Organic & Biomolecular Chemistry

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/obc

Efficient Phosphine ligands for the One-Pot Palladium-Catalyzed Borylation/Suzuki–Miyaura Cross-coupling Reaction

You Chen,[a] Hui Peng,[b] Yun-Xiao Pi,[c] Tong Meng,[a] Ze-Yu Lian,[a] Meng-Qi Yan,[a] Yan Liu,[a] Sheng-Hua Liu,[a] Guang-Ao Yu*,[a]

[a] *Key Laboratory of Pesticide & Chemical Biology, Ministry of Education, College of Chemistry, Central China Normal University, Wuhan 430079, People's Republic of China.*

[b] *Department of Chemistry, State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, People's Republic of China.*

[c] *State Key Laboratory of Catalysis, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, 457 Zhongshan Road, Dalian 116023, People's Republic of China*

***** *Corresponding authors: E-mail address, yuguang@mail.ccnu.edu.cn.*

Abstract

We report the synthesis of 2-(anthracen-9-yl)-1H-inden-3-yl dicyclohexylphosphine and its use in palladium-catalyzed borylation/Suzuki–Miyaura cross-coupling reaction to prepare a variety of symmetrical and unsymmetrical biaryl compounds in excellent yield.

Introduction

The Suzuki–Miyaura cross-coupling of boronic acids with organic halides is one of the most widely applied methods in modern synthetic organic chemistry.[1] Since the first report of the palladium-catalyzed cross-coupling reaction between an aryl halide and an arylboronic acid by Suzuki and Miyaura in 1981,[2] it has emerged as a synthetic method that tolerates a wide range of functional groups providing reliable and efficient access to structurally diverse biaryl motifs.[3] It is for these reasons that it remains one of the most important methods of choice for C–C bond formation in both industrial and academic groups. Fueled by the commercial availability of numerous organic halides and boronic acids, and the constant development of improved catalyst

systems,[4] intense research efforts continue in this area.

With all of the advances, the Suzuki–Miyaura cross-coupling reaction still suffers a major limitation in that it relies upon the direct use of boronic acids. Although many boronic acids are commercially available, they can be very expensive and decompose upon storage over time, often resulting in the need to use at least 1.2 equiv (with regard to the organic halide) in a typical Suzuki–Miyaura cross-coupling reaction.[5] Additionally, if the boronic acid is not commercially available, its synthesis is required, adding additional, often lengthy, steps to the synthetic process.[6]

Over the last two decades, progress has been made to circumvent some of the limitations of the Suzuki–Miyaura cross-coupling reaction with the advent of the one-pot borylation/Suzuki–Miyaura cross-coupling reaction. The first system was reported by Miyaura in 1997,[6d] which involved converting an aryl triflate *in situ* into a boronate ester followed by the addition of a second aryl triflate along with the palladium catalyst and base. Since then, the development of one-pot, catalytic C–H or C–X borylation/Suzuki–Miyaura coupling processes have allowed the preparation of unsymmetrical biaryl compounds.[7,8] This protocol has been applied to the syntheses of pharmaceuticals.[9] However, a high catalyst loading (5–10 mol%) and the addition of a second portion of the palladium catalyst are necessary. In 2007, Buchwald reported that $Pd_2(dba)_3$ and XPhos actively combine to efficiently catalyze the one-pot borylation/Suzuki–Miyaura coupling reaction without the need to add a second portion of the catalyst prior to conducting the Suzuki–Miyaura coupling reaction.[10] In this process, an excess amount of the phosphine ligand (P/Pd, 4:1) was required. Recently, Buchwald demonstrated an efficient synthesis of biaryl compounds from aryl halides using a lithiation/borylation/Suzuki–Miyaura coupling sequence under continuous-flow conditions.[11] In addition, the groups of Molander,[12] Kwong,[13] Zhang,[14] Wu,[15] and others have reported their progress. Despite these advances, many limitations remain. These include: (1) High catalyst loading is employed or a second loading of catalyst is often required to facilitate the Suzuki–Miyaura coupling reaction in the second step, and (2) Heteroaryl halides, which are important for medicinal chemistry applications, react slowly with narrow scope and often require a higher

catalyst loading when compared with aryl halides.

We have developed a series of 2-aryl indenyl phosphine ligands and have demonstrated their high reactivity in the Suzuki–Miyaura coupling reaction, Buchwald–Hartwig amination reaction, dehydrogenation reactions and hydration reactions.[16] Herein we report the application of 2-aryl indenyl phosphine ligands **1** and **2**[16c] (Scheme 1) in the one-pot, palladium-catalyzed borylation/Suzuki–Miyaura cross-coupling reaction. Excellent reactivity has been achieved on a series of aryl halide and heteroaryl halide substrates.

Results and discussion

The synthesis of **1** was accomplished in three steps from indenyl boronic ester **3**, which could be prepared on a kilogram scale from 2-bromo-1*H*-indene. The palladium-catalyzed Suzuki–Miyaura coupling of **3** with 9-bromoanthracene provided **4** in 87% yield.[17] Then, straightforward deprotonation of **4** using *n*BuLi and trapping of the lithiated intermediate with dicyclohexyl phosphine chloride (Cy_2PCl) afforded the monophosphine ligand **1** in 68% yield (Scheme 2). Ligand **1** was found to be stable in air.

To test the effectiveness of this new ligand **1**, we initially investigated the one-pot reaction of 4-chlorotoluene with bis(pinacolato)diboron to establish the feasibility of our strategy and to optimize the reaction conditions (Table 1). First, the reaction was conducted without any base and/or phosphine ligand and no product was obtained (Table 1, entries 1–3). Then 2.0 mol% $Pd(dba)_2$, 4.0 mol% phosphine ligand **1** and 3.0 equivalent KOAc were used and a 12% yield of the symmetrical biaryl product was observed (Table 1, entry 4). The use of base was found to be crucial for a high yield. Strong bases such as Cs_2CO_3, $CsOH{\cdot}H_2O$ and *t*BuONa provided moderate yields (Table 1, entries 5–7), while the weak base, $K_3PO_4{\cdot}3H_2O$ proved to be the most efficient and gave an 81% yield (GC yield is 91%) (Table 1, entry 8). A scanning of commercially available palladium precursors revealed that $Pd(dba)_2$ was the best choice (Table 1, entries 8–10). In addition to ligand **1**, the use of ligand **2** was examined for comparison with moderate conversions being observed in this reaction

(Table 1, entry 11).

Under the optimized reaction conditions (Table 1, entry 8), a wide range of aryl chlorides reacted smoothly to provide symmetrical biaryl products (Table 2). For example, 3-chlorotoluene was directly converted to the symmetrical biaryl product in high yield (Table 2, entry 1). Borylation/Suzuki–Miyaura cross-coupling reactions of substrates bearing electron-donating substituents such as $–OCH_3$ and –OH went smoothly, providing high yields of the expected products (Table 2, entries 2–3). The reaction of the relatively hindered 2-chlorotoluene gave the desired product in moderate yield (Table 2, entry 4). Aryl chlorides bearing electron-withdrawing groups such as –F, $–CF_3$, $–NO_2$ and $–COCH_3$ at the *para* position also permit the borylation/Suzuki–Miyaura cross-coupling reaction, giving the required products in good yields (Table 2, entries 5–8). Moreover, the base-sensitive –CN group was tolerated using our catalytic system and the corresponding symmetrical biaryl product was obtained in a near-quantitative yield (Table 2, entry 9). In addition, 2-chloronaphthalene and 3-chloronaphthalene underwent the desired reaction, giving the symmetrical binaphthalenes in moderate yield (Table 2, entries 10–11). To further extend the scope of reaction using our catalytic system, we investigated the reaction of 3-chloropyridine; fortunately, the desired 3, 3'-bipyridine was obtained in 76% yield (Table 2, entry 12).

To further extend the scope of our catalytic system, we carried out reactions towards the direct synthesis of unsymmetrical biaryl compounds. In this endeavor, a catalytic system based upon $Pd(dba)_2$ and ligand **1** proved to be effective for the borylation as well as the subsequent Suzuki–Miyaura cross-coupling reaction. In this process, aryl bromides were subjected to the Pd-catalyzed borylation conditions with the addition of the second aryl chloride and $K_3PO_4 \cdot 3H_2O$. No workup was performed nor catalyst added prior to conducting the second reaction in the sequence (Table 3). For example, bromobenzene was subject to the Suzuki–Miyaura cross-coupling reaction after the borylation reaction; the resulting boronic ester could smoothly couple with 3-chloroanisole and give the desired product in 96% yield (Table 3, entry 1). Aryl bromides bearing electron-donating and electron-withdrawing groups such as

–OH, –F, and –NO_2 were also tolerated in the borylation and subsequent cross-coupling reaction with aryl chloride and afforded the corresponding products in high yields (Table 3, entries 2–4). It is worth noting that this protocol avoids the α-arylation reaction of ketones with aryl boronate esters, and no reduction of ketone as previously observed in the aryl halide borylation of ketones was observed when they were employed in the second step (Table 3, entry 5).[18] In addition, aryl bromide bearing the base-sensitive –CN group was tolerated in our catalytic system (Table 3, entries 6–10). Moreover, aryl chlorides with both electron-donating and electron-withdrawing groups could be employed in the second step while maintaining good to excellent yields of the unsymmetrical biaryl products (Table 3, entries 6–10).

Heterocyclic compounds are of particular interest to the pharmaceutical industry.[19] The application of heterocyclic compounds in cross-coupling reactions still remains a synthetic challenge,[20] because the ligating ability of the heteroatoms present can lead to catalyst deactivation. In addition, the electronic properties at certain positions in the heterocycle can be unfavorable for the elementary reactions required for these catalytic processes.[21] We next turned our attention to exploring the scope of heteroaryl halides. As few heteroaryls performed exceptionally well under the general borylation conditions, we focused on their use as coupling partners in the second step. As outlined in Table 4, heteroaryl chlorides all undergo efficient cross-coupling reactions. For example, 3-chloropyridine and 2-chloropyridine provided good to excellent yields (Table 4, entries 1–3). 2-chlorothiophene coupled smoothly and provided a moderate yield over two steps (Table 4, entry 4). 4-Chlorobenzonitrile was also tolerated in the borylation reaction and subsequent cross-coupling reaction with heteroaryl chlorides such as 2-chloropyridine, 3-chloropyridine, 2-chloropyrazine and 2-chloroquinoxaline, to afford the desired heteroaryl products in good yield (Table 4, entries 5–8). In addition, 3-chloropyridine was tolerated in the borylation reaction and subsequent reaction with 2- chloroquinoxaline to give the corresponding heteroaryl product in 51% yield (Table 4, entry 9).

To carry out an economical large-scale synthesis of fine chemicals, a low loading catalyst is needed. To further study the efficiency of our catalystic system, we then

studied the TON (turnover number) of our catalytic system at low loading. For example, carrying out the one-pot reaction of 3-chloropyridine with bis(pinacolato)diboron at a palladium loading of 0.2 mol% led to a yield of 27% after 20 h (Table 5, entry 1). This corresponds to a TON of 135.

Conclusion

In summary, a novel, efficient and air-stable anthracenyl substituted indenyl phosphine ligand **1** was synthesized in high yield and used to generate a very active and broadly useful Pd catalyst system for the borylation/Suzuki–Miyaura cross-coupling reaction. With the Pd/**1** catalyst system, a range of aryl chlorides bearing various functional groups can be converted into symmetrical biaryl compounds. A direct synthesis of unsymmetrical biaryls from aryl chlorides or aryl bromides using a one-pot, two-step procedure can also be successfully accomplished using this catalyst system without an excess amount of ligand and the addition of catalyst in the second step. Such methodology tolerated not only a number of functional groups, but also was applied successfully to a range of heteroaryl chlorides.

Acknowledgements

The authors would like to thank the National Natural Science Foundation of China (Nos. 21472060, 21072071 and 21272088) and the Program for Academic Leader in Wuhan Municipality (No. 201271130441) for financial support.

Notes and references

1 (*a*) F. Bellina, A. Carpita and R. Rossi, *Synthesis*, 2004, **15**, 2419; (*b*) S. Kotha, K. Lahiri and D. Kashinath, *Tetrahedron*, 2002, **58**, 9633.

2 N. Miyaura, T. Yanagi and A. Suzuki, *Synth. Commun.*, 1981, **11**, 513.

3 A. Suzuki, *Acc. Chem. Res.*, 1982, **15**, 178.

4 (*a*) Q. Zhao, C. Li, C. H. Senanayake, and W. Tang, *Chem.–Eur. J.*, 2013, **19**, 2261; (*b*) W. Tang, A. G. Capacci, X. Wei, W. Li, A. White, N. D. Parel, J. Savoie, J. J. Gao, S. Rodriguez, B. Qu, N. Haddad, B. Z. Lu, D. Krishnamurthy, N. K. Yee and

C. H. Senanayake, *Angew. Chem.*, *Int. Ed.*, 2010, **49**, 5879; (*c*) M. R. Biscoe, B. P. Fors and S. L. Buchwald, *J. Am. Chem. Soc.*, 2008, **130**, 6686; (*d*) T. Kinzel, Y. Zhang and S. L. Buchwald, *J. Am. Chem. Soc.*, 2010, **132**, 14073.

5 (*a*) D. M. Knapp, E. P. Gillis and M. D. Burke, *J. Am. Chem. Soc.*, 2009, **131**, 6961; (*b*) G. A. Molander and B. Canturk, *Angew. Chem.*, *Int. Ed.*, 2009, **48**, 9240.

6 (*a*) W. Tang, S. Keshipeddy, Y. Zhang, X. Wei, J. Savoie, N. D. Patel, N. K. Yee and C. H. Senanayake, *Org. Lett.*, 2011, **13**, 1366; (*b*) H.-B. Deng, J.-K. Jung, T. Liu, K. W. Kuntz, M. L. Snapper and A. H. Hoveyda, *J. Am. Chem. Soc.*, 2003, **125**, 9032; (*c*) T. Ishiyama, H. Isou, T. Kikuchi and N. Miyaura, *Chem. Commun.*, 2010, 159; (*d*) T. Ishiyama, Y. Itoh, T. Kitano and N. Miyaura, *Tetrahedron Lett.*, 1997, **38**, 3447; (*e*) T. Ishiyama, M. Murata and N. Miyaura, *J. Org. Chem.*, 1995, **60**, 7508; (*f*) M. E. Jung and T. I. Lazarova, *J. Org. Chem.*, 1999, **64**, 2976; (*g*) T. Leermann, F. R. Leroux and F. Colobert, *Org. Lett.*, 2011, **13**, 4479; (*h*) I. A. I. Mkhalid, J. H. Barnard, T. B. Marder, J. M. Murphy and J. F. Hartwig, *Chem. Rev.*, 2010, **110**, 890; (*i*) T. E. Pennington, C. Kardiman and C. A. Hutton, *Tetrahedron Lett.*, 2004, **45**, 6657; (*j*) W. Yang, H. He and D. G. Drueckhammer, *Angew. Chem.*, *Int. Ed.*, 2001, **40**, 1714; (*k*) H. C. Brown and T. E. Cole, *Organometallics*, 1983, **2**, 1316.

7 (*a*) A. Kondoh and T. F. Jamison, *Chem. Commun.*, 2010, **46**, 907; (*b*) T. E. Hurst, T. K. Macklin, M. Becker, E. Hartmann, W. Kügel, J.–C. P.–L. Salle, A. S. Batsanov, T. B. Marder and V. Snieckus, *Chem.–Eur. J.*, 2010, **16**, 8155; (*c*) M. Klečka, R. Pohl, B. Klepetářová and M. Hocek, *Org. Biomol. Chem.*, 2009, **7**, 866; (*d*) P. Harrisson, J. Morris, T. B. Marder and P. G. Steel, *Org. Lett.*, 2009, **11**, 3586; (*e*) P. Harrisson, J. Morris, P. G. Steel and T. B. Marder, *Synlett.*, 2009, 147; (*f*) V. J. Olsson and K. J. Szabó, *Org. Lett.*, 2008, **10**, 3129; (*g*) A. D. Finke and J. S. Moore, *Org. Lett.*, 2008, **10**, 4851.

8 (*a*) N. PraveenGanesh and P. Y. Chavant, *Eur. J. Org. Chem.*, 2008, **27**, 4690; (*b*) L. Zhu, M. Patel and M.-B. Zhang, *Tetrahedron Lett.*, 2008, **49**, 2734; (*c*) O. Baudoin, M. Cesario, D. Guénard and F. Guéritte, *J. Org. Chem.*, 2002, **67**, 1199; (*d*) O. Baudoin, D. Guénard and F. Guéritte, *J. Org. Chem.*, 2000, **65**, 9268; (*e*) T.

Martin, C. Laguerre, C. Hoarau and F. Marsais, *Org. Lett.*, 2009, **11**, 3690; (*f*) H. A. Duong, S. Chua, P. B. Huleatt and C. L. L. Chai, *J. Org. Chem.*, 2008, **73**, 9177; (*g*) E. F. DiMauro and J. R. Vitullo, *J. Org. Chem.*, 2006, **71**, 3959; (*h*) P.-E. Broutin, I. Čerňa, M. Campaniello, F. Leroux and F. Colobert, *Org. Lett.*, 2004, **6**, 4419; (*i*) I. C. F. R. Ferreira, M.-J. R. P. Queiroz and G. Kirsch, *Tetrahedron Lett.*, 2003, **44**, 4327; (*j*) A. S. Abreu, N. O. Silva, P. M.T. Ferreira and M.–J. R.P. Queiroz, *Tetrahedron Lett.*, 2003, **44**, 6007; (*k*) L. Zhu, J. Duquette and M.-B. Zhang, *J. Org. Chem.*, 2003, **68**, 3729; (*l*) M. Miura, T. Koike, T. Ishihara, F. Hirayama, S. Sakamoto, M. Okada, M. Ohta and S. Tsukamoto, *Synth. Commun.*, 2006, **36**, 3809; (*m*) M. Penhoat, V. Levacher and G. Dupas, *J. Org. Chem.*, 2003, **68**, 9517.

9 (*a*) G. Uray, A. –M. Kelterer, J. Hashim, T. N. Glasnov, C. O. Kappe and W. M.F. Fabian, *J. Mol. Struct.*, 2009, **929**, 85; (*b*) E. F. DiMauro and J. R. Vitullo, *J. Org. Chem.*, 2006, **71**, 3959; (*c*) A. S. Abreu, P. M. T. Ferreira, M.-J. R. P. Queiroz, I. C. F. R. Ferreira, R. C. Calhelha and L. M. Estevinho, *Eur. J. Org. Chem.*, 2005, **14**, 2951; (*d*) M. Melucci, G. Barbarella, M. Zambianchi, P. D. Pietro and A. Bongini, *J. Org. Chem.*, 2004, **69**, 4821; (*e*) O. Skaff , K. A. Jolliffe and C. A. Hutton, *J. Org. Chem.*, 2005, **70**, 7353; (*f*) G. W. Kabalka and M.-L. Yao, *Tetrahedron Lett.*, 2003, **44**, 7885.

10 K. L. Billingsley, T. E. Barder and S. L. Buchwald, *Angew. Chem.*, *Int. Ed.*, 2007, **46**, 5359.

11 W. Shu, L. Pellegatti, M. A. Oberli and S. L. Buchwald, *Angew. Chem.*, *Int. Ed.*, 2011, **45**, 10665.

12 G. A. Molander, S. L. J. Trice and S. M. Kennedy, *J. Org. Chem.*, 2012, **77**, 8678.

13 W. K. Chow, O. Y. Yuen, C. M. So, W. T. Wong and F. Y. Kwong, *J. Org. Chem.*, 2012, **77**, 3543.

14 Y.-D. Zhang, J. Gao, W.- J. Li, H. Lee, B. Z. Lu and C. H. Senanayake, *J. Org. Chem.*, 2011, **76**, 6394.

15 L.- H. Wang, X.-L. Cui, J.-Y. Li, Y.-S. Wu, Z.-W. Zhu and Y.-J. Wu, *Eur. J. Org. Chem.*, 2012, **3**, 595.

16 (a) S.-L. Mao, Y. Sun, G.-A. Yu, C. Zhao, Z.-J. Han, J. Yuan, X. Zhu, Q. Yang and S.-H. Liu, *Org. Biomol. Chem.*, 2012, **10**, 9410. (b) J. Yuan, Y. Sun, G.-A. Yu, C. Zhao, N.-F. She, S.-L. Mao, P.-S. Huang, Z.-J. Han, J. Yin and S.-H. Liu, *Dalton Trans.*, 2012, **41**, 10309; (c) X. Hao, J. Yuan, G.-A. Yu, M.-Q. Qiu, N.-F. She, Y. Sun, C. Zhao, S.-L. Mao, J. Yin and S.-H. Liu, *J. Organomet. Chem.*, 2012, **706-707**, 99; (d) L. Chen, G.-A. Yu, F. Li, X. Zhu, B. Zhang, R. Guo, X. Li, Q. Yang, S. Jin, C. Liu, S.-H. Liu, *J. Organomet. Chem.*, 2010, **695**, 1768; (e) Z. Han, S. Mao, H. Peng, X. Pi, Y. Chen, S. Liu and G. Yu, *Chin. J. Org. Chem.*, 2014, **34**, 893.

17 (a) K. Nikitin, H. Müller-Bunz, Y. Ortin and M. J. McGlinchey, *Org. Biomol. Chem.*, 2007, **5**, 1952. (b) D.-W. Lee and J. Yun, *Bull. Korean Chem. Soc.*, 2004, **25**, 29.

18 (a) K. L. Billingsley, T. E. Barder and S. L. Buchwald, *Angew. Chem., Int. Ed.*, 2007, **46**, 5359. (b) G. A. Molander, S. L. J. Trice and S. D. Dreher, *J. Am. Chem. Soc.*, 2010, **132**, 17701; (c) G. A. Molander, S. L. J. Trice, S. M. Kennedy, S. D. Dreher and M. T. Tudge, *J. Am. Chem. Soc.*, 2012, **134**, 11667.

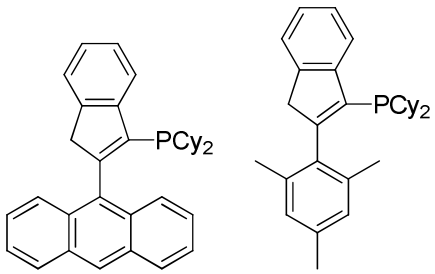
19 (*a*) D. Zhao, J. You and C. Hu, *Chem.-Eur. J.*, 2011, **17**, 5466; (*b*) V. F. Slagt, A. H. M. de Vries, J. G. de Vries and R. M. Kellogg, *Org. Process Res. Dev.*, 2010, **14**, 30; (*c*) R. A. Hughes and C. J. Moody, *Angew. Chem., Int. Ed.*, 2007, **46**, 7930.

20 (*a*) K. L. Billingsley and S. L. Buchwald, *Angew. Chem., Int. Ed.*, 2008, **47**, 4695; (*b*) R. Ghosh, N. N. Adarsh and A. Sarkar, *J. Org. Chem.*, 2010, **75**, 5320; (*c*) K. Billingsley and S. L. Buchwald, *J. Am. Chem. Soc.*, 2007, **129**, 3358; (*d*) A. Thakur, K. Zhang and J. Louie, *Chem. Commun.*, 2012, **48**, 203; (*e*) K. L. Billingsley, K. W. Anderson and S. L. Buchwald, *Angew. Chem., Int. Ed.*, 2006, **45**, 3484; (*f*) T. Noël and A. J. Musacchio, *Org. Lett.*, 2011, **13**, 5180; (*g*) N. Kudo, M. Perseghini and G. C. Fu, *Angew. Chem., Int. Ed.*, 2006, **45**, 1282.

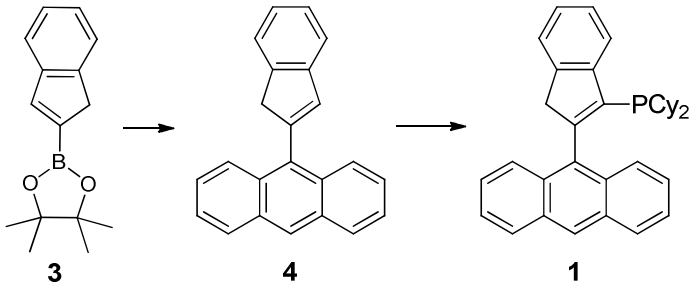
21 (*a*) M. Su, N. Hoshiya and S. L. Buchwald, *Org. Lett.*, 2014, **16**, 832; (*b*) M. A. Düfert, K. L. Billingsley and S. L. Buchwald, *J. Am. Chem. Soc.*, 2013, **135**, 12877; (*c*) I. P. Beletskaya and A. V. Cheprakov, *Organometallics,* 2012, **31**,

7753; (*d*) S. G. Newman and M. Lautens, *J. Am. Chem. Soc.*, 2010, **132**, 11416; (*e*) Q. Shen, S. Shekhar, J. P. Stambuli and J. F. Hartwig, *Angew. Chem., Int. Ed.*, 2005, **44**, 1371; (*f*) Q. Shen and J. F. Hartwig, *J. Am. Chem. Soc.*, 2007, **129**, 7734; (*g*) G. B. Smith, G. C. Dezeny, D. L. Hughes, A. O. King and T. R. Verhoeven, *J. Org. Chem.*, 1994, **59**, 8151.

Figure Legends

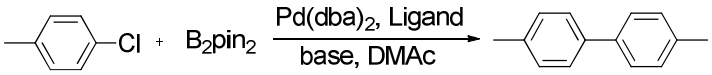


Scheme 1 Ligands used in this study.



Scheme 2 Synthesis of ligand **1**.

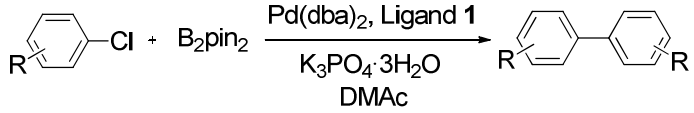
Table 1 Optimization of the reaction conditions[a]

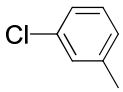
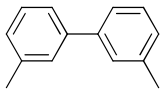
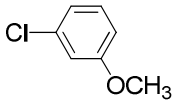
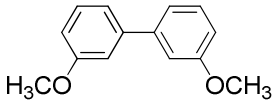
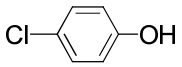
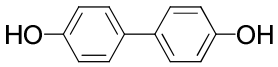
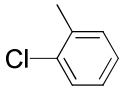
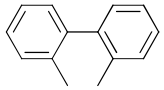
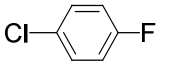
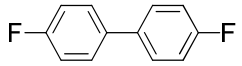
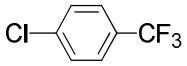
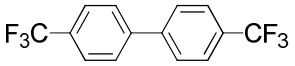
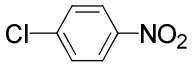
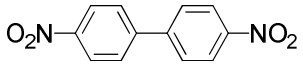
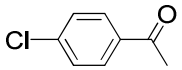
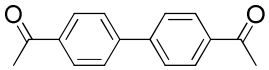
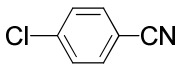
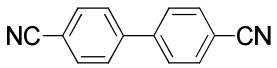
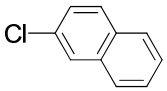
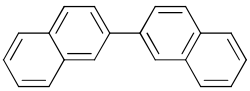
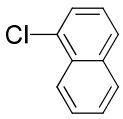
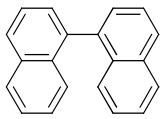
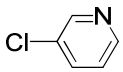
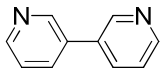


entry	Pd precursor	ligand	base	yield[b] (%)
1	$Pd(dba)_2$	–	–	0
2	$Pd(dba)_2$	**1**	–	0
3	$Pd(dba)_2$	–	KOAc	0
4	$Pd(dba)_2$	**1**	KOAc	12
5	$Pd(dba)_2$	**1**	Cs_2CO_3	40
6	$Pd(dba)_2$	**1**	$CsOH·H_2O$	44
7	$Pd(dba)_2$	**1**	*t*BuONa	36
8	$Pd(dba)_2$	**1**	$K_3PO_4·3H_2O$	81 (91)[c]
9	$Pd(OAc)_2$	**1**	$K_3PO_4·3H_2O$	47
10	$PdCl_2$	**1**	$K_3PO_4·3H_2O$	44
11	$Pd(dba)_2$	**2**	$K_3PO_4·3H_2O$	58

[a]Reaction conditions: 2.4 mmol 4-chlorotoluene, 1.0 mmol bis(pinacolato)diboron, 0.02 mmol Pd source, 0.04 mmol ligand, 3.0 mmol base, 2.0 mL DMAc, 100 ºC, 20 h. [b]Isolated yield. [c] GC yield.

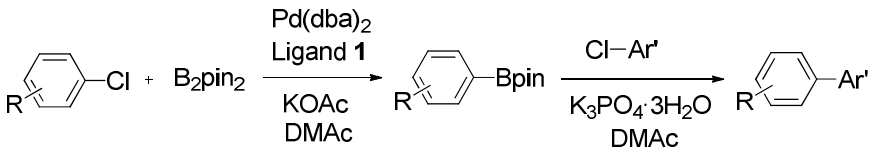
Table 2 Palladium-catalyzed one-pot preparation of symmetrical biaryl compounds[a]

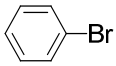
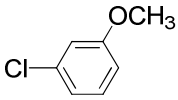
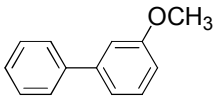
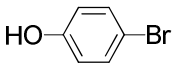
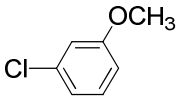
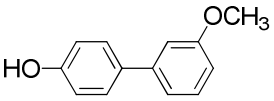
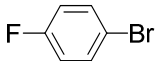
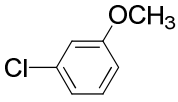
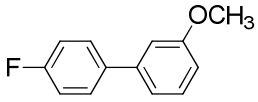
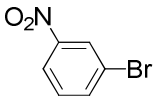
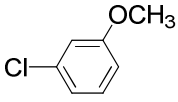
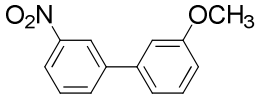
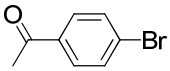
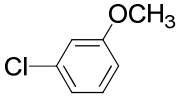
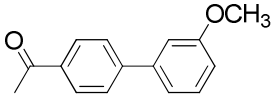
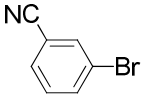
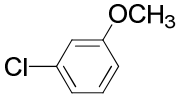
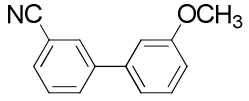
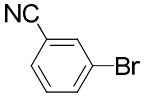
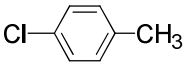
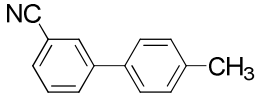
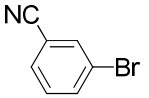
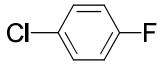
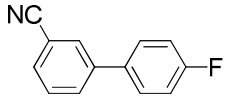
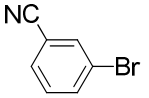
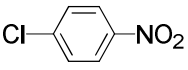
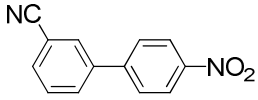
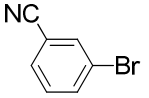
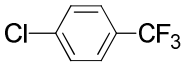
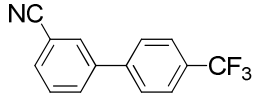


Entry	Substrate	Product	yield[b] (%)
1			90
2			95
3			90
4			72
5			82
6			84
7			88
8			81
9			97
10			70
11			72
12			76

[a]Reaction conditions: 2.4 mmol aryl chlorides or heteroaryl chloride， 1.0 mmol bis(pinacolato)diboron， 2.0 mmol % $Pd(dba)_2$，4.0 mmol % ligand **1**，3.0 mmol $K_3PO_4·3H_2O$，2.0 mL DMAc, 100 ºC, 20 h. [b]Isolated yield.

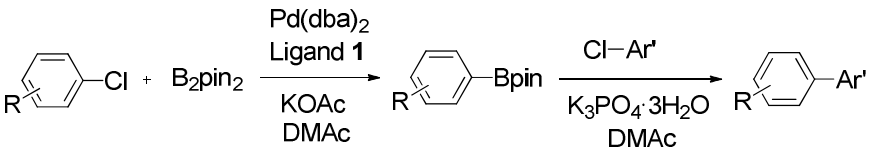
Table 3 Palladium-catalyzed one-pot two-step preparation of unsymmetrical biaryl compounds[a]

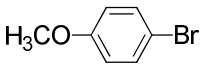
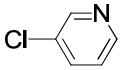
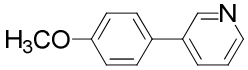
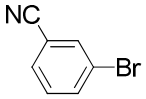
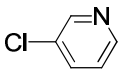
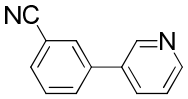
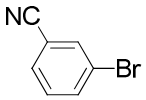
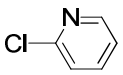
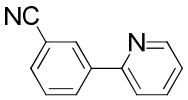
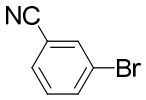
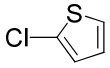
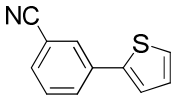
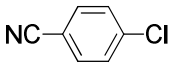
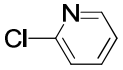
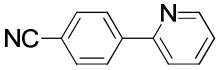
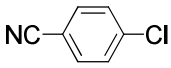
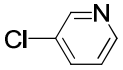
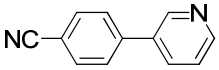
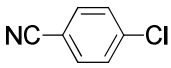
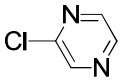
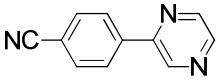
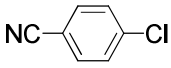
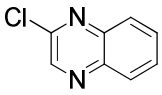
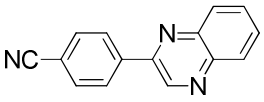
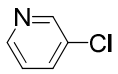
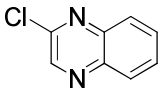
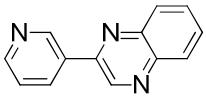


Entry	Ar-X	Ar'Cl	Product	Yield[b] (%)
1				96
2				88
3				82
4				81
5				93
6				95
7				88
8				82
9				88
10				89

[a]Reaction conditions: 1.2 mmol the first aryl bromides, 1.0 mmol the second aryl chlorides, 1.2 mmol bis(pinacolato)diboron, 2.0 mmol % $Pd(dba)_2$, 4.0 mmol % ligand **1**, 3.0 mmol KOAc, 3.0 mmol $K_3PO_4 \cdot 3H_2O$, 2.0 mL DMAc, 100 ºC. [b]Isolated yield.

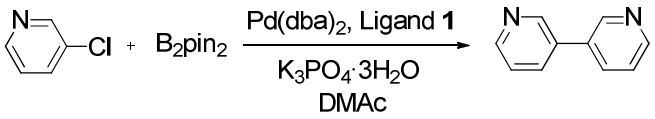
Table 4 Use of heteroaryl chlorides as electrophile in the palladium-catalyzed one-pot two-step preparation of unsymmetrical biaryl compounds[a]



Entry	Ar-X	Ar'Cl	Product	Yield[b] (%)
1				87
2				92
3				94
4				65
5				81
6				89
7				88
8				91
9				51

[a]Reaction conditions: 1.2 mmol of aryl halides, 1.0 mmol of heteroaryl chlorides, 1.2 mmol of bis(pinacolato)diboron, 2 mmol% $Pd(dba)_2$, 4 mmol% $\mathbf{L_1}$, 3.0 mmol KOAc, 3.0 mmol of $K_3PO_4 \cdot 3H_2O$, 2.0 mL DMAC, 100 ºC. [b]Isolated yield.

Table 5 Palladium-catalyzed one-pot preparation of symmetrical heteroaryl compound using ultra-low loading of catalyst [a]



Entry	Mol% Pd	Yield (%)[b]	TON
1	0.2	27	135
2	0.02	<5	–

[a]Reaction conditions: 2.4 mmol 3-chloropyridine，1.0 mmol bis(pinacolato)diboron，$Pd(dba)_2$/ligand **1** = 1: 2, 3.0 mmol $K_3PO_4·3H_2O$，2.0 mL DMAc, 100 ºC, 20 h. [b]Isolated yield.