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Tetrahedron

Tetrahedron 63 (2007) 6879–6886

Efficient palladium-catalyzed Suzuki–Miyaura coupling of aryl chlorides with arylboronic acids using benzoferrocenyl phosphines as supporting ligands

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Received 3 April 2007; accepted 17 April 2007
Available online 25 April 2007

Abstract—Four monodentate benzoferrocenyl phosphines were studied as supporting ligands in palladium-catalyzed Suzuki–Miyaura coupling of aryl chlorides with arylboronic acids. Of these ligands, the more electron-rich and steric demanding benzoferrocenyl dicyclohexyl phosphine was found highly effective for the reaction followed by the benzoferrocenyl diisopropyl phosphine. The corresponding diethyl and diphenyl phosphines are much less active. When the dicyclohexyl phosphine was used, both electron-rich and electron-poor aryl chlorides were coupled with arylboronic acids within 1 h giving good to excellent yields. Chloro-substituted pyridines were also found highly reactive under these conditions giving excellent yields of biaryl products. Sterically hindered biaryls can also be prepared using the dicyclohexyl phosphine as ligand.

1. Introduction

Many bioactive natural products such as the vancomycin antibiotics contain biaryl units, which increase the rigidity of the molecule and are beneficial to or indispensable for biological function.[1] As a result, the development of methodologies that are useful for constructing biaryl function has received much attention in organic chemistry. Compared with other methods for the synthesis of biaryls such as Stille,[2] Kumada,[3] and Negishi[2a,3,4] coupling reactions, Suzuki–Miyaura coupling of aryl halides with arylboronic acids has several practical advantages. The nucleophilic reaction partner boronic acids are usually non-toxic, inert to air and moisture, and are thermally stable; the side products arising from them can be easily removed from the reaction mixture; and the weak nucleophilic nature of boronic acids makes the reaction compatible with certain functional groups such as nitriles, ketones, and aldehydes. As to the electrophilic reaction partner aryl halides, aryl chlorides are most attractive because they are more available and less expensive than aryl bromides and iodides.[2a,3,4] However, until late 1990s, unactivated aryl chlorides are not feasible substrates for Suzuki–Miyaura coupling reactions because of their reluctance toward oxidative addition, which is the first step of the oxidative addition, transmetallation, and reductive elimination process. In order to extend the scope of this reaction to aryl chlorides, Fu and co-workers used tri-*tert*-butylphosphine as supporting ligand for palladium-catalyzed Suzuki–Miyaura coupling. Because of the bulkiness of the ligand, the less reactive species $[Pd(PtBu_3)_2]$ can be transformed into the more reactive $[Pd(PtBu_3)]$ during the reaction. Together with the highly electron-rich nature of the ligand, this mono-coordinated palladium(0) can activate electron-deficient aryl chlorides at room temperature and electron-rich ones at elevated temperature allowing Suzuki–Miyaura coupling of both electron-rich and -poor aryl chlorides.[5] Independently, Buchwald and co-workers designed and synthesized a series of air-stable biaryl-based electronically rich and sterically bulky ligands; using these ligands, both electron-rich and -poor aryl chlorides were activated for the coupling reaction at room temperature.[6]

Later, some other bulky electron-rich phosphine ligands were designed and synthesized for the Suzuki–Miyaura coupling of aryl chlorides.[7] Among them, those based on the ferrocene attracted significant attention (see Fig. 1 for examples). Ferrocene is electron-rich as indicated by its ability to stabilize adjacent carbocation[8] and is sterically bulky especially when additional substituent groups are attached to one or both of its Cp rings; as a result, ferrocene is an excellent starting point for making electron-rich and sterically hindered ligands for Suzuki–Miyaura coupling of aryl chlorides. For example, Fu and co-workers found that **1** is an active ligand for this reaction even though **1** is a triarylphosphine, which is less electron-rich than trialkylphosphines; the ligand is active with both electron-rich and -poor aryl chlorides including those with di-*ortho*

Keywords: Benzoferrocenyl phosphine ligand; Suzuki coupling; Aryl chloride; Chloropyridine.

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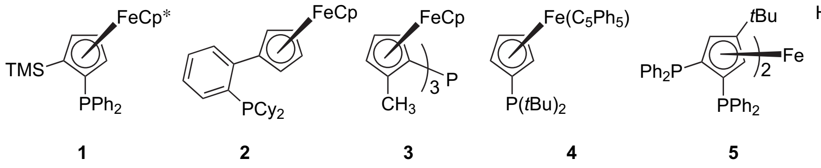
doi:10.1016/j.tet.2007.04.057



$Cp^* = C_5(CH_3)_5$, $Cp = C_5H_5$, $Cy = C_6H_{11}$

Figure 1. Examples of ferrocenyl phosphine ligands for Suzuki–Miyaura coupling.

substituted ones.[9] Richards and co-workers synthesized **2** and the C_3-symmetric **3**;[10] using **2** as ligand, coupling of certain aryl chlorides with phenylboronic acid proceeded at 60 °C;[10a] when **3** was used, under optimized conditions, coupling of electron-poor aryl chloride gave excellent yield, but in the case of electron-rich ones, yields less than 60% were obtained.[10b] Hartwig's group used **4** in Suzuki–Miyaura coupling and other reactions, in the most challenging case the authors reported in the paper that a di-*ortho* substituted biaryl can be prepared from electron-rich aryl chloride in 80% at 100 °C.[11] Hierso's group reported using the tetraphosphine **5** as ligands in coupling reactions involving aryl chlorides; when electron-poor substrates were used, excellent yields could be obtained, but with electron-rich substrates, yields were moderate; **5** is not considered electron-rich by the authors and forms bis-coordinated complex with palladium, the authors attributed its activity in activating aryl chlorides to the stability of its palladium complex.[12] Recently, Johannsen's and Xiao's research groups reported **6** and other similar ligands for coupling of aryl chlorides, both electron-rich and -poor aryl chlorides were coupled with high to excellent yields in 8–24 h;[13] in the most challenging case, a tri-*ortho* substituted biaryl was synthesized in 88% yield at 100 °C within 24 h;[13a] in addition, enantiopure **6** was applied for asymmetric synthesis of 2,2′-dimethyl binaphthalene from aryl bromide and arylboronic acid, the best *ee* obtained was 54%.[13b]

Recently, we reported the synthesis and characterization of four novel benzoferrocenyl phosphine ligands **7a–d** (Fig. 2) and demonstrated that these ligands could be easily prepared and are chemically and configurationally stable in air and in solution.[14] In the X-ray crystal structure of **7a**, we noticed that the lone pair on the phosphorus atom points to the *endo* face of the benzoferrocene. We reasoned that coordination of these ligands with palladium would favor mono-coordinated unsaturated organometallic species; because benzoferrocene, like ferrocene, is electron-rich, these ligands might represent a new class of bulky electron-rich ligands that are useful in Suzuki–Miyaura coupling of aryl chlorides with arylboronic acids. Furthermore, the phosphorus atom is not attached to the bulky ferrocene moiety directly; this might provide mono-coordinated yet less hindered palladium complexes that are suitable for coupling reactions. In this paper, we report our results on this investigation.

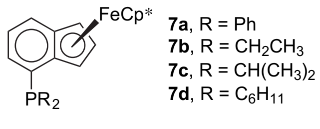


Figure 2. Benzoferrocenyl phosphine ligands.

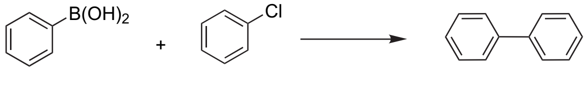
2. Results and discussion

2.1. Optimization of reaction conditions

Because several bases such as CsF, KF, Cs_2CO_3, K_2CO_3, and K_3PO_4 were shown to be suitable for Suzuki–Miyaura coupling of aryl chlorides,[5,6b,6c,7b,9,11] we first planned to identify the best one for the reaction using our ligands. Among the four benzoferrocenyl phosphine ligands (**7a–d**), **7d** is most electron-rich and most sterically hindered; we reasoned that it should offer the best results for activation of aryl chlorides, which was indeed the case as shown later. As a result, **7d** was chosen for the base-screening. When the electron-neutral chlorobenzene and phenylboronic acid were used as substrates, 1,4-dioxane as solvent, and $Pd_2(dba)_3$ as the palladium source, both Cs_2CO_3 and K_3PO_4 gave excellent results. At 100 °C, quantitative conversions were achieved within 1 h as shown by GC even when 1 to 1 molar ratio of the two substrates was used and the isolated yield of the biphenyl in both cases was 88% (Table 1, entries 1 and 2). CsF was found equally effective (entry 3). However, when K_2CO_3 and KF were used for the reaction, under these conditions much less yields were obtained (entries 4 and 5).

Next, the effects of the solvent and temperature on the reaction were studied. As shown in Table 2, under similar conditions described above, when 1,4-dioxane, DME, and toluene were used as solvent, good to excellent isolated yields of biaryl product were obtained; among them, 1,4-dioxane gave best results, within 1 h, 100% conversion was achieved (entry 1). In contrast, longer reaction time was needed to complete the reaction when DME or toluene was used as solvents (entries 2 and 3). The more polar solvents THF, DMM, and DMF were found unsuitable for the reaction (entries 4, 5, and 6). We also explored the possibility of room temperature Suzuki–Miyaura coupling of aryl chlorides, when the

Table 1. Identifying suitable base for Suzuki–Miyaura coupling of aryl chlorides[a]

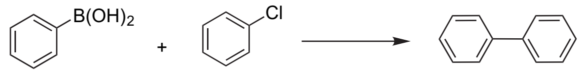


Entry	Base	Time (h)	Yield[b] (%)
1	Cs_2CO_3	1	88
2	K_3PO_4	1	88
3	CsF	1	87
4	K_2CO_3	21	68
5	KF	1	20

[a] Conditions: phenylboronic acid 1 equiv, chlorobenzene 1 equiv, $Pd_2(dba)_3$ 1.5 mol %, **7d** 3.6 mol %, base 2 equiv, 1,4-dioxane, reflux.

[b] Isolated yields.

Table 2. Effects of solvents and temperature on Suzuki–Miyaura coupling of aryl chlorides[a]



Entry	Solvent	Temperature	Time (h)	Yield[b] (%)
1	1,4-Dioxane	Reflux	1	88
2	DME[c]	Reflux	24	84
3	Toluene	Reflux	24	72
4	THF	Reflux	1	45
5	DMM[c]	Reflux	24	14
6	DMF	rt	8	<5
7	1,4-Dioxane	rt	24	<5
8	1,4-Dioxane	50 °C	23	70

[a] Conditions: phenylboronic acid 1 equiv, chlorobenzene 1 equiv, $Pd_2(dba)_3$ 1.5 mol %, **7d** 3.6 mol %, Cs_2CO_3 2 equiv, solvent.

[b] Isolated yields.

[c] DME, dimethoxyethane; DMM, dimethoxymethane.

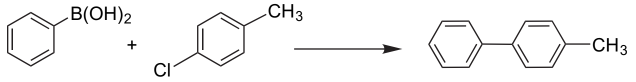
electron-neutral chlorobenzene was used as the substrate, there was virtually no conversion in 24 h (entry 7). At 50 °C, the reaction proceeded but at much slower rate; after 23 h, an isolated yield of only 70% was obtained (entry 8). We also tested to pre-form the ligand–palladium complex at elevated temperature in 1,4-dioxane and then perform the reaction at room temperature, the reaction did not proceed.

2.2. Comparison of the activity of the four benzoferrocenyl phosphine ligands

After the suitable conditions for the cross-coupling reaction were identified, we next set up to compare the activities of the four benzoferrocenyl ligands (**7a**–**d**). Phenylboronic acid and the electron-rich 4-chlorotoluene were chosen as substrates. Under the optimized conditions shown in Table 3, when **7a** was used as ligand, only 15% yield of the biaryl product was obtained (Table 3, entry 1). Ligand **7b** was also found not suitable for the reaction, even after 15 h, the yield of biaryl product was less than 5% (entry 2). However, under the same conditions, ligand **7c** gave very good results, within 1 h, the reaction was nearly completed and an isolated yield of 79% was obtained (entry 3). As expected, best results were obtained when **7d** was used as the ligand for the reaction; 100% conversion was realized within 1 h and the isolated yield of biaryl product was 92% (entry 4).

The above results are consistent with the theory that electron-rich bulky ligands favor oxidative addition of palladium(0) to aryl chlorides. In the case of **7a**, the phosphorus atom is less electron-rich than those in **7b**,**c** because phenyl groups are less electron-donating than alkyl groups; as a result, its palladium(0) complex is not nucleophilic enough to activate the aryl C–Cl bonds. Ligand **7b** is the least sterically hindered among the four but it is more electron-rich than **7a**; its complexes with palladium favor the bi-coordinated L_2Pd over the mono-coordinated LPd to the extent that the latter, which is believed to be responsible for activating aryl C–Cl bonds, does not have sufficient quantity to catalyze the reaction. Ligands **7c**,**d** are both electron-rich and sterically bulky, they form mono-coordinated highly nucleophilic complexes with palladium or can be transformed into such species under reaction conditions, and therefore are highly active for activation of aryl C–Cl bonds.

Table 3. Comparison of benzoferrocenyl ligands in Suzuki–Miyaura coupling of aryl chlorides[a]



Entry	Ligand	Time (h)	Yield[b] (%)
1	**7a**	1	15
2	**7b**	15	<5
3	**7c**	1	79
4	**7d**	1	92

[a] Conditions: phenylboronic acid 1 equiv, 4-chlorotoluene 1 equiv, $Pd_2(dba)_3$ 1.5 mol %, ligand 3.6 mol %, Cs_2CO_3 2 equiv, 1,4-dioxane, reflux.

[b] Isolated yields.

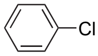
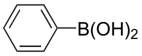
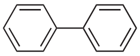
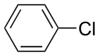
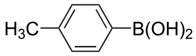
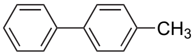
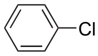
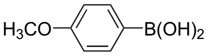
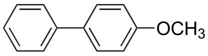
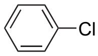
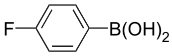
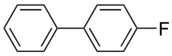
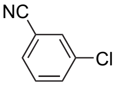
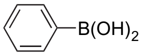
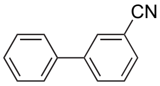
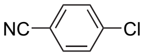
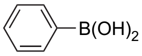
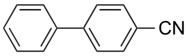
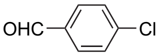
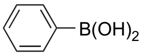
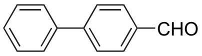
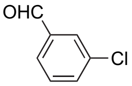
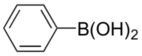
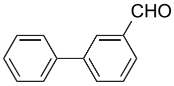
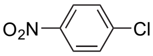
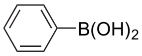
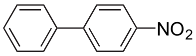
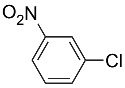
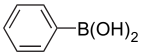
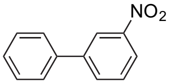
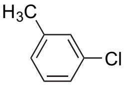
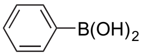
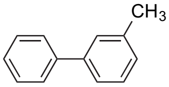
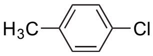
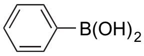
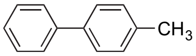
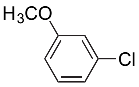
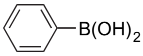
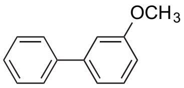
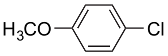
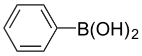
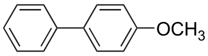
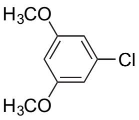
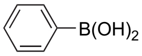
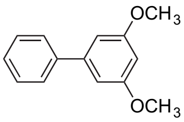
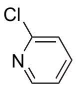
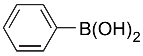
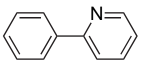
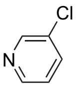
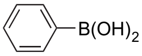
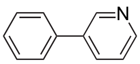
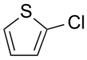
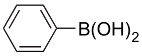
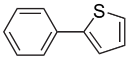
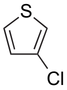
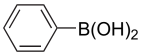
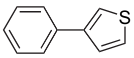
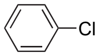
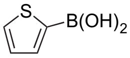
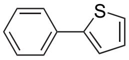
It is interesting to note that **7b** is the most active ligand in palladium-catalyzed allylic alkylation of 1,3-diphenyl-2-propen-1-yl acetate with dimethyl malonate while **7c**,**d** are least active for this reaction.[14] It is well known that the 14e L_2Pd can ionize allyl acetates in allylic alkylation reactions as indicated by many bidentate ligands in this application; thus it is reasonable that **7b** shows high activity in this reaction. The reduced activity of **7c**,**d** in allylic alkylation was attributed to the difficulty for the substrates to access palladium because of the bulkiness of the ligands. However, it is not easy to understand why an LPd of **7c**,**d** is more sterically hindered than an L_2Pd of **7b**. One possibility is that L_2Pd of **7d** predominates at room temperature, which was the temperature we used for allylic alkylation reaction; it can only dissociate to LPd complex with a reasonable rate at elevated temperature and so can catalyze Suzuki–Miyaura reaction of aryl chlorides. Another possibility is that the mono-coordinated 12e LPd complex is less active than the 14e L_2Pd in allylic alkylation reactions.

It was reported that the conjugated double bonds in benzoferrocene could participate in hydrogenation[15] and Diels–Alder[16] reactions under certain conditions due to the reduced aromaticity of the benzene ring of the indene moiety. Keeping this information in mind during our investigation, we were trying to observe if our ligands (**7a**–**d**) could participate in Heck reaction as an alkene. Under all reaction conditions we studied, no product arising from this reaction was detected. This may be attributed to the partial aromatic nature of the conjugated double bonds and the steric hindrance of the ligands.

2.3. Substrate scope studies

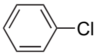
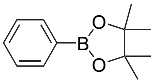
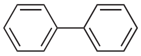
Under optimized conditions (see Table 4 and Section 4) using **7d** as the supporting ligand, a wide range of aryl chlorides can be coupled with various arylboronic acids. Table 4 shows substrates without any substituent in the *ortho* positions of the chlorides and boronic acids, this excludes steric effect on the reaction allowing electronic effects to be studied separately. For the nucleophilic partner of the reaction, both electron-neutral and -rich arylboronic acids coupled with phenyl chloride with high efficiency (entries 1–3); but when the electron-poor 4-fluorophenylboronic acid was used, lower yield was obtained (entry 4). As to the electrophilic reaction partner, electron-poor aryl chlorides gave best results; in all of the examples, quantitative isolated

Table 4. Suzuki–Miyaura coupling of unhindered substrates[a]

Entry	Aryl chloride	Boronic acid	Product	Yield[b] (%)	Reference
1				88	17
2				95	18
3				85	18
4				72	19
5				98	20
6				96	20
7				99	20
8				98	20
9				98	19
10				99	19
11				89	18
12				92	18
13				92	18
14				68	18
15				97[c]	21
16				89	22
17				98	22
18				23	23
19				40	24
20				20	23

(*continued*)

Table 4. (*continued*)

Entry	Aryl chloride	Boronic acid	Product	Yield[b] (%)	Reference
21				60	17

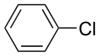
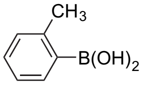
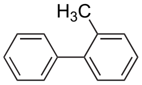
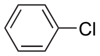
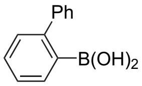
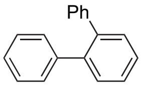
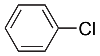
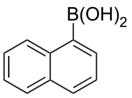
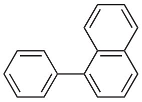
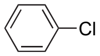
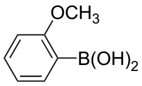
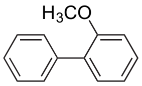
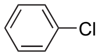
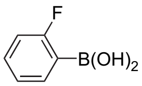
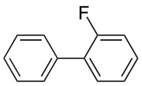
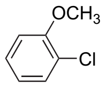
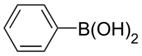
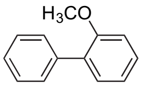
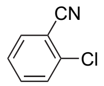
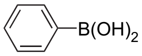
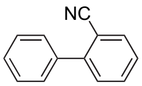
[a] Conditions: aryl chloride 1 equiv, arylboronic acid 1 equiv, $Pd_2(dba)_3$ 1.5 mol %, **7d** 3.6 mol %, Cs_2CO_3 2 equiv, 1,4-dioxane, reflux, 1 h.
[b] Isolated yield.
[c] Yield after 6 h; at 1 h, 86% conversion shown by GC.

yields were obtained within 1 h (entries 5–10). For electron-rich aryl chlorides, some of them gave excellent yields within 1 h (entries 11–13) but for some other substrates, longer reaction time was needed to achieve quantitative conversion (compare entry 14 with 15).

We next investigated the coupling of heteroaromatic chlorides with arylboronic acid under our reaction conditions using **7d** as ligand. As shown in Table 4, for both 2- and 3-chloropyridines coupled with phenylboronic acid with high efficiency, excellent isolated yields were obtained within 1 h (entries 16 and 17). However, coupling of chlorothiophenes with phenylboronic acid was much less effective (entries 18 and 19). The 2-thienylboronic acid and phenylboronic acid pinacol ester were also found to be less efficient coupling partners of this reaction under our conditions (entries 20 and 21).

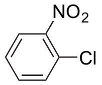
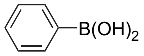
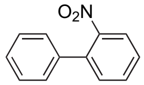
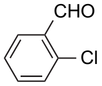
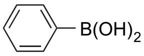
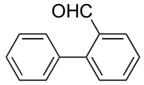
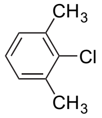
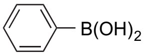
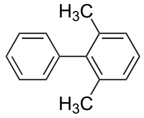
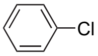
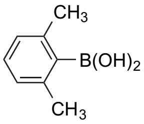
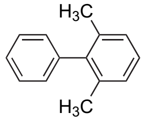
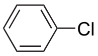
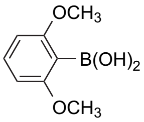
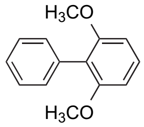
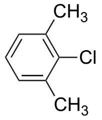
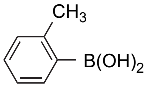
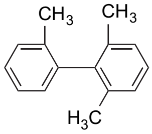
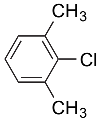
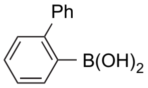
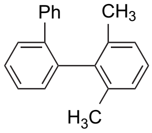
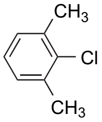
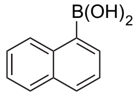
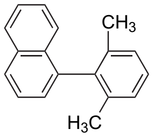
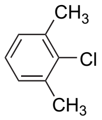
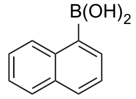
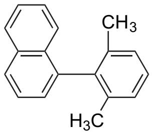
It is well known that Suzuki–Miyaura coupling reaction is sensitive to steric hindrance of substrates and synthesis of highly hindered biaryls using this method remains challenging.[6c] Table 5 shows our results on this study. Under optimized reaction conditions using **7d** as ligand, arylboronic acids with one *ortho* substituent all coupled with chlorobenzene with high efficiency, isolated yields ranging from 76% to 92% were obtained (Table 5, entries 1–5). With an *ortho* substituent on aryl chlorides, the reaction is even better and higher yields were obtained (entries 6–9); in these examples, electron-poor chlorides gave better results than electron-rich ones, which are consistent with our observation in studies on electronic effects. When the di-*ortho* substituted 2-chloro-1,3-dimethylbenzene was used, although the isolated yield was lower than those obtained with unhindered substrates, it was still high (78%, entry 10). However, when di-*ortho* substituted boronic acids were used, only traces of products could be isolated (entries 11 and 12). These observations indicate that oxidative addition may not be the rate-limiting step under our reaction conditions at least when hindered substrates are involved, even though the aryl chloride used here is electron-rich and is normally considered challenging for activation. Instead, the rate-controlling step is more likely to be transmetallation of boronic acid to palladium.

Table 5. Suzuki–Miyaura coupling of substrates with one or more *ortho* substituents[a]

Entry	Aryl chloride	Boronic acid	Product	Yield[b] (%)	Reference
1				80	18
2				83	25
3				92	26
4				82	18
5				76	27
6				84	18
7				94	28

(*continued*)

Table 5. (*continued*)

Entry	Aryl chloride	Boronic acid	Product	Yield[b] (%)	Reference
8				99	19
9				99	28
10				78	22
11				<5	22
12				<5	29
13				57	29
14				33	—
15				61	29
16				72[c]	29

[a] Conditions: aryl chloride 1 equiv, arylboronic acid 1 equiv, $Pd_2(dba)_3$ 1.5 mol %, **7d** 3.6 mol %, Cs_2CO_3 2 equiv, 1,4-dioxane, reflux, 1 h.

[b] Isolated yield.

[c] Catalyst loading was reduced to $Pd_2(dba)_3$ 0.75 mol %, **7d** 1.8 mol %.

Because the oxidative addition is less sensitive to steric hindrance than transmetallation under our reaction conditions, we next tested to synthesize the more challenging tri-*ortho* substituted biaryls from di-*ortho* substituted aryl chlorides (as opposed to from di-*ortho* substituted arylboronic acids). As shown in Table 5, the isolated yield ranged from moderate to good within 1 h (entries 13–15); extending the reaction time to 24 h did not increase the yields significantly. It is remarkable that under these conditions, the highly hindered 2,6-dimethyl-2-phenyl-1,1′-biphenyl (entry 14), an unknown compound, could be synthesized although in moderate yield. We also challenged our reaction conditions by lowering catalyst loading and using sterically hindered substrates, the yield was not affected (entry 16). These results are superior to those obtained with known ferrocene-based catalysts discussed in Section 1.[9–13] For example, ligands **1**–**5** were not used to synthesize tri-*ortho* substituted biaryls;[9–12] **6** was used for such a purpose, but long reaction time (24 h) and high temperature (100 °C) were needed, and only two examples were given;[13] and when **3** and **5** were applied for coupling electron-rich aryl chlorides, much lower yields (less than 60%) were obtained.[10b,12] However, some non-ferrocene-based ligands gave better results than ligand **7d** on certain substrates.[6]

Further challenges for Suzuki–Miyaura coupling that could be overcome by our catalyst include the reaction of di-*ortho* substituted aryl chlorides with di-*ortho* substituted arylboronic acids to synthesize tetra-*ortho* substituted biaryls and stereoselective coupling of aryl chlorides with alkenylboronic acids to synthesize *cis*- and *trans*-vinylarenes. Because under current reaction conditions, our catalytic system is sensitive to the steric hindrance imposed by di-*ortho* substituted boronic acids (see Table 5, entries 11 and 12), the synthesis of tetra-*ortho* substituted biaryls was not pursued. For stereoselective coupling of aryl chlorides with alkenylboronic acids, currently, there is no general efficient protocol in literature;[30] under reported conditions, alkene isomerization is unavoidable and mixtures of *cis*- and *trans*-vinylarenes are obtained.[6c,31] Our preliminary studies on coupling of aryl chlorides with *cis*- and *trans*-alkenylboronic acids have shown that this challenge can be overcome using the current catalytic protocol; a systematic study is under way and results will be reported separately.

3. Conclusion

In conclusion, we have shown that the benzoferrocenyl phosphine ligand **7d** is highly active for Suzuki–Miyaura coupling of aryl chlorides with arylboronic acids. Under optimized conditions, a wide range of aryl chlorides including the challenging electron-rich and sterically hindered ones were coupled with arylboronic acids with high efficiency within short reaction time. The catalytic system is also efficient for the stereoselective coupling of aryl chlorides with alkenylboronic acids, results on which will be reported shortly. Our future studies include tuning ligand structure to improve catalyst activity, applying this new class of ligands in other reactions as well as the synthesis of enantiopure benzoferrocenyl ligands for enantioselective catalysis.

4. Experimental

4.1. General

All reactions were performed under a nitrogen atmosphere using standard Schlenk techniques. Reagents and solvents available from commercial sources were used as received unless otherwise noted. 1,4-Dioxane and THF were distilled from Na/benzophenone ketyl. Toluene and dimethoxyethane were distilled over CaH_2. ^1H and ^{13}C NMR were measured on a Varian UNITY INOVA spectrometer at 400 MHz. GC–MS were measured on GCMS-QP5050A, Shimadzu; column, DB-5MS, 0.25 μm thickness, 0.25 mm diameter, 25 m length; MS, positive EI.

4.2. General procedure for Suzuki–Miyaura coupling of aryl chlorides

A two-necked round-bottomed flask with a magnetic stirring bar and a reflux condenser was dried in an oven and connected to nitrogen through a double bank inert gas/vacuum manifold and cooled to room temperature. Arylboronic acid (for quantities of materials, see Tables 1–5 and their footnotes), $Pd_2(dba)_3$, and a base were added under positive nitrogen pressure. The flask with the condenser was switched from nitrogen to vacuum by turning the double oblique hollow glass plug of the manifold and remained under vacuum for about 10 min and then turned back to nitrogen carefully. The benzoferrocenyl phosphine ligand in a one-necked round-bottomed flask was dried under vacuum overnight and the flask was then filled with nitrogen carefully and remained under a nitrogen atmosphere. A freshly distilled solvent (1,4-dioxane, dimethoxyethane, toluene or THF) or an anhydrous solvent from commercial source (dimethoxymethane or DMF) was added to both flasks via oven-dried syringes. Aryl chloride was added to the two-necked round-bottomed flask via syringe if it is a liquid; otherwise, it was dissolved in the same solvent for the reaction in another round-bottomed flask and added to the two-necked flask via a cannula. Finally, the ligand solution was added to the two-necked flask via a cannula. The reaction mixture was then heated to specific temperature (see Tables 1–5) and the reaction was occasionally monitored by TLC and/or GC–MS (but the reaction time was not minimized). After specific time as indicated in Tables 1–5, the mixture was cooled to room temperature gradually under nitrogen and filtered through a pack of Celite® 545, which was washed thoroughly with Et_2O. The filtrate and the washing solvent were combined and evaporated to dryness under reduced pressure. The product was then purified by flash column chromatography. All products in this study are known (references are given in Tables 4 and 5) and were identified by ^1H and ^{13}C NMR and GC–MS except 2,6-dimethyl-2-phenyl-1,1′-biphenyl (Table 5, entry 14), which is characterized below.

4.2.1. Analytical data for 2,6-dimethyl-2-phenyl-1,1′-biphenyl. Colorless oil; ^1H NMR (400 MHz, $CDCl_3$) δ 7.53–7.51 (m, 1H), 7.48–7.41 (m, 2H), 7.22–7.08 (m, 7H), 7.00 (d, J=8.0 Hz, 2H), 1.98 (s, 6H); ^{13}C NMR (400 MHz, $CDCl_3$) δ 141.6, 141.1, 141.0, 139.2, 136.3, 130.6, 130.4, 129.0, 127.9, 127.7, 127.6, 127.4, 127.2, 126.8, 21.1; EI-MS Calcd for $C_{20}H_{18}$ (*m*/*z*) [M^+] 258, found 258; Anal. Calcd for $C_{20}H_{18}$: C 92.98, H 7.02; found: C 92.99, H 7.40.

Acknowledgements

Financial support from Department of Chemistry, Michigan Tech; a Research Seed Award from Michigan Tech Research Excellence Fund; and the assistance from Mr. Jerry L. Lutz (NMR), Mr. Shane Crist (computation) and Mr. Dean W. Seppala (electronics) are gratefully acknowledged. The authors also thank NSF for an equipment grant (CHE-9512445).

References and notes

1. (a) Nicolaou, K. C.; Boddy, C. N. C.; Brase, S.; Winssinger, N. *Angew. Chem., Int. Ed.* **1999**, *38*, 2097–2152; (b) Baudoin, O. *Eur. J. Org. Chem.* **2005**, 4223–4229; (c) Bringmann, G.; Mortimer, A. J. P.; Keller, P. A.; Gresser, M. J.; Garner, J.; Breuning, M. *Angew. Chem., Int. Ed.* **2005**, *44*, 5384–5427; (d) Wallace, T. W. *Org. Biomol. Chem.* **2006**, *4*, 3197–3210.
2. (a) Yin, L.; Liebscher, J. *Chem. Rev.* **2007**, *107*, 133–173; (b) Kosugi, M. *Organomet. News* **2006**, 75–78; (c) De Souza, M. V. N. *Curr. Org. Synth.* **2006**, *3*, 313–326.
3. Schnurch, M.; Flasik, R.; Khan, A. F.; Spina, M.; Mihovilovic, M. D.; Stanetty, P. *Eur. J. Org. Chem.* **2006**, 3283–3307.
4. Corbet, J.-P.; Mignani, G. *Chem. Rev.* **2006**, *106*, 2651–2710.
5. Littke, A. F.; Dai, C. Y.; Fu, G. C. *J. Am. Chem. Soc.* **2000**, *122*, 4020–4028.
6. (a) Old, D. W.; Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 9722–9723; (b) Wolfe, J. P.; Singer, R. A.; Yang, B. H.; Buchwald, S. L. *J. Am. Chem. Soc.* **1999**, *121*,

9550–9561; (c) Barder, T. E.; Walker, S. D.; Martinelli, J. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2005**, *127*, 4685–4696; (d) Anderson, K. W.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2005**, *44*, 6173–6177.

7. (a) Guram, A. S.; King, A. O.; Allen, J. G.; Wang, X. H.; Schenkel, L. B.; Chan, J.; Bunel, E. E.; Faul, M. M.; Larsen, R. D.; Martinelli, M. J.; Reider, P. J. *Org. Lett.* **2006**, *8*, 1787–1789; (b) Liu, D.; Gao, W. Z.; Dai, Q.; Zhang, X. M. *Org. Lett.* **2005**, *7*, 4907–4910; (c) Zapf, A.; Jackstell, R.; Rataboul, F.; Riermeier, T.; Monsees, A.; Fuhrmann, C.; Shaikh, N.; Dingerdissen, U.; Beller, M. *Chem. Commun.* **2004**, 38–39; (d) Dai, Q.; Gao, W. Z.; Liu, D.; Kapes, L. M.; Zhang, X. M. *J. Org. Chem.* **2006**, *71*, 3928–3934.
8. Allenmar, S. *Tetrahedron Lett.* **1974**, *15*, 371–374.
9. Liu, S. Y.; Choi, M. J.; Fu, G. C. *Chem. Commun.* **2001**, 2408–2409.
10. (a) Roca, F. X.; Richards, C. J. *Chem. Commun.* **2003**, 3002–3003; (b) Pickett, T. E.; Richards, C. J. *Tetrahedron Lett.* **2001**, *42*, 3767–3769.
11. Kataoka, N.; Shelby, Q.; Stambuli, J. P.; Hartwig, J. F. *J. Org. Chem.* **2002**, *67*, 5553–5566.
12. Hierso, J. C.; Fihri, A.; Amardeil, W.; Meunier, P. *Organometallics* **2003**, *22*, 4490–4499.
13. (a) Baillie, C.; Zhang, L. X.; Xiao, J. L. *J. Org. Chem.* **2004**, *69*, 7779–7782; (b) Jensen, J. F.; Johannsen, M. *Org. Lett.* **2003**, *5*, 3025–3028.
14. Thimmaiah, M.; Luck, R. L.; Fang, S. *J. Organomet. Chem.* **2007**, *692*, 1956–1962.
15. King, R. B.; Bisnette, M. B. *Inorg. Chem.* **1964**, *3*, 796–800.
16. Wang, B. Q.; Mu, B.; Chen, D.; Xu, S. S.; Zhou, X. Z. *Organometallics* **2004**, *23*, 6225–6230.
17. Nising, C. F.; Schmid, U. K.; Nieger, M.; Brase, S. *J. Org. Chem.* **2004**, *69*, 6830–6833.
18. Stevens, P. D.; Fan, J. D.; Gardimalla, H. M. R.; Yen, M.; Gao, Y. *Org. Lett.* **2005**, *7*, 2085–2088.
19. Li, J. H.; Liu, W. J. *Org. Lett.* **2004**, *6*, 2809–2811.
20. Tao, B.; Boykin, D. W. *J. Org. Chem.* **2004**, *69*, 4330–4335.
21. Ackermann, L.; Althammer, A. *Org. Lett.* **2006**, *8*, 3457–3460.
22. Su, W. P.; Urgaonkar, S.; Verkade, J. G. *Org. Lett.* **2004**, *6*, 1421–1424.
23. Xiong, Z. C.; Wang, N. D.; Dai, M. J.; Li, A.; Chen, J. H.; Yang, Z. *Org. Lett.* **2004**, *6*, 3337–3340.
24. Su, W.; Urgaonkar, S.; McLaughlin, P. A.; Verkade, J. G. *J. Am. Chem. Soc.* **2004**, *126*, 16433–16439.
25. Dong, C. G.; Hu, Q. S. *J. Am. Chem. Soc.* **2005**, *127*, 10006–10007.
26. Cella, R.; Cunha, R. L. O. R.; Reis, A. E. S.; Pimenta, D. C.; Klitzke, C. F.; Stefani, H. A. *J. Org. Chem.* **2006**, *71*, 244–250.
27. Liang, L. C.; Chien, P. S.; Huang, M. H. *Organometallics* **2005**, *24*, 353–357.
28. Mino, T.; Shirae, Y.; Sakamoto, M.; Fujita, T. *J. Org. Chem.* **2005**, *70*, 2191–2194.
29. Song, C.; Ma, Y. D.; Chai, Q.; Ma, C. Q.; Jiang, W.; Andrus, M. B. *Tetrahedron* **2005**, *61*, 7438–7446.
30. Denmark, S. E.; Kallemeyn, J. M. *J. Am. Chem. Soc.* **2006**, *128*, 15958–15959.
31. Navarro, O.; Marion, N.; Mei, J. G.; Nolan, S. P. *Chem.—Eur. J.* **2006**, *12*, 5142–5148.