Available online at www.sciencedirect.com
ScienceDirect
Tetrahedron
Tetrahedron 62 (2006) 9359–9364

PEG (300)–$PdCl_2$ promoted efficient and convenient Suzuki–Miyaura coupling of aryl chlorides with arylboronic acids

Liang Yin, Zhan-hui Zhang and Yong-mei Wang*

Department of Chemistry and the State Key Laboratory of Elemento-Organic Chemistry, Nankai University, Tianjin 300071, PR China

Received 12 April 2006; revised 22 July 2006; accepted 25 July 2006

Abstract—PEG (300) was found as an effective medium for the $PdCl_2$-catalyzed Suzuki–Miyaura cross-coupling of aryl chlorides with various phenylboronic acids. This cross-coupling pathway conveniently and efficiently gave good to excellent yields of corresponding biaryl nucleus under mild conditions.

1. Introduction

The palladium-catalyzed Suzuki–Miyaura cross-coupling has become one of the most versatile and powerful reactions for the construction of carbon–carbon bonds, in particular for the formation of biaryls.[1,2] The traditional protocols for the Suzuki–Miyaura reaction prescribe a palladium species with phosphine ligands as the catalyst. However, many phosphines, which are necessary to stabilize the catalytically active Pd species, are toxic and/or expensive. Meanwhile, some phosphines are sensitive to air and moisture with conversion to, for example, phosphine oxide species. Consequently, the development of phosphine-free catalytic systems to overcome these difficulties is considered to be one of the most challenging fields in organic chemistry. Improved conditions have been developed for the Suzuki–Miyaura reaction, including the use of palladium nanoparticles,[3] water-soluble phosphines as ligands,[4] microwave technology,[5] nucleophilic carbene ligands,[6] ionic liquids,[7] and so on.[8] While aryl iodides and bromides are the more reactive substrates in the reaction, it is aryl chlorides which have an attraction to synthetic chemists due to the availability of a broad range of inexpensive materials in this class. As a result, significant research effort has been focused on the preparation and use of catalysts capable of activating aryl chloride substrates.[9] Complexes bearing bulky phosphines,[10] *N*-heterocyclic carbenes[11,12] or palladacyclic complexes[13] have recently been introduced as particularly active catalysts. Now, it is a new challenge to utilize phosphine-free catalytic systems to couple aryl chlorides with arylboronic acids.

PEGs have clear advantages as solvents for use in chemistry because they are inexpensive, readily available, easily degradable, and possess low toxicity.[14] Recently, the phosphine-free Suzuki reaction involving PEG (400) as the solvent was reported by Li and co-workers.[15] In the presence of $Pd(OAc)_2$ and DABCO, coupling of aryl iodides or aryl bromides with arylboronic acids was carried out to afford good to excellent yields on the condition of heating for 110 °C. At the same time, Zhang and co-workers developed an easier method of Suzuki reaction by using water combining with PEG (2000) as solvent and $Pd(OAc)_2$ as the catalyst.[16] The reaction can be conducted to give biaryl nucleus under heating conditions (50 °C) without the use of microwave or ligand in high yield. However, in the case of aryl chlorides, the above mentioned $Pd(OAc)_2$–DABCO–PEG (400) and $Pd(OAc)_2$–H_2O–PEG (2000) systems proved not to be effective. Here, we report that $PdCl_2$, in combination with PEG (300) as the solvent, is quite an efficient system for the coupling of aryl chlorides with arylboronic acids at room temperature.

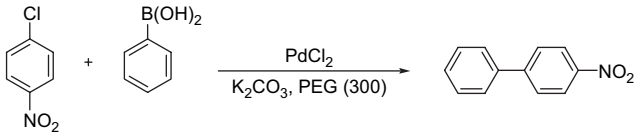
2. Results and discussion

We initiated our study of the Suzuki–Miyaura cross-coupling reaction by optimizing the conditions in terms of Pd species, solvents, and bases. The Suzuki–Miyaura cross-coupling reaction was first evaluated with some Pd species in order to study their catalytic activity. We chose as a model reaction the coupling between *p*-nitrochlorobenzene and phenylboronic acid in PEG (300) at room temperature (Table 1). Both reactions catalyzed by $PdCl_2$ and $Pd(OAc)_2$ provided good yields in 1.5 h (Table 1, entries 1

* Corresponding author. E-mail: ymw@nankai.edu.cn

0040–4020/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.tet.2006.07.067

Table 1. Effect of Pd species on cross-coupling of *p*-nitrochlorobenzene with phenylboronic acid[a]



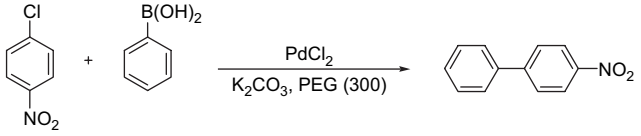
Entry	Pd species	Time (h)[b]	Yield (%)[c]
1	$PdCl_2$	1.5	92
2	$PdCl_2(PPh_3)_4$	6	85
3	$Pd(OAc)_2$	1.5	93
4	$Pd(PPh_3)_4$	12	Trace

[a] Reaction conditions: 1.0 mmol *p*-nitrochlorobenzene, 1.1 mmol phenylboronic acid, 2.5 mmol K_2CO_3, 5 mmol % Pd species, 4 mL PEG (300), at room temperature.
[b] The reaction was monitored by TLC.
[c] Isolated yield.

and 3). $PdCl_2(PPh_3)_4$ also presented good yield but needed longer time (Table 1, entry 2). However, $Pd(PPh_3)_4$ was not an effective catalyst for the Suzuki–Miyaura cross-coupling reaction in PEG (300). In view of the cheaper price of $PdCl_2$ than $Pd(OAc)_2$, we selected $PdCl_2$ as the catalyst for our research.

Our next investigation into an effective Suzuki reaction began with *p*-nitrochlorobenzene, phenylboronic acid, and an array of solvents combined with PEG (300). The results are summarized in Table 2. The choice of solvent has a significant impact on the efficiency of the cross-coupling: the reaction of *p*-nitrochlorobenzene with 1.1 equiv of phenylboronic acid in PEG/DMSO, PEG/H_2O at room temperature for 12 h scarcely afforded the corresponding biaryl. When PEG/CH_3OH, PEG/C_2H_5OH, PEG/*n*-C_3H_7OH, PEG/*i*-C_3H_7OH, PEG/toluene, PEG/CH_3CN or PEG/dioxane were used as solvents, the yields of *p*-nitro-biphenyl were also very low. In the case of employing DMF, the reaction was carried out smoothly to give a marked enhancement in yield in 12 h (entry 4, 75%). Evidently, the best solvent for the reaction was pure PEG (300), which produced 92% of *p*-nitro-biphenyl in only 1.5 h (entry 1).

Table 2. Effect of solvent on $PdCl_2$-catalyzed cross-coupling of *p*-nitrochlorobenzene with phenylboronic acid[a]

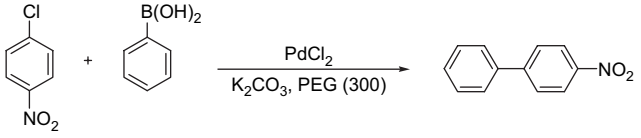


Entry	Solvent	Time (h)[b]	Yield (%)[c]
1	PEG	1.5	92
2	PEG/DMSO	12	Trace
3	PEG/toluene	12	25
4	PEG/DMF	12	75
5	PEG/CH_3CN	12	8
6	PEG/dioxane	12	36
7	PEG/H_2O	12	Trace
8	PEG/CH_3OH	12	6
9	PEG/C_2H_5OH	12	8
10	PEG/*n*-C_3H_7OH	12	15
11	PEG/*i*-C_3H_7OH	12	17

[a] Reaction conditions: 1.0 mmol *p*-nitrochlorobenzene, 1.1 mmol phenylboronic acid, 2.5 mmol K_2CO_3, 5 mmol % $PdCl_2$, 4 mL PEG (300), and 4 mL other solvents, at room temperature.
[b] The reaction was monitored by TLC.
[c] Isolated yield.

In our following experiments, when we used K_2CO_3 as base, the optimum yield was obtained by using 3.0 equiv with respect to the aryl halide (Table 3, entries 1–3). Use of less or more than the amount resulted in a lower yield. Employing 1.5 equiv of phenylboronic acid gave *p*-nitro-biphenyl in a better yield of 98% compared to the above 1.1 equiv amount (Table 3, entry 4). Using 1.5 equiv of phenylboronic acid, we screened a range of other bases. $KF\cdot 2H_2O$, KOAc, KOH, Na_2CO_3, NaOAc, NaOH, and *n*-Bu_4NOH were found to be effective in the reaction. $NaHCO_3$, Cs_2CO_3, and $K_3PO_4\cdot 3H_2O$ led to acceptable moderate yields of product, while $BaCO_3$ resulted in *p*-nitro-biphenyl in a lower yield. Ag_2CO_3 and Et_3N proved to be particularly inefficient bases, while MgF_2, AlF_3, DMAP were completely inactive. Finally, K_2CO_3, an effective base for the cyclopalladated-imine catalyst for the Suzuki–Miyaura reaction,[17] proved to be the most effective, leading to 98% isolated yield in 1.5 h.

Table 3. Effect of base on PEG (300)–$PdCl_2$-catalyzed cross-coupling of *p*-nitrochlorobenzene with phenylboronic acid[a]

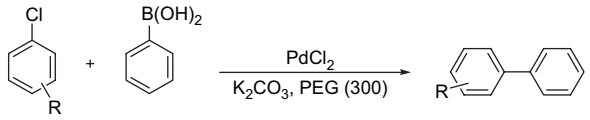


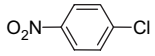
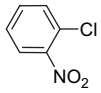
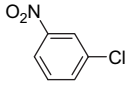
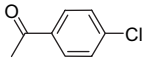
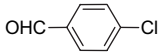
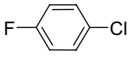
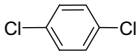
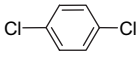
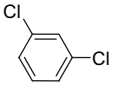
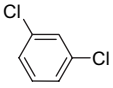
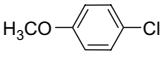
Entry	Base	Time (h)[b]	Yield (%)[c]
1[d,e]	K_2CO_3	2	87
2[d]	K_2CO_3	1.5	92
3[d,f]	K_2CO_3	1.5	90
4	K_2CO_3	1.5	98
5	$K_3PO_4\cdot 3H_2O$	12	72
6	$KF\cdot 2H_2O$	4	98
7	KOAc	8	92
8	KOH	1.5	90
9	Na_2CO_3	8	95
10	$NaHCO_3$	12	60
11	NaOAc	12	90
12	NaOH	8	98
13	Cs_2CO_3	12	50
14	Ag_2CO_3	12	Trace
15	$BaCO_3$	12	30
16	AlF_3	12	—
17	MgF_2	12	—
18[g]	*n*-Bu_4NOH	3	94
19	Et_3N	12	Trace
20	DMAP	12	—

[a] Reaction conditions: 1.0 mmol *p*-nitrochlorobenzene, 1.5 mmol phenylboronic acid, 3.0 mmol base, 5 mmol % $PdCl_2$, 4 mL PEG (400), at room temperature.
[b] The reaction was monitored by TLC.
[c] Isolated yield.
[d] Phenylboronic acid: 1.1 mmol.
[e] Base: 2.5 mmol.
[f] Base: 3.5 mmol.
[g] 25% in methanol.

As illustrated in Table 4, the PEG (300)–$PdCl_2$ system was applicable to a wide range of aryl chloride substrates to give the products with good to excellent yields. A wide array of functional groups such as aldehyde, nitro, ketone, and

Table 4. PEG (300)–$PdCl_2$-catalyzed cross-coupling of aryl chlorides with phenylboronic acid[a]



Entry	Aryl chloride	Time (h)[b]	Yield (%)[c]
1		1.5	98
2		8	93
3		8	52
4		4	96
5		4	96
6		5	84
7[d]		3	86
8[e,f]		12	50
9[d,g]		8	45
10[e,g]		12	82
11[d]		12	Trace
12		6	98
13		8	80

[a] Reaction conditions: 1.0 mmol aryl halide, 1.5 mmol phenylboronic acid, 3 mmol K_2CO_3, 5 mmol % $PdCl_2$, 4 mL PEG (300), at room temperature.
[b] The reaction was monitored by TLC.
[c] Isolated yield.
[d] Phenylboronic acid: 1.1 mmol.
[e] Phenylboronic acid: 3.0 mmol.
[f] Product: 50% *p*-terphenyl and 52% 4-chloro-biphenyl.
[g] Product: *m*-terphenyl.

methoxy were tolerated in the reaction and not affected by the system. For example, with *p*-chlorobenzaldehyde, a high yield of coupling product (96%) was obtained (entry 5). We found that electron-withdrawing chlorides such as *p*-nitrochlorobenzene (entry 1) and 1-(4-chloro-phenyl)-ethanone (entry 4) were more efficiently utilized as substrates, compared to chlorides with electron-donating groups such as *p*-methoxychlorobenzene (entry 13). Surprisingly, the reaction of *m*-nitrochlorobenzene with phenylboronic acid only gave a moderate yield of 52% after 8 h and 45% material was recovered. Furthermore, it was noteworthy that the treatment of *p*-dichlorobenzene with 1 equiv of phenylboronic acid produced 4-chloro-biphenyl in 86% yield after 3 h at room temperature. Utilization of 3 equiv of phenylboronic acid afforded 50% *p*-terphenyl and 52% 4-chloro-biphenyl (entries 7 and 8). However, both 1 and 3 equiv of phenylboronic acid generated *m*-terphenyl as the only main product (entries 9 and 10). It was quite surprising that treatment of *o*-dichlorobenzene with phenylboronic acid scarcely afforded any main product (entry 11).

The effect of varying the phenylboronic acids in the Suzuki–Miyaura cross-coupling reactions was also investigated using various aryl chlorides (Table 5). From Table 5, it is evident that the reaction of phenylboronic acid with electron-donating groups such as methoxy occurred faster than when electron-withdrawing groups such as fluoro were employed. For example, treatment of chlorobenzene with *p*-methoxyphenylboronic acid afforded the corresponding coupled product in shorter time and higher yield than coupling of chlorobenzene with *p*-fluorophenylboronic acid (entries 5 and 10). Compared to *p*-nitrochlorobenzene and *m*-nitrochlorobenzene, 2,4-dinitrochlorobenzene afforded the corresponding product in lesser time and with higher yield, which suggested that the electron-withdrawing effect of a nitro group had more influence on the chloride than the effect of static hindrance. Remarkably, phenylboronic acid containing electron-withdrawing groups or electron-donating groups could be coupled in good to excellent yields at room temperature. However, when *p*-methoxychlorobenzene was utilized, the reaction with *p*-fluorophenylboronic acid and 3,4,5-trifluorophenylboronic acid only gave moderate yields (65 and 60%, entries 12 and 16). Moreover, we were pleased to observe that 1-naphthylboronic acid could be coupled with *p*-nitrophenylboronic acid to afford 1-(4-nitro-phenyl)-naphthalene with 90% yield (entry 19), while when 1-(4-chloro-phenyl)-ethanone was employed, only 50% yield of the corresponding product was isolated (entry 20).

3. Conclusion

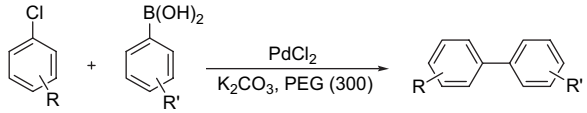
In conclusion, we have disclosed an efficient and convenient system for the Suzuki coupling of aryl chlorides with various phenylboronic acids using $PdCl_2$ as catalyst and PEG (300) as solvent at room temperature. The system proved to be quite efficient for a wide array of electron-withdrawing and electron-donating groups in both aryl chlorides and phenylboronic acids. Currently, further studies are underway in our laboratory, addressing extension of the system to other palladium-catalyzed transformations.

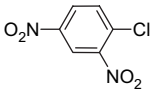
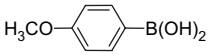
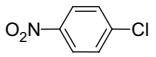
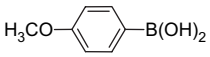
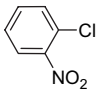
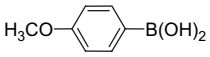
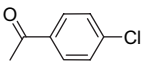
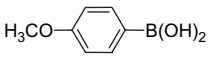
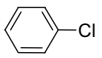
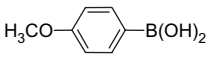
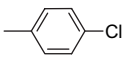
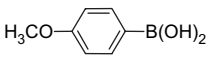
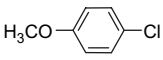
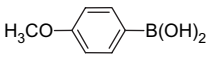
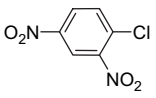
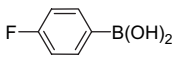
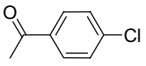
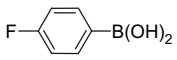
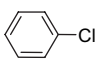
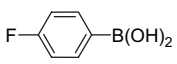
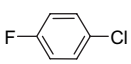
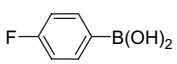
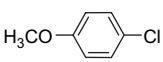
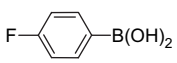
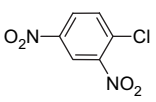
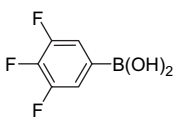
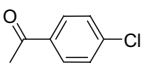
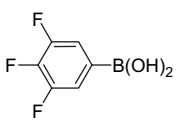
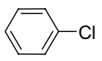
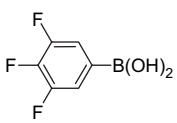
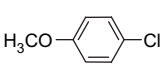
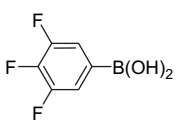
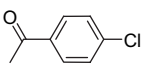
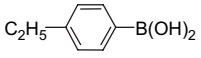
4. Experimental

4.1. Typical experimental procedure for the PEG (300)–$PdCl_2$-catalyzed Suzuki–Miyaura cross-coupling reaction

A mixture of aryl chlorides (1.0 mmol), arylboronic acid (1.5 mmol), $PdCl_2$ (0.05 mmol), K_2CO_3 (3 mmol), and PEG (300) (4 mL) were added to a 100 mL round-flask, and stirred at room temperature for the desired time until complete consumption of starting material as judged by

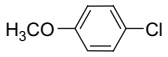
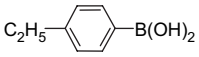
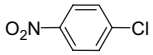
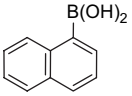
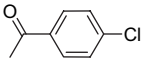
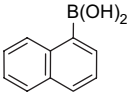
Table 5. PEG (300)–$PdCl_2$-catalyzed cross-coupling of aryl halides with various phenylboronic acids[a]



Entry	Aryl chloride	Phenylboronic acid	Time (h)[b]	Yield (%)[c]
1			0.5	98
2			1	95
3			5	90
4			4	92
5			5	87
6			3.5	93
7			5	98
8			2	96
9			6	90
10			10	83
11			5	95
12			10	65
13			3	87
14			6	85
15			10	82
16			12	60
17			5	86

(*continued*)

Table 5. (*continued*)

Entry	Aryl chloride	Phenylboronic acid	Time (h)[b]	Yield (%)[c]
18			6	80
19			5	90
20			8	50

[a] Reaction conditions: 1.0 mmol aryl halide, 1.5 mmol phenylboronic acid, 3 mmol K_2CO_3, 5 mmol % $PdCl_2$, 4 mL PEG (300), at room temperature.
[b] The reaction was monitored by TLC.
[c] Isolated yield.

TLC. Thus, after the mixture was extracted with dry ethyl ether (5×10 mL) and evaporated, the residue was purified by flash column chromatography (hexane or hexane/ethyl acetate) to afford the desired coupled products.

4.2. Analytical data for new compounds

4.2.1. 2,4-Binitro-4′-fluoro-biphenyl (Table 5, entry 8). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 8.72 (d, J=2.4 Hz, 1H), 8.48 (dd, J=2.4 Hz, J=8.4 Hz, 1H), 7.66 (d, J=8.4 Hz, 1H), 7.36–7.30 (m, 2H), 7.21–7.16 (m, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 161.8, 149.1, 147.0, 141.2, 133.2, 131.2, 130.0, 126.5, 119.8, 116.3. HRMS: calcd for $C_{12}H_7FN_2O_4$ 262.0390; found 262.0381.

4.2.2. 2,4-Binitro-3′,4′,5′-trifluoro-biphenyl (Table 5, entry 13). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 8.80 (d, J=2.4 Hz, 1H), 8.52 (dd, J=2.4 Hz, J=8.4 Hz, 1H), 7.65 (d, J=8.4 Hz, 1H), 6.99 (dd, J=6.3 Hz, J=7.5 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 162.4, 153.2, 147.7, 139.1, 133.1, 130.9, 128.8, 126.9, 120.1, 112.6. HRMS: calcd for $C_{12}H_5F_3N_2O_4$ 298.0201; found 298.0205.

4.2.3. 1-(3′,4′,5′-Trifluoro-biphenyl-4-yl)-ethanone (Table 5, entry 14). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 8.04 (d, J=8.5 Hz, 2H), 7.60 (d, J=8.5 Hz, 2H), 7.24 (dd, J=6.3 Hz, J=8.5 Hz, 2H), 2.65 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 197.4, 153.2, 150.0, 142.5, 138.2, 136.8, 129.2, 127.1, 111.4, 26.7. HRMS: calcd for $C_{14}H_9F_3O$ 250.0606; found 250.0598.

4.2.4. 3,4,5-Trifluoro-biphenyl (Table 5, entry 15). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.51–7.39 (m, 5H), 7.19 (dd, J=6.6 Hz, J=8.4 Hz, 2H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 162.3, 153.1, 149.8, 138.2, 129.1, 129.4, 126.8, 111.0. HRMS: calcd for $C_{12}H_7F_3$ 208.0500; found 208.0499.

4.2.5. 4-Methoxy-3′,4′,5′-trifluoro-biphenyl (Table 5, entry 16). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.43 (d, J=8.7 Hz, 2H), 7.13 (dd, J=6.6 Hz, J=9.0 Hz, 2H), 6.97 (d, J=8.7 Hz, 2H), 3.85 (s, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ: 162.4, 159.9, 127.9, 114.5, 110.6, 110.5, 110.4, 110.3, 55.4. HRMS: calcd for $C_{13}H_9F_3O$ 238.0606; found 238.0607.

4.2.6. 1-(4′-Ethyl-biphenyl-4-yl)-ethanone (Table 5, entry 17). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 8.02 (d, J=8.4 Hz, 2H), 7.68 (d, J=8.4 Hz, 2H), 7.57 (d, J=8.1 Hz, 2H), 7.31 (d, J=8.1 Hz, 2H), 2.71 (q, J=7.5 Hz, 2H), 2.64 (s, 3H), 1.29 (t, J=7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ: 197.7, 145.8, 144.6, 137.2, 135.7, 128.9, 128.5, 127.2, 127.0, 28.6, 26.6, 15.5. HRMS: calcd for $C_{16}H_{16}O$ 224.1201; found 224.1200.

4.2.7. 4-Methoxy-4′-ethyl-biphenyl (Table 5, entry 18). ^{1}H NMR (300 MHz, $CDCl_3$) δ: 7.51 (d, J=8.7 Hz, 2H), 7.47 (d, J=8.1 Hz, 2H), 7.25 (d, J=8.1 Hz, 2H), 6.96 (d, J=8.7 Hz, 2H), 3.84 (s, 3H), 2.68 (q, J=7.5 Hz, 2H), 1.27 (t, J=7.5 Hz, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ: 158.9, 142.7, 138.2, 133.8, 128.2, 128.0, 126.7, 114.2, 55.3, 28.5, 15.9. HRMS: calcd for $C_{15}H_{16}O$ 212.1201; found 212.1199.

Acknowledgements

We are grateful for the financial support provided by the National Natural Science Foundation of China (No. 20472032).

Supplementary data

Supplementary data associated with this article can be found in the online version, at doi:10.1016/j.tet.2006.07.067.

References and notes

1. For recent reviews see: (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457; (b) *Metal-Catalyzed Cross-coupling Reactions*; Diederich, F., Stang, P. J., Eds.; Wiley-VCH: New York, NY, 1998; (c) Suzuki, A. *J. Organomet. Chem.* **1999**, *576*, 147; (d) Miyaura, N. *Cross-Coupling Reaction*; Springer: Berlin, 2002; (e) Hassan, J.; Sévignon, M.; Gozzi, C.; Schulz, E.; Lemaire, M. *Chem. Rev.* **2002**, *102*, 1359; (f) Kotha, S.; Lahiri, K.; Kashinath, D. *Tetrahedron* **2002**, *58*, 9633; (g) Miyaura, N. *Top. Curr. Chem.* **2002**, 11; (h) Nakamura, I.; Yamamoto, Y. *Chem. Rev.* **2004**, *104*, 2127; (i) Miura, M. *Angew. Chem., Int. Ed.* **2004**, *43*, 2201; (j) Bellina, F.;

Carpita, A.; Rossi, R. *Synthesis* **2004**, 2419; (k) Suzuki, A. *Proc. Jpn. Acad., Ser. B* **2004**, *80*, 359; (l) Christmann, U.; Vilar, R. *Angew. Chem., Int. Ed.* **2005**, *44*, 366; (m) Zapf, A.; Beller, M. *Chem. Commun.* **2005**, 431.

2. For recent representative examples see: (a) Barder, T. E.; Walker, S. D.; Martinelli, J. R.; Buchwald, S. L. *J. Am. Chem. Soc.* **2005**, *127*, 4685; (b) Dong, C.-G.; Hu, Q.-S. *J. Am. Chem. Soc.* **2005**, *127*, 10006; (c) Barder, T. E. *J. Am. Chem. Soc.* **2006**, *128*, 898; (d) Korenaga, T.; Kosaki, T.; Fukumura, R.; Ema, T.; Sakai, T. *Org. Lett.* **2005**, *7*, 4915; (e) Lemo, J.; Heuzé, K.; Astruc, D. *Org. Lett.* **2005**, *7*, 2253.
3. (a) Reetz, M. T.; Westermann, E. *Angew. Chem., Int. Ed.* **2000**, *39*, 165; (b) Thathagar, M. B.; Beckers, J.; Rothenberg, G. *J. Am. Chem. Soc.* **2002**, *124*, 11858; (c) Kogan, V.; Aizenshtat, Z.; Popovitz-Biro, R.; Neumann, R. *Org. Lett.* **2002**, *4*, 3529; (d) Calò, V.; Nacci, A.; Monopoli, A.; Montingelli, F. *J. Org. Chem.* **2005**, *70*, 6040.
4. (a) Shaughnessy, K. H.; Booth, R. S. *Org. Lett.* **2001**, *3*, 2757; (b) Dupuis, C.; Adiey, K.; Charruault, L.; Michelet, V.; Savignac, M.; Genêt, J.-P. *Tetrahedron Lett.* **2001**, *42*, 6523; (c) Kataoka, N.; Shelby, Q.; Stambuli, J. P.; Hartwig, J. F. *J. Org. Chem.* **2002**, *67*, 5553; (d) Adjabeng, G.; Brenstrum, T.; Wilson, J.; Frampton, C.; Robertson, A.; Hillhouse, J.; McNulty, J.; Capretta, A. *Org. Lett.* **2003**, *5*, 953; (e) Moore, L. R.; Shaughnessy, K. H. *Org. Lett.* **2004**, *6*, 225; (f) Anderson, K. W.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2005**, *44*, 6173.
5. (a) Kabalka, G. W.; Pagni, R. M.; Wang, L.; Namboodiri, V.; Hair, C. M. *Green Chem.* **2000**, *2*, 120; (b) Namboodiri, V. V.; Varma, R. S. *Green Chem.* **2001**, *3*, 146; (c) Leadbeater, N. E.; Marco, M. *Org. Lett.* **2002**, *4*, 2973; (d) Wu, T. Y. H.; Schultz, P. G.; Ding, S. *Org. Lett.* **2003**, *5*, 3587; (e) Leadbeater, N. E.; Macro, M. *J. Org. Chem.* **2003**, *68*, 888; (f) Leadbeater, N. E.; Marco, M. *J. Org. Chem.* **2003**, *68*, 5660; (g) Wang, Y.; Sauer, D. R. *Org. Lett.* **2004**, *6*, 2793; (h) Arvela, R. K.; Leadbeater, N. E. *Org. Lett.* **2005**, *7*, 2101.
6. (a) Alonso, D. A.; Nájera, C.; Pacheco, M. C. *J. Org. Chem.* **2002**, *67*, 5588; (b) Navarro, O.; Kelly, R. A., III; Nolan, S. P. *J. Am. Chem. Soc.* **2003**, *125*, 16194; (c) Navarro, O.; Kaur, H.; Mahjoor, P.; Nolan, S. P. *J. Org. Chem.* **2004**, *69*, 3173; (d) Xiong, Z.-C.; Wang, N.-D.; Dai, M.-J.; Li, A.; Chen, J.-H.; Yang, Z. *Org. Lett.* **2004**, *6*, 3337.
7. (a) Mathews, C. J.; Smith, P. J.; Welton, T. *Chem. Commun.* **2000**, 1249; (b) Revell, J. D.; Ganesan, A. *Org. Lett.* **2002**, *4*, 3071; (c) Rajagopal, R.; Jarikote, D. V.; Srinivasan, K. V. *Chem. Commun.* **2002**, 616; (d) Miao, W.-S.; Chan, T. H. *Org. Lett.* **2003**, *5*, 5003; (e) Xiao, J.-C.; Shreeve, J. M. *J. Org. Chem.* **2005**, *70*, 3072.
8. (a) Indolese, A. F. *Tetrahedron Lett.* **1997**, *38*, 3513; (b) Botella, L.; Nájera, C. *Angew. Chem., Int. Ed.* **2002**, *41*, 179; (c) Sakurai, H.; Tsukuda, T.; Hirao, T. *J. Org. Chem.* **2002**, *67*, 2721; (d) Baleizão, C.; Corma, A.; García, H.; Leyva, A. *Chem. Commun.* **2003**, 606; (e) Mori, Y.; Seki, M. *J. Org. Chem.* **2003**, *68*, 1571; (f) Tao, B.; Boykin, D. W. *J. Org. Chem.* **2004**, *69*, 4330.
9. For a general review see: Littke, A. F.; Fu, G. C. *Angew. Chem., Int. Ed.* **2002**, *41*, 4176.
10. For recent representative examples see: (a) Colacot, T. J.; Shea, H. A. *Org. Lett.* **2004**, *6*, 3731; (b) Smith, R. C.; Woloszynek, R. A.; Chen, W.-Z.; Ren, T.; Protasiewicz, J. D. *Tetrahedron Lett.* **2004**, *45*, 8327; (c) Tewari, A.; Hein, M.; Zapf, A.; Beller, M. *Synthesis* **2004**, 935.
11. For reviews see: (a) Jafarpour, L.; Nolan, S. P. *Adv. Organomet. Chem.* **2001**, *46*, 181; (b) Hillier, A. C.; Grasa, G. A.; Viciu, M. S.; Lee, H. M.; Yang, C.-L.; Nolan, S. P. *J. Organomet. Chem.* **2002**, *653*, 69; (c) Peris, E.; Crabtree, R. H. *Coord. Chem. Rev.* **2004**, *248*, 2239; (d) Crudden, C. M.; Allen, D. P. *Coord. Chem. Rev.* **2004**, *248*, 2247.
12. For recent representative examples see: (a) Singh, R.; Viciu, M. S.; Kramareva, N.; Navarro, O.; Nolan, S. P. *Org. Lett.* **2005**, *7*, 1829; (b) Hadei, N.; Kantchev, E. A. B.; O'Brien, C. J.; Organ, M. G. *Org. Lett.* **2005**, *7*, 1991; (c) Liu, D.; Gao, W.-Z.; Dai, Q.; Zhang, X.-M. *Org. Lett.* **2005**, *7*, 4907; (d) Mino, T.; Shirae, Y.; Sakamoto, M.; Fujita, T. *J. Org. Chem.* **2005**, *70*, 2191; (e) Navarro, O.; Marion, N.; Oonishi, Y.; Kelly, R. A., III; Nolan, S. P. *J. Org. Chem.* **2006**, *71*, 685.
13. For reviews see: (a) Bedford, R. B.; Cazin, C. S. J.; Holder, D. *Coord. Chem. Rev.* **2004**, *248*, 2283; (b) Chinchilla, R.; Nájera, C.; Yus, M. *Chem. Rev.* **2004**, *104*, 2667; (c) Bedford, R. B. *Chem. Commun.* **2003**, 1787.
14. (a) Heldebrant, D.; Jessop, P. G. *J. Am. Chem. Soc.* **2003**, *125*, 5600; (b) Zhang, Z.-H.; Yin, L.; Wang, Y.-M.; Liu, J.-Y.; Li, Y. *Green Chem.* **2004**, *6*, 563.
15. (a) Li, J.-H.; Liu, W.-J.; Xie, Y.-X. *J. Org. Chem.* **2005**, *70*, 5409; (b) Liu, W.-J.; Xie, Y.-X.; Liang, Y.; Li, J.-H. *Synthesis* **2006**, 860.
16. Liu, L.-F.; Zhang, Y.-H.; Wang, Y.-G. *J. Org. Chem.* **2005**, *70*, 6122.
17. Littke, A. F.; Dai, C.-Y.; Fu, G. C. *J. Am. Chem. Soc.* **2000**, *122*, 4020.