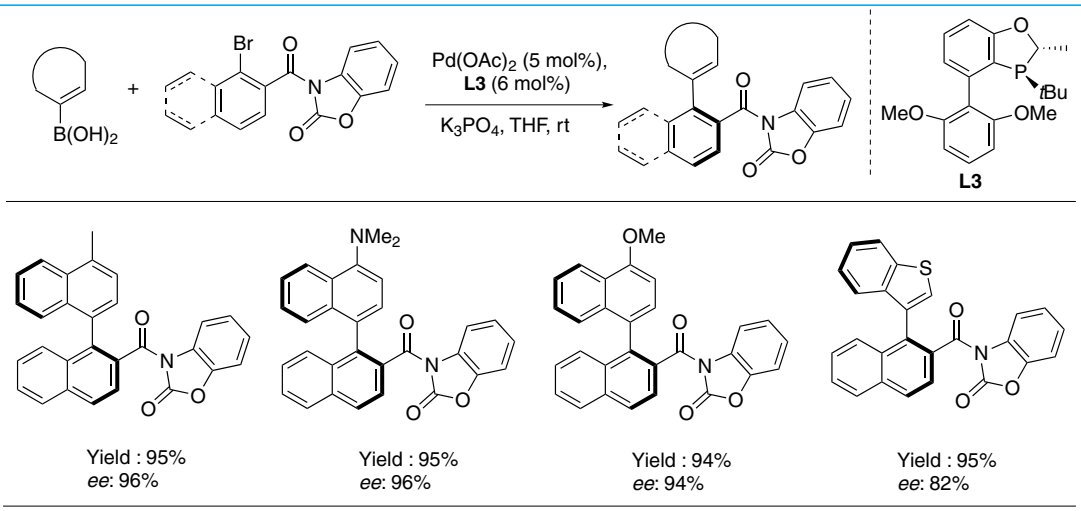
Scheme 11. New catalytic mode for highly reactive and enantioselective Suzuki-Miyaura cross-couplings

aryl coupling partners in combination with the employment of a well-defined chiral monophosphorus ligand (Scheme 11b).[20] The choice of an auxiliary should follow the two principles: 1) The auxiliary can be easily introduced and transformed; 2) The auxiliaries should have the capabilities to offer a noncovalent interaction to the other aryl group such as π-π, polar-π, hydrogen bonding, and cation-π interactions.

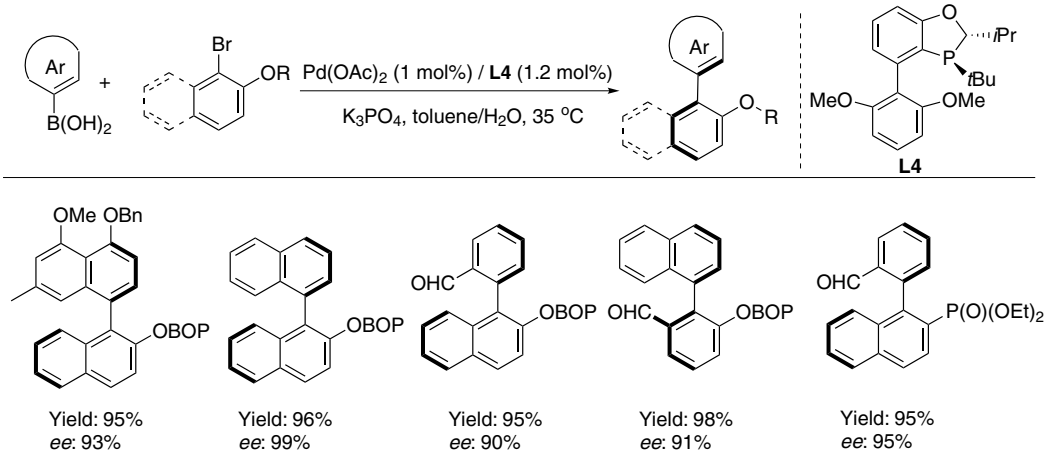
Following this strategy, we first investigated the synthesis of *ortho*-carbonyl substituted biaryls by Suzuki-Miyaura cross-coupling. Gratifyingly, excellent enantioselectivity was achieved when 2-benzoxazolinonyl imide group was employed with **L3** as the ligand. Functional groups such as methoxy and dimethylamino groups were well tolerated. Heteroaryl substrates with strong coordinating abilities such as benzothiazole were also applicable, providing excellent yield and good *ee* value (Scheme 12). It is noteworthy that the biaryl products were easily derivatized to form acids and alcohols by hydrolysis or reduction, respectively.[21] DFT calculations revealed the existence of a π-π interaction between the oxazolidinonyl group and the naphthyl group from the boronic acid. This secondary interaction played a significant role in achieving the high enantioselectivity.

Since numerous biaryl natural products contain *ortho*-hydroxyl/methoxy substituents, efficient construction of *ortho*-oxygen functionalized biaryls by asymmetric Suzuki-Miyaura couplings is highly desirable and yet to be developed. In contrast to *ortho*-carbonyl groups, the *ortho*-oxygen functional groups are more flexible and much more difficult to offer a reliable noncovalent interaction for high enantioselectivity. Fortunately, we found that OBOP (BOP = bis(2-oxo-3-oxazolidinyl)phosphinyl) group could provide excellent reactivity and enantieselectivity when **L4** was employed as ligand. It was noteworthy that the *ortho*-aldehyde substituted substrates were well-tolerable providing high yields and *ee* values, and *ortho*-phosphonate functional biaryls could also be synthesized efficiently (Scheme 13), indicating the compatibility of this cross-coupling with various functional groups.[22] Using this efficient methodology, we successfully finished the total synthesis of biaryl natural products korupensamine A & B, and their heterodimer michellamine B for the first time in a concise and highly stereoselective fashion. This work further demonstrated the practical utility in total synthesis of natural products.

Recently, we reported an asymmetric Suzuki-Miyaura coupling of *ortho*-bromo aryl triflates with various arylboronic acids with **L3** as the ligand, affording a series of chiral biaryl triflates in high yields and up to 91% *ee*. The aryl triflates were easily transformed to various chiral biaryl products via simple derivatizations.[23]



Scheme 12. Substrate scope of asymmetric cross-couplings with *ortho*-carbonylbenzooxazolidinone substituents



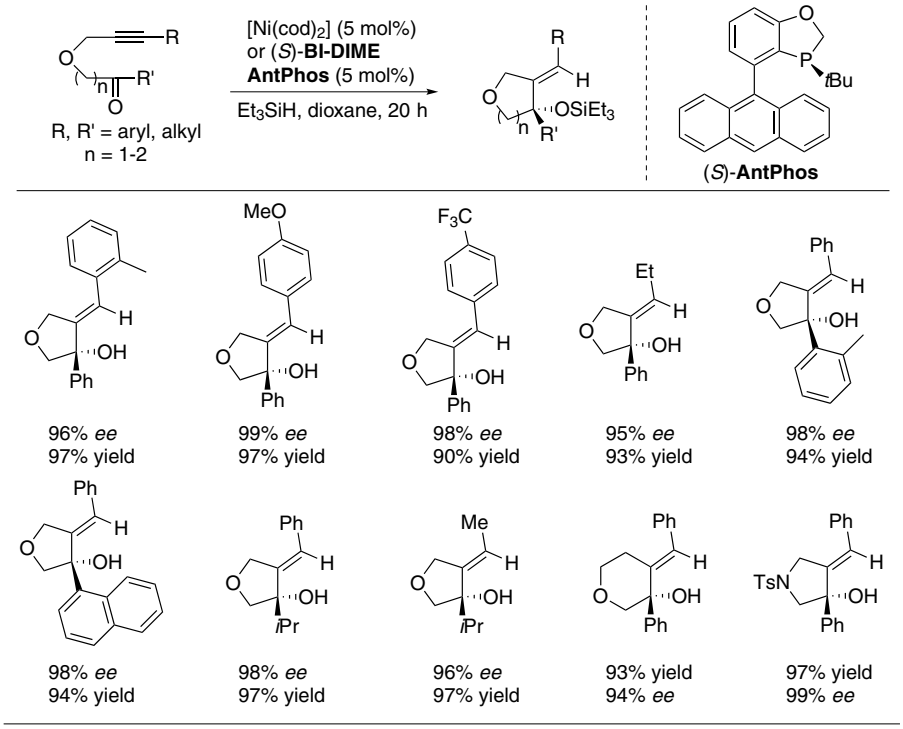
Scheme 13. Substrate scope of asymmetric cross-couplings with OBOP substituents

5. Efficient Cyclizations Promoted by Chiral Monophosphorus Ligands

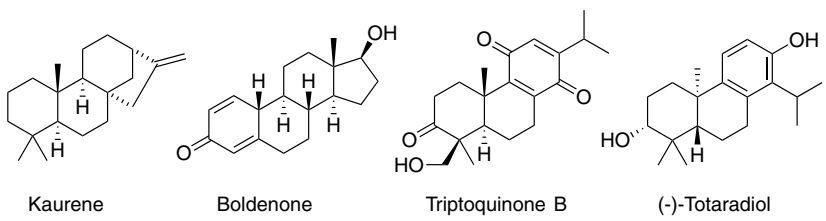
Chiral tetrahydrofuran/tetrahydropyran moieties exist in a broad range of bioactive natural products.[24] As one of most convenient and powerful methodology for constructing those chiral structures, the transition metal catalyzed intramolecular cyclization of alkynals/alkyones has received great interests.[25] Recent years have witnessed the ever expanding scope of such cyclizations along with the employment of various transition-metal catalysts including Ni, Pd, Rh, Ru and Ir catalytic systems. Among those metals, the application of cost-effective Ni in reductive cyclization is particularly attractive.[26] Although a number of Ni-catalyzed cyclizations of alkynals/alkynones with high reactivities are developed, no efficient enantioselective reductive/alkylative cyclization of alkynones has been reported. Encouraged by early work from Jamison's group,[27] we envisioned that P-chiral monophosphorus ligands developed in our laboratory could be applicable for enantioselective Ni-catalyzed cyclizations. With these easily prepared alkynones as substrates, we were pleased that the reductive cyclizations proceeded smoothly with chiral monophosphorus ligand (*S*)-BI-DIME or (*S*)-AntPhos as the ligand, providing cyclic allylic alcohols in excellent yields and *ee* values.[28] A series of aromatic and aliphatic alkynes were all suitable for this system. Aromatic ketones with various substituents such as methyl, methoxy and trifluoromethyl were compatible with the reaction conditions. In addition, various aliphatic ketones were also converted efficiently to chiral 2-alkyl furanols. Besides the chiral tetrahydrofuran products, a chiral tetrahydropyran product was also synthesized in high yield and 94% *ee* (Scheme 14).

This asymmetric cyclization was applied in the efficient synthesis of the lignan dehydroxycubebin as well as the facile construction of chiral dibenzocyclooctadiene skeletons,[28] which demonstrated its utility in natural product syntheses.

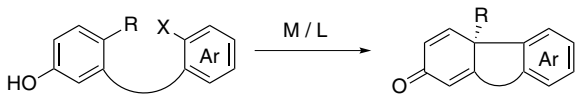
Tricyclic skeletons bearing all-carbon quaternary centers exist in numerous biological interesting natural products, such as complex terpenes and steroids (Scheme 15).[29] Although



Scheme 14. Substrate scope of asymmetric reductive cyclization of alkynones



Scheme 15. Terpenes and steroids bearing all-carbon quaternary centers

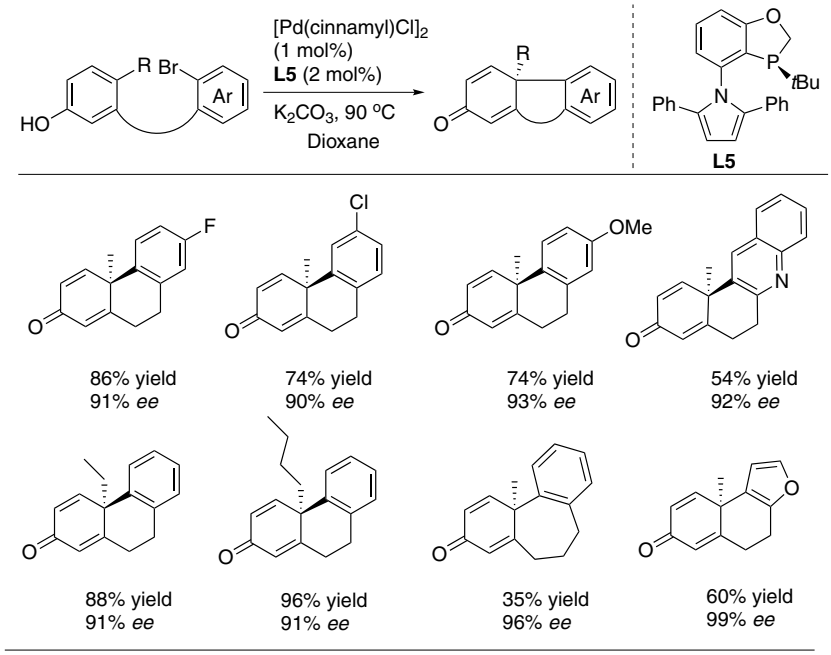


Scheme 16. Novel asymmetric dearomative cyclization

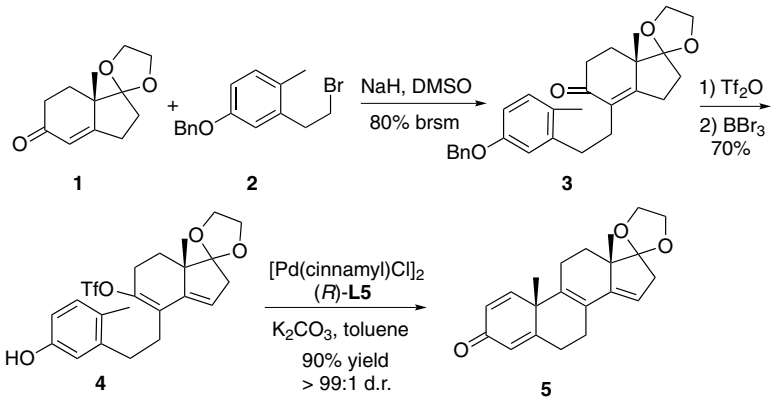
various methods were successfully applied in synthesis of those compounds, there remains great demand for developing more powerful and efficient strategies in the construction of such chiral skeletons. We believed that the asymmetric intramolecular dearomative cyclization can offer good synthetic efficiency owing to the availability of aryl systems as well as the convenience in the derivatization of the cyclized products (Scheme 16).[30]

According to this design, we screened a series of chiral monophosphorus ligands developed in our group. Interestingly, high yield and excellent enantioselectivity was obtained when a new ligand **L5** bearing a 2,5-diphenylpyrrole moiety was employed and $[Pd(cinnamyl)Cl]_2$ as the catalyst precursor.[31] A series of tricyclic phenanthrenone derivatives bearing an all-carbon quaternary center were efficiently synthesized with this protocol. Various functional groups such as fluoro, chloro, and methoxy substituents were well tolerated. Quinone and furan heteroaryls were also compatible with the catalytic conditions (Scheme 17).

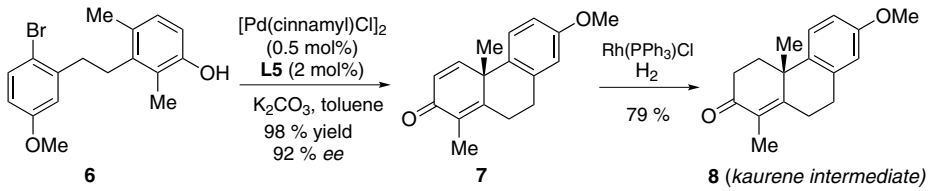
The cyclization was applied to the construction of the skeleton of the anabolic steroid boldenone (Scheme 18). Thus, chiral ketal **1** was reacted with bromide **2** in the presence



Scheme 17. Substrates scope of asymmetric dearomative cyclizations



Scheme 18. Efficient synthesis of boldenone skeleton **5**

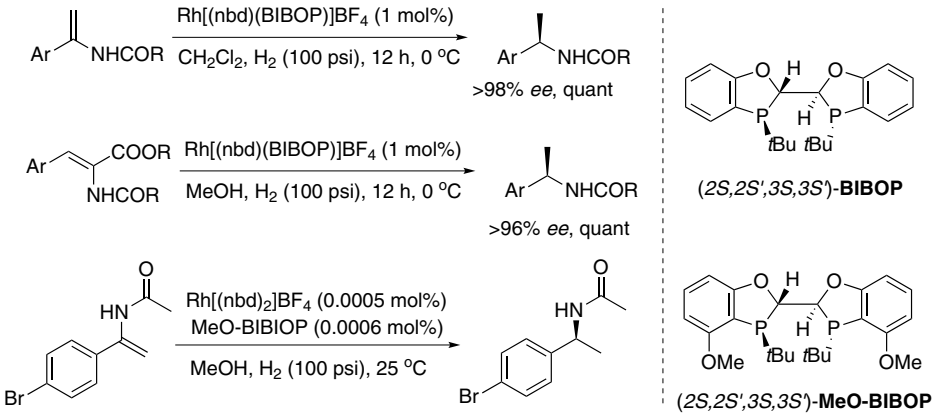


Scheme 19. Efficient synthesis of kaurene intermediate **8**

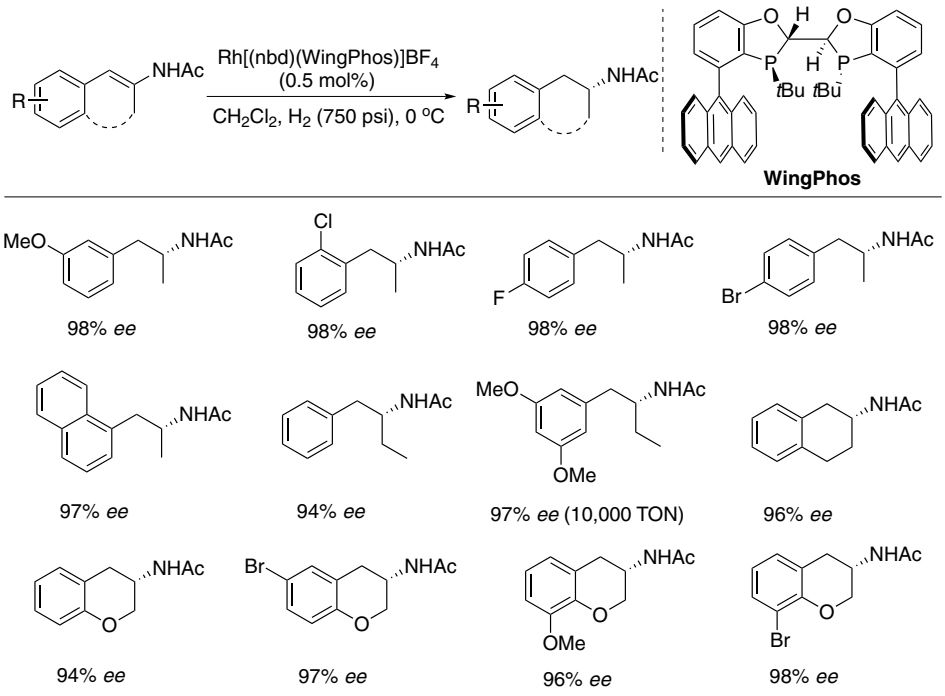
of NaH to form **3** in an unoptimized yield of 80% based on recovered starting material. Then, conversion of **3** into the cyclized precursor vinyl triflate **4** by two steps. Cyclization of triflate **4** by our protocol provides boldenone skeleton **5** in 90% yield and a diastereomeric ratio of > 99:1. This strategy was also applied in the synthesis of enone **8**, a key chiral intermediate[32] for the synthesis of kaurene, abietic acid, and a bruceantin analogue. Up to 98% yield and 92% *ee* value of tricyclic product was obtained by the key dearomative cyclization (Scheme 19). At the same time, we also finished the total synthesis of (-)-totaradiol by the employment of this efficient strategy.[31]

6. Asymmetric Hydrogenation

Although tremendous progress has been achieved in asymmetric hydrogenation, there remains numerous unsolved problems that call for developing new and efficient catalytic systems. P-chiral phosphorus ligands has demonstrated several advantages owing to its innate features,[3a] and a number of well-known, efficient ligands and catalysts were developed in recent years.[33] However, many of these are inconvenient to operate as oily or air-sensitive ligands. From the practical point of view, and in order to meet the increasing demand of green chemistry, highly efficient and operationally convenient phosphorus ligands are needed to be developed. Our group designed a novel skeleton with benzooxaphosphole as backbone in 2010, and then synthesized a series of C_2-symmetric P-chiral phosphorus ligands BIBOP and MeO-BIBOP (Scheme 20). Both of them are air-stable, crystalline solid that has been provide a great deal



Scheme 20. Asymmetric hydrogenation by BIBOP and MeOBIBOP



Scheme 21. Substrate scope of asymmetric hydrogenation by WingPhos

of operational convenience. With BIBOP as ligand, various α-arylenamides and α-(acylamino)acrylic acid derivatives can be hydrogenated in excellent yields and enantioselectivities with $Rh(nbd)_2BF_4$ as the metal precursor.[5] To our delight, MeO-BIBOP has provided 200,000 TON in rhodium-catalyzed asymmetric hydrogenation of *N*-[1-(4-bromophenyl)vinyl]-acetamide, which has been considered as the most efficient processes in rhodium-catalyzed asymmetric hydrogenation of α-arylenamides up to date.

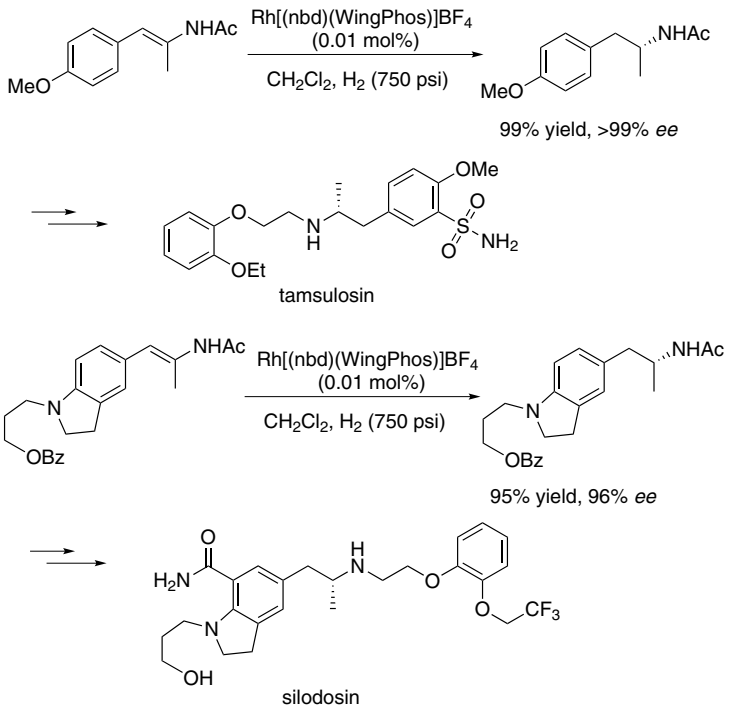
We further modified the BIBOP by introducing anthracenyl groups and thus synthesized the new ligand WingPhos. In contrast to the traditional bisphosphorus ligands, WingPhos contains anthracenyl groups that protrude directly forward to the substrate coordination and provide a well-defined and deep chiral pocket, which could enable efficient asymmetric hydrogenation for some challenging substrates. Since chiral β-arylamines exist in numerous biologically interesting natural products and therapeutic agents,[34] we embarked a program on searching for efficient phosphorus ligands to synthesize chiral β-arylamines by asymmetric hydrogenation. Gratifyingly, we found WingPhos was an efficient ligand for asymmetric hydrogenation of both (*E*)-β-arylenamides and cyclic β-arylenamides. A series of chiral β-arylisopropylamines, 2-aminotetralines, and 3-aminochromans were easily accessed by using this method (Scheme 21). Hydrogenation of (*E*)-*N*-[1-(3,4-dimethoxyphenyl]-prop-1-en-2-yl)acetamide as substrate showed that the highest TON could be reached up to 10,000 without erosion of the *ee* value, thus demonstrating the high efficiency and reactivity of WingPhos for this transformation.[35]

By using this method, several key chiral intermediates for therapeutic agents such as the α-blocker tamsulosin and α_1-adrenoceptor antagonist silodosin, can be efficiently synthesized by asymmetric hydrogenation (Scheme 22).

7. Enantioselective Addition of Arylboron Reagents to Arylketones

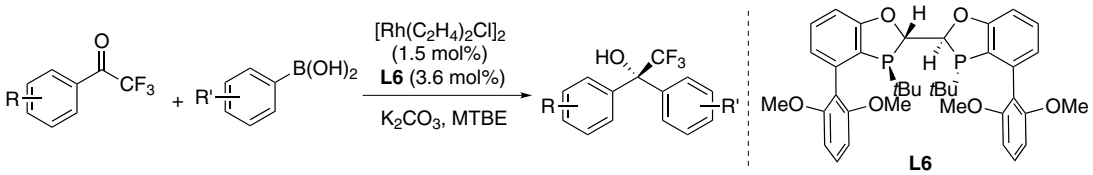
Chiral tertiary carbinol moieties bearing diaryl and alkyl groups exist in a number of therapeutic agents and natural products,[36] such as the antidepressant escitalopram, antihistamine clemastine, and cough suppressant chlophedianol. The efficient synthesis of these chiral tertiary alcohols have received significant attention. The asymmetric addition of nontoxic, stable and operationally convenient aryl boron reagents to simple aryl ketones is highly attractive yet remains challenging. In 2013, we described a highly enantioselective Rh-catalyzed addition of trifluromethyl ketones by arylboronic acids[37] by using **L6** as ligand. A series of chiral tertiary trifluoromethyl alcohols were synthesized in good to excellent yields and excellent *ee* values (Scheme 23).

Low yield (25%) was observed for the addition of 4-methoxyphenylboronic acid to acetophenone when **L6** was employed as ligand, albeit with an excellent *ee* (96%). This promising result encouraged us to search for more efficient catalytic system. After intensive optimization of the reaction conditions, we were pleased that an excellent yield and enantioselectivity were obtained in the addition of phenylboroxine to acetophenone with WingPhos as Ligand. The employment of magnesium bromide as additive is very important to enhance the yield presumably by activating the ketone substrate. With this new protocol, a range of chiral tertiary carbinols were synthesized in excellent *ee* values and yields.[38] Functional groups such as halide, nitro, ester, and sulfone were well tolerated. Notably, the *ortho*-substituted aryl ketones were also compatible and provided tertiary alcohols with excellent enantioselectivities, albeit with diminished yields. In addition, the Rh/WingPhos system could also be employed in enantioselective addition to benzofused five-membered cyclic ketones, providing cyclic tertiary alcohols in excellent *ee* values (Scheme 24).

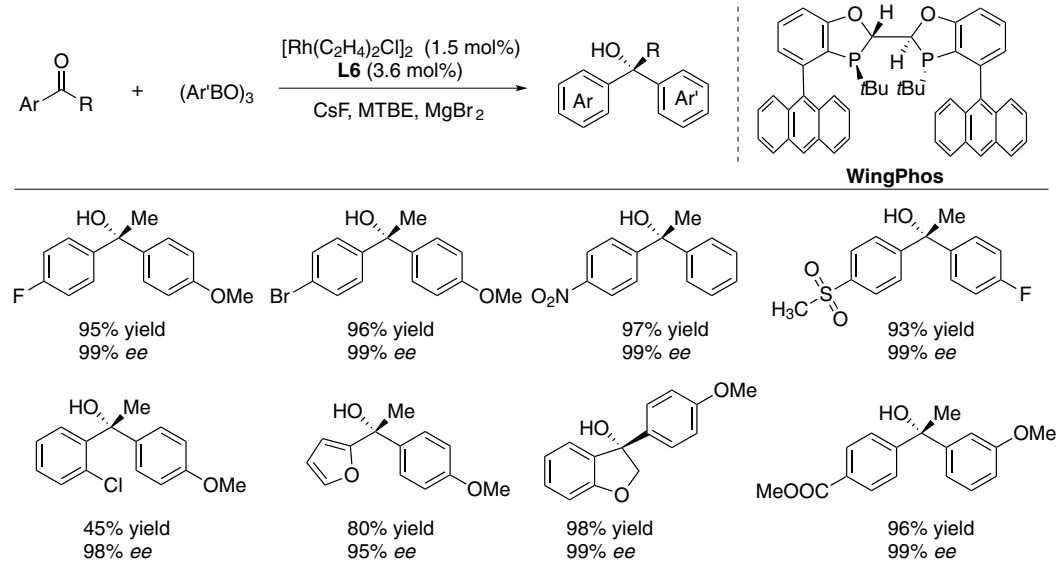


Scheme 22. The application in the synthesis of key intermediates for therapeutic agents

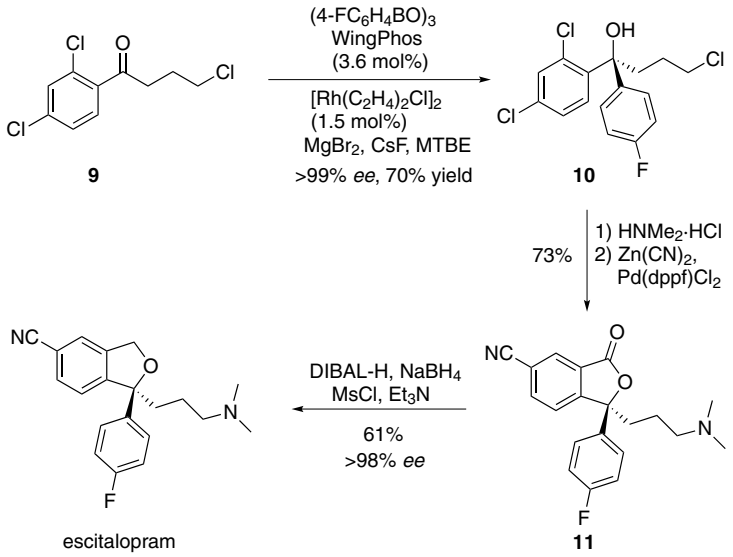
This catalytic methodology was successfully applied in enantioselective synthesis of antidepressant drug escitalopram (Scheme 25). 4-Fluorophenylboroxine was added to 4-chloro-1-(2,4-dichlorophenyl)butan-1-one (**9**) with the Rh/(*R*,*R*,*R*,*R*)-WingPhos catalyst, providing the desired tertiary alcohol **10** on gram scale with 70% yield and >99% *ee* value. Introduction of dimethylamine by displacement of the chloride in **10** and subsequent palladium-catalyzed dicyanation-lactonization afforded the lactone **11** in 73% overall yield. After reduction of lactone **11** and subsequent cyclization, providing escitalopram in 61% overall yield and with greater than 98% *ee*. Thus, a new highly enantioselective synthesis of escitalopram was successfully developed with this methodology.[38]



Scheme 23. Highly enantioselective addition of arylboronic acids to aryl trifluoromethyl ketones



Scheme 24. Substrate scope of asymmetric addition of arylboroxines to aryl ketones



Scheme 25. Synthesis of escitalopram

8. Summary

In this article, we outlined our recent efforts in the development of novel phosphorus ligands and its applications in efficient transition metal catalyzed reactions. In particular, we developed four categories of new phosphorus ligands on the basis of a benzooxaphosphole backbone. All of those novel ligands are air-stable and operationally convenient solids. In search of highly efficienct and practical catalyst, we have developed the bulky biaryl monophosphorus ligands BI-DIME and AntPhos that have enabled sterically hindered aryl-aryl cross-couplings; two P,P=O.

Ligands have been successfully applied in sterically hindered aryl-isopropyl cross-couplings; several P-chiral monophosphorus ligands have been synthesized and employed successfully in efficient asymmetric aryl-aryl cross-couplings or cyclizations; several P-chiral bisphosphorus ligands are applied in highly enantioselective asymmetric hydrogenation as well as asymmetric addition of arylboron reagents. The high reactivity, chemoselectivity, and enantioselectivity achieved in these catalytic systems allow practical applications in construction of therapeutic agents and natural products. Despite those progresses, the current applications remains very limited with respect to the increasing demand of numerous catalytic reactions. We are convinced that the development of novel phosphorus ligands will continue to be an important method for discovering efficient and practical catalytic reactions and the future is bright down this path.

Acknowledgment

We are grateful to NSFC-21432007, 21272254, 21572246, the “Thousand Plan” Youth program, the Innovation Fund of State Key Laboratory of Bioorganic and Natural Products Chemistry.

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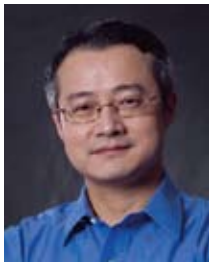
Guangqing Xu was born in 1987 in Shandong Province, China. He received his Bachelor of Science from Qingdao University of Science and Technology in 2009. After one year of experience in pharmaceutical company, he then joined in Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, and received his Ph.D. in 2015 under the guidance of Prof. Wenjun Tang. Now, he is working on development of efficient asymmetric catalyst and reactions in Prof. Wenjun Tang's group as assistant researcher.



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Wenjun Tang was born in 1974 in Zhejiang Province, China. He received his B. Eng. degree in 1995 from East China University of Sciences and Technology, his M.S. degree in 1998 from Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences, and his Ph.D. in 2003 from the Pennsylvania State University. After two-year postdoctoral research at the Scripps Research Institute, he worked six years as a process chemist at Boehringer Ingelheim Pharmaceuticals Inc. In 2011, he took his current position as a research professor at Shanghai Institute of Organic Chemistry, Chinese Academy of Sciences. His research interests are in the areas of asymmetric catalysis, total synthesis of natural products, and development of efficient chemical processes.

Chemistry Chat -Focusing on the Elements-

Naming Elements — What Will Be the Name For Element 113?

Kentaro Sato

Great news arrived for the Japanese scientific community at the end of 2015. The new "Element 113" synthesized by the research team at RIKEN Institute led by Professor Kosuke Morita (currently of Kyushu University) was officially recognized by IUPAC and the group was given the right to name it. It was a significant achievement considering that it was the first time a new element was discovered in Asia, let alone in Japan.

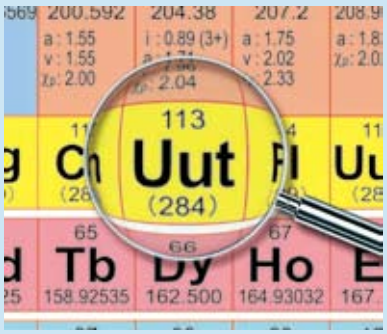
Because Element 113 has a lifetime in the order of milliseconds and only three atoms have been synthesized so far, it will take a while before we can learn about its properties. In this column, I would like to write about the episodes of naming newly discovered elements.

The Elusive Nipponium

In the earlier paragraph, I mentioned it was the first time a new element was discovered in Japan. However, there was a time, almost 100 years ago, when the discovery of a new element was reported by a Japanese scientist. Masataka Ogawa, who was studying at University College London at the time (and would later become the president of Tohoku Imperial University), isolated a hitherto unknown element from Sri Lankan mineral thorianite. Presuming it had an atomic weight of about 100, he thought it was the element that would fit the empty 43rd spot of the periodic table. In 1908, following the recommendation of his mentor William Ramsay, Ogawa reported this new element with the name *nipponium* (and the atomic symbol Np).

Unfortunately though, this discovery could not be confirmed by his scientific peers and none of his students was able to repeat the isolation. The supposed new element *nipponium* therefore never found a legitimate spot in the periodic table and disappeared into oblivion.

In 2003, in an interesting twist, Professor Kenji Yoshiwara of Tohoku University re-evaluated the record left by Ogawa and found that *nipponium* actually corresponded to rhenium (having atomic number 75). Rhenium is positioned right below the 43rd spot in the periodic table and has similar properties. If only X-ray spectroscopy had been available to Ogawa back then, he could have characterized his element accurately and the 75th element would have been named *nipponium*. Ogawa was very close to catching the big fish, but it just slipped out of his hands.



Element 43 in the periodic table is like the Sargasso Sea in the Atlantic Ocean so to speak, in a sense that many scientific adventurers had to experience shipwreck-like failures as they challenged to claim that spot. A number of discovery attempts and naming proposals, such as *polonium* and *pluranium* (Osann, 1828), *pelopium* (H. Rose, 1845), *ilmenium* (R. Hermann, 1846), *davium* (S. Kern, 1877), and *lucium* (P. Barrière, 1896), were made but all of them turned out to be wrong assignments of other elements. Even the claim by Noddack and his coworkers, who correctly identified rhenium in 1925, to having captured Element 43 as well (they named it *masurium*) turned out to be erroneous.

The 43rd spot was finally filled in 1937. A minute amount of that elusive element was detected and isolated from the molybdenum-based component of cyclotron. When molybdenum (Element 42) was hit by the deuteron accelerated by cyclotron, it led to the formation of Element 43.

Even though there were more than one candidates when it came to naming it, including *panormium* (after the old name of Palermo, Italy), the element was eventually named *technetium* after the Greek word meaning synthetic. After more than a century of twists and turns, Element 43 was finally given an official name.

As most chemists know today, technetium has no stable isotope and thus does not exist in nature (except in outer space, where it has been spectroscopically detected in certain planets). This kind of "a hole in the periodic table" is rare and the 61st promethium is the only other example. For chemists, it was such an unfortunate mischief of the creator.

Of interesting note is that there is a rule that names of the previously proposed but disqualified so-called "phantom elements" cannot be used again for newly discovered elements. For this reason, the new Element 113 cannot be named *nipponium*, even if it sounds most fitting.

Confusions Caused by Naming Elements

Given its nature, naming elements often creates confusions. After all, the names are to be used for hundreds of years to come and naming them is an utmost honor for scientists. Therefore, there have been a number of disputes in the past over claiming the right to name elements.

Things became particularly tumultuous during the era when the race for the synthesis of transuranium elements (the elements with an atomic weight greater than 92) gained intensity. Since this era happened to overlap the US-Soviet Cold War, the national pride factor added extra heat to the competition for synthesis and naming of new elements. The race for the elements from 104th through 109th became particularly complicated with the participation of German teams and all sides proposing different names. Moreover, there was even an instance in which one of the US teams reported the synthesis of Element 118 in 1999 but the result was soon found to have been fabricated, and the paper was withdrawn three years later.

So, scientists are not given the right to pick a name for their element immediately after reporting its discovery. They must prepare and provide enough proofs and be authorized by the specialized committee, and only after passing through this process naming rights are granted.

It goes back to July of 2004 when Element 113 was synthesized for the first time by colliding bismuth and zinc nuclei (atomic number 83 and 30, respectively). Eleven and half years passed since then before the RIKEN researchers finally got the naming right. The second atom of Element 113 was obtained in April 2005, but struggling days and years continued after that. In August of 2012, the third atom was synthesized and it seems that this data became the conclusive piece of proof. The perseverance and hard work of the people who are involved in the project definitely deserve the respect and recognition.

The Name for Element 113

In the world of science, you can find really fascinating names. For example, since there is essentially no limitation when it comes to naming small planets, there are names like *Jodie Foster*, *Tokyo Giants*, and *Totoro*. In the field of biology, there are genes having names like *Harakiri*, *Sonic Hedgehog*, and *Musashi*, all of which show playfulness of the scientists.

As for chemical elements, however, there are some rules and you can't just pick any names you like. First, elements that are considered metallic have to have the suffix *ium*. There is also a tradition that the word root is chosen based on the place of discovery, the name of scientist, property of the element, and mythical names.

Considering that there are many precedents such as americium, francium, and germanium, Element 113 will likely be named after the country of origin. But since *nipponium* cannot be used as mentioned earlier, names like *japonium* are reportedly being considered. Rikenium is reportedly another candidate (after RIKEN Institute), but the chance for this one is unclear since RIKEN is not exactly a place.

Many of the transuranium elements are named after scientists. Even though Element 102 and 112 are named nobelium and copernicium, respectively, after Alfred Nobel (chemist) and Nicolaus Copernics (astronomer), most are named after nuclear physicists. In Japan, candidates would probably be the likes of Hideki Yukawa, Hantaro Nagaoka, and Yoshio Nishina.

It is said to take a year or so for the name of Element 113 to be approved after the proposal. Let us follow closely how the naming process develops and what will be chosen at the end.

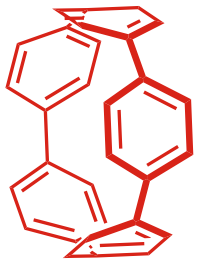
Introduction of the author :

Kentaro Sato

[Brief career history] He was born in Ibaraki, Japan, in 1970. 1995 M. Sc. Graduate School of Science and Engineering, Tokyo Institute of Technology. 1995-2007 Researcher in a pharmaceutical company. 2008-Present Freelance science writer. 2009-2012 Project assistant professor of the graduate school of Science, the University of Tokyo. 2014-present Publicist for π-system figuration, scientific research on innovative areas.
[Specialty] Organic chemistry
[Website] The Museum of Organic Chemistry <http://www.org-chem.org/yuuki/MOC.html>

The Smallest "Carbon Nanoring": [5]Cycloparaphenylene ([5]CPP)

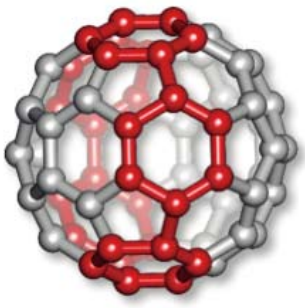
C2931 [5]Cycloparaphenylene (= [5]CPP) (1) **20mg 100mg**



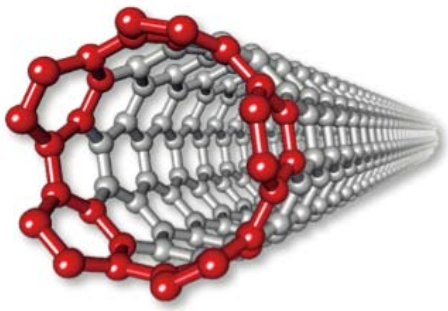
[5]CPP (**1**)

A cycloparaphenylene (CPP), the so-called carbon nanoring, has a cyclic structure formed by linkages of *p*-substituted benzenes. The CPP attracted researchers in fundamental chemistry and material science, because it is a unit structure of a CNT. In fact, Itami *et al*. successfully synthesized a uniform CNT by a bottom-up procedure starting from CPP as a template.[1] A CPP also receives attention as a molecular host material, because the CPP with a specified diameter forms an inclusion complex with fullerene.[2]

Recently, this research area has been extended to synthesize a CPP of smaller diameter having large distortion. Yamago[3,4] and Jasti[5] groups independently reported synthesis of the [5]CPP (**1**), which has been the smallest CPP so far. It is expected that a bottom-up synthesis of the smallest diameter CNT may be possible by **1** as a template material. **1** is also a unit structure of C_{60} with a similar diameter (0.7 nm) to the fullerene. **1** has narrow HOMO-LUMO gap that is comparable with C_{60}. **1** is nicely soluble in an organic solvent.



C_{60}



[5,5]CNT

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3) Synthesis and characterization of [5]cycloparaphenylene
E. Kayahara, V. K. Patel, S. Yamago, *J. Am. Chem. Soc.* **2014**, *136*, 2284.
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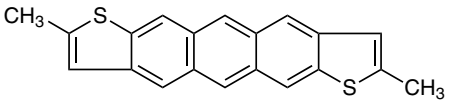
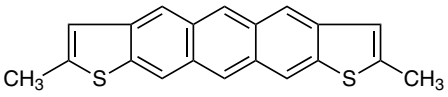
5) Efficient room-temperature synthesis of a highly strained carbon nanohoop fragment of buckminsterfullerene
P. J. Evans, E. R. Darzi, R. Jasti, *Nat. Chem.* **2014**, *6*, 404.

Isomerically Pure Anthradithiophene Derivatives

D4617 ***anti*-DMADT (purified by sublimation) (1)** **100mg**
D4618 ***syn*-DMADT (purified by sublimation) (2)** **100mg**



anti-DMADT (**1**)



syn-DMADT (**2**)

Pentacene shows good hole-transporting properties, but it is unstable toward oxidation due to its inherent high HOMO-level. This instability causes variability of device-performance and also limits long-term use of devices. Anthradithiophene also shows good hole-transporting properties, and is more stable toward oxidation because of its lower HOMO-level compared with pentacene. Anthradithiophene derivatives have been reported as mixtures of *syn*- and *anti*- isomers according to the direction of the thiophene moiety, and the effect of each isomer in device performance is not clear.

Tokito and Mamada have reported the synthesis and properties of isometrically-pure *syn*- and *anti*-2,8-dimethylanthradithiophenes (DMADTs).[1] Both isomers (*anti*-DMADT and *syn*-DMADT) show similar optical properties and energy levels, but the more symmetric *anti*-DMADT (μ = 0.41 cm^2/Vs) shows five times superior hole-mobility compared with *syn*-DMADT (μ = 0.084 cm^2/Vs). This result clearly shows the importance of using the single isomer in device-fabrication.

TCI developed new synthetic approach to provide high pure *anti*-DMADT (**1**) and *syn*-DMADT (**2**) with no isomer contamination.

Reference

1) M. Mamada, T. Minamiki, H. Katagiri, S. Tokito, *Org. Lett.* **2012**, *14*, 4062.

Related Product

P0030 Pentacene (purified by sublimation) 100mg 1g

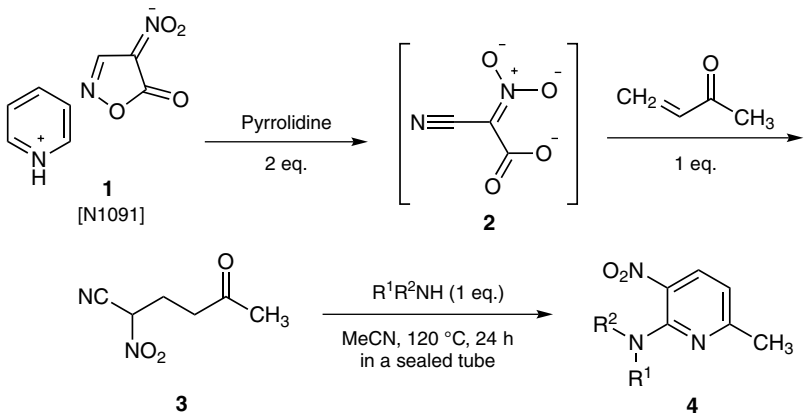
A Safe Cyano(nitro)methylation Reagent

N1091 4-Nitro-5(2*H*)-isoxazolone Pyridinium Salt (1) 1g

Nitroacetonitrile (NAN) is useful as a cyano(nitro)methylation reagent for synthetic chemistry because it has a highly-acidic methylene connected with reactive cyano and nitro functionalities. However, NAN has an explosive nature. Therefore, a safe alternative for cyano(nitro)methylation reagent is required.

The pyridinium salt of nitroisoxazolone **1**, which has been developed by Nishiwaki *et al.*, undergoes a ring opening reaction quantitatively under mild conditions upon treatment with two equivalents of organic base and is converted to cyano-*aci*-nitroacetate **2**, which works as a synthetic equivalent of NAN.[1] **2** has high solubility in organic solvents whether polar or non-polar. Hence, it is useful as a safe and easy-to-handle cyano(nitro)-methylation reagent for synthesis of versatile polyfunctionalized compounds.

For example, bifunctional pyridine **4**, which possesses vicinally substituted nitro group and amino group, is formed when the Michael adduct **3**, which is obtained by adding a vinyl ketone to generated **2**, reacts with amines.[2] Also, the syntheses of polyfunctionalized heterocyclic compounds such as isoxazolines, isoxazoles, dihydropyridines, and naphthyridines by using **2** have been reported.[2-4]



1 [N1091] **2** **3** **4**

In addition, products obtained using cyano-*aci*-nitroacetate **2** derived from **1** can be introduced to versatile frameworks because they possess a cyano group and a nitro group.

References

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N. Nishiwaki, Y. Takada, Y. Inoue, Y. Tohda, M. Ariga, *J. Heterocycl. Chem.* **1995**, *32*, 473.
2) Safe cyano(nitro)methylating reagent – Michael addition of cyano-*aci*-nitroacetate leading to δ-functionalized α-nitronitriles
H. Asahara, K. Muto, N. Nishiwaki, *Tetrahedron* **2014**, *70*, 6522.
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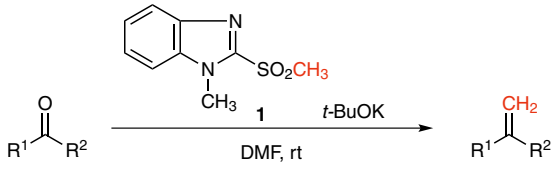
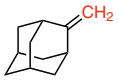
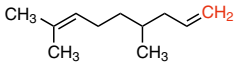
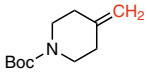
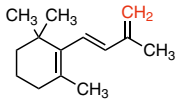
4) Synthesis of vicinally functionalized 1,4-dihydropyridines and diazabicycles via a pseudo-intramolecular process
N. Nishiwaki, S. Hirao, J. Sawayama, H. Asahara, R. Sugimoto, K. Kobiro, K. Saigo, *Tetrahedron* **2014**, *70*, 402.
5) Review
H. Asahara, N. Nishiwaki, *Oreo Saiensu* **2015**, *15*, 165.

A New Julia-Type Reagent for Methylenation Reactions

M2860 1-Methyl-2-(methylsulfonyl)benzimidazole (1) 1g 5g

Ando *et al.* have reported that 1-methyl-2-(methylsulfonyl)benzimidazole (**1**) can be used as a methylene source and applied to the Julia–Kocienski-type methylenation reaction. **1** successfully reacts with aldehydes and ketones in the presence of a base at room temperature to afford the desired methylene derivatives. In this reaction, various ketones such as α,β-unsaturated ketones and sterically hindered ketones are applicable. In addition, after the reaction, formed byproducts of a benzimidazole derivative can be easily removed by the extraction.



Product	Yield (%)	Product	Yield (%)
	96		97
	99		91

Reference

K. Ando, T. Kobayashi, N. Uchida, *Org. Lett.* **2015**, *17*, 2554.

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http://www.TCIchemicals.com/pdf/Q6001E.pdf

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Boronic Acid Esters
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Trifluoroborates
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Others

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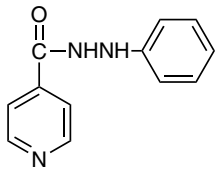
Fullerenes
Carbon Nanotubes
Graphene / Graphene Oxide
Nanodiamonds
Nanocarbon Unit Structures

Stearoyl-CoA Desaturase Inhibitor

I0975 PluriSIn 1 (1) **20mg 100mg**



1

Research progresses of iPSCs (induced pluripotent stem cells) and ESCs (embryonic stem cells) are expected that their differentiation into various cell type are applied to regenerative medicine.[1-3] However, their properties, self-renewing and differentiation, make these cells tumorigenic.[4-7] The tumor formation was found to positively correlate with the residual undifferentiated pluripotent cells.[6]

PluriSIn 1 (**1**) a stearoyl-CoA desaturase inhibitor, resulting in inhibition of oleate synthesis, and can eliminate human pluripotent stem cells (hPSCs) selectively.[8] Ben-David *et al*. have proposed mechanism that the inhibition selectively leads to endoplasmic reticulum (ER) stress, unfolded protein response, and translational attenuation in hPSCs, which finally result in apoptosis.[8]

This product is for research purpose only.

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