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Palladium–benzimidazolium salt catalyst systems for Suzuki coupling: development of a practical and highly active palladium catalyst system for coupling of aromatic halides with arylboronic acids

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Abstract—Palladium–benzimidazolium salt catalyst systems have been studied for the Suzuki coupling. A different substitutent effect has been uncovered with respect to nitrogen substituents in the benzimidazolium salts from the palladium–imidazolium salt analogs. A practical and highly active palladium catalyst system, $PdCl_2$/*N*,*N*′-dibenzylbenzimidazolium chloride **2**, has been identified for the Suzuki coupling of aromatic halides with arylboronic acids. The coupling of a wide array of aromatic halides with arylboronic acids with the $PdCl_2$–**2** catalyst system gave good to excellent yields. The effective palladium loading could be as low as 0.0001 mol% and 0.01–0.1 mol% for iodide and bromide substrates, respectively. The coupling of unactivated aromatic chlorides with arylboronic acids also gave good results using Cs_2CO_3 as base with a 2 mol% palladium loading. The electronic factors from aromatic halides exert a significant influence on the Suzuki coupling catalyzed by the $PdCl_2$–**2** system while the electronic effect from the arylboronic counterparts is negligible. The aromatic halides with modest steric hindrance could also couple smoothly with phenylboronic acids using the $PdCl_2$–**2** catalyst system.

1. Introduction

The imidazolium-based nucleophilic *N*-heterocyclic carbenes (NHC), imidazolylidenes, have recently emerged as a versatile class of ligands in transition metal chemistry.[1] With their stronger donor electronic property, thus high dissociation energies of the corresponding metal–carbon bonds,[2] the transition metal complexes of imidazolylidenes appeared to be extraordinarily stable toward heat, air and moisture, showing potential in practical organic synthesis. These advantages of imidazolylidene ligands make them ideal alternatives to tertiary phosphines used in a variety of transition-metal based homogeneous catalysts. Through formation of catalytic species in situ, use of a combination of imidazolium salts with metal precursors has proven to be not only practical but also more efficient in some cases than the isolated NHC–metal complexes of imidazolylidenes.[3] A variety of highly active catalyst systems have recently been developed by combination of proper imidazolium salts with palladium precursors.[3,4] However, possibly due to the lower stability of free benzimidazolylidenes than imidazolylidenes few attention has been paid to the nucleophilic *N*-heterocyclic carbenes derived from benzimidazole[5] although fundamental thermodynamic studies have shown that benzimidazolylidenes behave intermediately between imidazolylidenes and their saturated analogs, imidazolinylidenes.[6] The first NHC, derived from benzimidazole, *N*,*N*′-bis(2,2-dimethylpropyl)benzimidazolylidene, was isolated in 1998 by reduction of thione.[7] Direct deprotonation of *N*,*N*′-bis-alkylsubstituted benzimidazolium salts with a less sterically demanding substituent yields an enetetramine instead of a free carbene.[8] However, it has recently been shown that NHC-transition metal complexes containing benzimidazolylidene ligands could be generated from the corresponding benzimidazolium salts as well as enetetramines under mild conditions.[9] That means, similar to imidazolium salts, a combination of benzimidazolium salts with metal precursors would finally lead to the corresponding NHC–metal complexes under proper conditions.

The Suzuki coupling, where organoboronic acids are employed as neuclophilic partners to couple with electrophiles such as arylhalides, is one of the most important protocols in organic synthesis, permitting the construction of a wide variety of organic compounds ranging from

Keywords: Palladium; Suzuki coupling; Benzimidazolium; Arylboronic acid; Aromatic halide.
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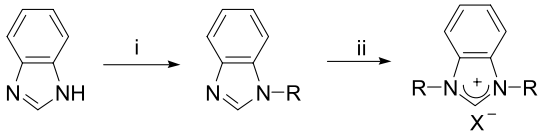
artificial materials to natural products.[10] Compared with the other nucleophilic partners in the cross-coupling with organic halides, such as organomagnesium, organotin, and organozinc, organoboron compounds possess many attractive features, such as air- and water-stability, non-toxicity and excellent compatibility with a variety of functional groups. The palladium–imidazolium salt systems have proved to be one of the most successful catalysts for the Suzuki coupling. Substituents on nitrogen atoms of imidazolium significantly influence the catalytic activities of the corresponding palladium–imidazolium salt systems in the Suzuki coupling. As mentioned above, little is known about the catalyst systems based on benzimidazolium salts in the Suzuki coupling. We report here the development of a highly active palladium–benzimidazolium catalyst system employing the simplest palladium source $PdCl_2$ and the readily accessible *N*,*N*′-dibenzylbenzimidazolium chloride for Suzuki coupling of aromatic halides, including chlorides.

2. Results and discussion

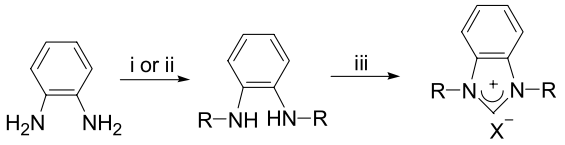
2.1. Synthesis of benzimidazolium salts

N,*N*′-Dialkylbenzimidazolium salts with primary alkyl groups could be readily prepared from benzimidazoles by consecutive alkylations with alkylhalides. *N*,*N*′-Dibutylbenzimidazolium bromide **1**, *N*,*N*′-dibenzylbenzimidazolium chloride **2** and *N*,*N*′-bis-ethoxycarbonylmethylbenzimidazolium bromide **3** were obtained following this procedure in good yields (Scheme 1).



Scheme 1. Reagents and conditions: (i) 1.2 equiv RX, 30% NaOH(aq), $Bu_4N^+Br^-$ (1.5% equiv), 55 °C. (ii) 2.0 equiv RX, toluene, reflux.

According to the systematic work from Nolan group that aryl or bulky alkyl substituents on nitrogen atoms were crucial to the high performance of the corresponding palladium–imidazolium salt systems.[4] Thus, we wonder if the palladium–benzimidazolium systems show a similar trend. However, synthesis of *N*,*N*′-dibenzhydrylbenzimidazolium chloride **4** with the same procedure suffered from poor yields under various conditions although the first alkylation of benzimidazole with benzhydryl chloride proceeded smoothly. Benzimidazolium salts with aromatic substituents on *N* atoms are not accessible with a simple alkylation procedure from benzimidazole. Thus, alternative procedures were used to obtain **4** and *N*,*N*′-diphenylbenzimidazolium chloride **5** (Scheme 2). Benzimidazolium **4** was prepared by alkylation of 1,2-diaminobenzene with benzhydryl chloride followed by cyclization of the resulting *N*,*N*′-dibenzhydryl 1,2-diaminobenzene with orthoformate in the presence of HCl (aq). Introduction of phenyl group to the amino groups of 1,2-diaminobenzene was first tried using palladium-catalyzed procedures with iodobenzene[11] and copper-promoted arylation[12] with phenylboronic acid. Unfortunately, both resulted in complicated mixtures, from which only trace amount of the desired product, *N*,*N*′-diphenyl-1,2-diaminobenzene, was isolated. The preparation of *N*,*N*′-diphenyl-1,2-diaminobenzene was finally achieved by a slightly modified amino acid-promoted Ullmann coupling in 30% yield.[13] A similar cyclization to that for **4** with orthoformate in the presence of HCl(con.) provided *N*,*N*′-diphenylbenzimidazolium chloride **5** in 90% yield.

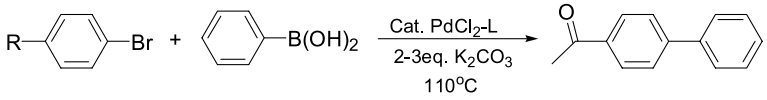


Scheme 2. Reagents and conditions: (i) 2.5 equiv Ph_2CHCl, 30% NaOH (aq), $Bu_4N^+Br^-$ (1.5% equiv), 55 °C. (ii) iodobenzene (5.0 equiv) CuI (0.20 equiv), L-proline (0.40 equiv), K_2CO_3 (4.1 equiv), DMSO, N_2, 80 °C, 18 h. (iii) $HC(OEt)_3$, HCl (con. aq), HCO_2H, N_2, 80 °C, 2 h.

2.2. Suzuki coupling of arylboronic acids with aromatic halides

2.2.1. Establishing catalyst system. With these benzimidazolium derivatives in hand, we started to investigate the performance of the palladium–benzimidazolium catalyst systems in the Suzuki coupling. Cross-coupling of 4-bromoacetophone with phenylboronic acid was selected as the model reaction considering the ease of monitoring the reaction progress. Although there are a couple of parameters, such as base, temperature and solvent to be scanned to optimize the reaction conditions, thanks to the extensive research on NHC–palladium catalysts in recent years, we have readily set the starting point: 0.01%Pd loading, 2–3 equiv K_2CO_3 in DMF–H_2O at 110 °C. Although palladium sources have showed effects on the performance of the corresponding palladium catalyst systems,[3] it is possibly the most practical and economical to use palladium chloride. Thus palladium chloride $PdCl_2$ was chosen as the palladium source in our palladium–benzimidazolium catalyst systems. The reaction 4-bromoacetophone with phenylboronic acid catalyzed by the palladium–benzimidazolium **1**–**5** catalyst systems gave the cross-coupling product in good to excellent yields while no reaction occurred in the absence of a benzimidazolium salt under the otherwise identical conditions (Table 1, entries 1–6). On the effects of *N*,*N*′-substituents of benzimidazolium on the performance of the catalyst systems, benzimidazolium salts displayed a trend in contrast to the reported imidazolium analogs. Aromatic or bulky substituents on the N atoms of imidazolium normally increase the catalytic activity of the corresponding systems.[4d] However, the palladium–benzimidazolium catalyst system based on **5**, the *N*,*N*′-diphenylbenzimidazolium salt, displayed lower catalytic activity in the model reaction than those based on alkyl substituted ones, such as butyl **1**, benzyl **2** and benzhydryl **4**. Bis-ethoxycarbonylmethyl imidazolium **3** also showed a lower activity although the imidazolium with coordinative side arms was reported to display higher activities than the corresponding simple alkyl analogs in palladium-catalyzed C–C bond forming reactions.[14] The systems of dibenzylbenzimidazolium **2** and dibenzhydryl imidazolium **4** displayed higher activities than that of **1** and

Table 1. Cross-coupling of 4-bromoacetophone with phenylboronic acid catalyzed by palladium–benzimidazolium catalyst systems



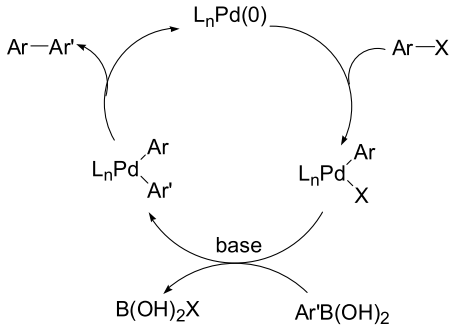
Entry	Ligand	R	Pd loading (%)	Pd/L	Solvent (vol%)	Time (h)	Yield (%)[a]
1	/	CH_3CO	0.01	/	DMF–5%H_2O	3	Trace
2	**1**	CH_3CO	0.01	1/2	DMF–5%H_2O	3	91
3	**2**	CH_3CO	0.01	1/2	DMF–5%H_2O	1	94
4	**3**	CH_3CO	0.01	1/2	DMF–5%H_2O	12	85
5	**4**	CH_3CO	0.01	1/2	DMF–5%H_2O	1	96
6	**5**	CH_3CO	0.01	1/2	DMF–5%H_2O	3	94
7	**2**	CH_3CO	0.001	1/2	DMF–5%H_2O	12	12[b,c]
8	**2**	CH_3	0.01	1/2	DMF–5%H_2O	12	20[b,c]
9	**1**	CH_3	0.1	1/2	DMF–5%H_2O	3	86
10	**2**	CH_3	0.1	1/2	DMF–5%H_2O	2	87
11	**3**	CH_3	0.1	1/2	DMF–5%H_2O	12	73
12	**4**	CH_3	0.1	1/2	DMF–5%H_2O	4	83
13	**5**	CH_3	0.1	1/2	DMF–5%H_2O	6	71[c]
14	**2**	CH_3CO	0.01	1/1	DMF–5%H_2O	5	93
15	**2**	CH_3CO	0.01	1/5	DMF–5%H_2O	1	90
16	**2**	CH_3CO	0.01	1/2	DMF–25%H_2O	8	82
17	**2**	CH_3CO	0.01	1/2	DMF	3	12[b,c]
18	**2**	CH_3CO	0.01	1/2	Dioxane–5%H_2O	3	20[b,c]
19	**2**	CH_3CO	0.01	1/2	Tol–10%H_2O	3	25[b,c]

[a] Isolated yield.
[b] Conversion determined by GC.
[c] Aromatic halides recovered.

3 with butyl and ethoxycarbonylmethyl groups, respectively. These results clearly indicated a sharp difference between the imidazolium and benzimidazolium catalyst systems. The trend displayed in the model reaction was unmistakably confirmed by the coupling of 4-bromotoluene with phenylboronic acid although the reaction required a higher loading of palladium (Table 1, entries 8–13). Indeed, the loading of palladium showed a significant effect on the performance of the catalyst systems. When the loading of $PdCl_2$ was decreased to 0.001 mol% from 0.01 mol%, the coupling of 4-bromoacetophone with phenylboronic acid became rather sluggish (Table 1, entry 7). *N*,*N*′-Dibenzylbenzimidazolium salt **2** was chosen for further optimization of the reaction conditions considering its easy accessibility. The palladium–ligand ratio did not show significant impact on the model reaction (Table 1, entries 3, 14 and 15). The 2:1 ratio of benzimidazolium salt to palladium gave slightly better results than 1:1 ones. But an excess amount of benzimidazolium salt looked like not necessary for the stabilization of the active catalytic species. DMF proved to be the choice of solvent (Table 1, entries 3, 18 and 19). The presence of some amount (5–10% v/v) of water as co-solvent was crucial to the success of the coupling albeit larger amount of water depressed the reaction (Table 1, entries 2, 16 and 17).

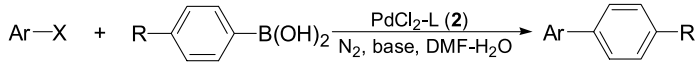
The generally accepted catalytic cycle for the Suzuki coupling reaction involves an oxidative-addition of the arylhalide to a coordinatively unsaturated palladium $L_nPd(0)$, transmetalation between organoboronic acid and the palladium intermediate $L_nPd(Ar)(X)$ assisted by base and a reductive-elimination producing the coupling product and regeneration of $L_nPd(0)$ (Scheme 3).[10]

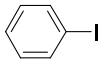
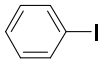
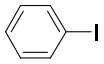
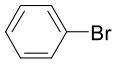
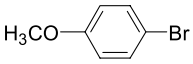
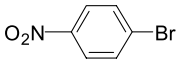
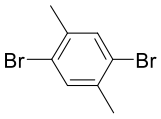
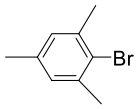
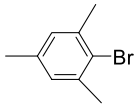
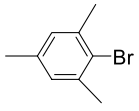
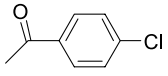
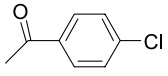
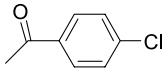
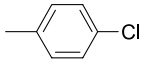
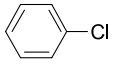
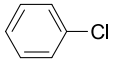
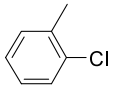
In the model reactions with 4-bromoacetophone or 4-bromotoluene, the behavior of these catalyst systems employing **1**–**5** as supporting ligands looked like to abide by a general rule for phosphine–palladium systems, that is electronic-rich ligands perform better for substrates resistant to oxidative-addition, for example, chlorides, while sterically demanding ligands would show higher activities in coupling reactions if the reductive-elimination is the rate-determining step.[15] For example, the comparative electronic-rich *N*,*N*′-dialkylbenzimidazolium salts **1**, **2** and **4** displayed better performances than **3** and **5** with ethoxycarbonylmethyl and phenyl groups, respectively (Table 1, entries 2–6 and 9–13). Within the sub-sort of *N*,*N*′-dialkylbenzimidazolium salts **1**, **2** and **4**, the catalytic activities to the activated substrate, 4-bromoacetophone, slightly increased with the increase of the bulk of alkyl groups, implying that the reductive-elimination could be a slow step. However, these are in contrast to those reported for the imidazolium catalyst systems, in which electronic-rich *N*,*N*′-dialkylimidazoliums showed lower activities, especially for the substrates resistant to oxidative addition, than the comparative electronic-poor *N*-aryl analogs in Suzuki coupling.[4d] Obviously, further investigations employing benzimidazoliums with various electron properties are needed to shed light on the issue.



Scheme 3. A general catalytic cycle for Suzuki coupling.

Table 2. Suzuki coupling of arylboronic acids with aromatic halides catalyzed by the palladium–benzimidazolium catalyst system



Entry	Ar–X	R	Pd loading (%)	Base	T (°C)	Time (h)	Yield (%)[a]
1		H	0.01	3 equiv K_2CO_3	110	1	93 (100)[b]
2		H	0.0001	3 equiv K_2CO_3	110	1	/ (91)[b]
3		H	0.0001	3 equiv K_2CO_3	110	2	94 (100)[b]
4		H	0.1	3 equiv K_2CO_3	110	2	93 (100)[b]
5		H	0.1	3 equiv K_2CO_3	110	12	76
6		H	0.1	3 equiv K_2CO_3	110	2	92
7[c]		H	0.1	3 equiv K_2CO_3	110	8	90
8		H	0.1	3 equiv K_2CO_3	110	12	16
9		H	0.5	3 equiv K_2CO_3	110	12	44
10[d]		H	3	3 equiv K_2CO_3	110	6	94
11		H	0.5	3 equiv $Ba(OH)_2$	140	12	70
12		H	2	3 equiv $Ba(OH)_2$	140	6	82
13		H	2	3 equiv Cs_2CO_3	140	6	88 (100)[b]
14[d]		H	2	3 equiv Cs_2CO_3	140	12	64
15[d]		*p*-CH_3CO	2	3 equiv Cs_2CO_3	140	12	70
16[d]		*p*-CH_3O	2	3 equiv Cs_2CO_3	140	12	77
17[d]		H	2	3 equiv Cs_2CO_3	140	12	69

[a] Isolated yield and the products were identified by comparison data with those reported in literature, see Section 4 for details.
[b] Conversion determined by GC.
[c] 2.5 equiv phenylboronic acid was used and diarylation product was isolated.
[d] Xylenes (2 mL) were added to maintain a reflux and prevent the chlorides from evaporating.

2.3. Coupling of arylboronic acids with aromatic halides

The Suzuki coupling catalyzed by the $PdCl_2$–**2**–K_2CO_3 system was explored in details (Table 2). At the loading of $PdCl_2$ as low as 0.0001 mol%, the coupling of iodobenzene with phenylboronic acid still proceeded smoothly, indicating the system are highly active for aromatic iodides. The conversion of iodobenzene reached to 91% in 1 h determined by GC, showing TOF up to 9.1×10^5 mol/mol h. We next focused on the Suzuki reactions of usually less reactive electrophiles, aromatic bromides and chlorides using the $PdCl_2$–**2**–K_2CO_3 catalyst system. However, at the low loading of palladium (0.001 mol%) for iodobenzene, bromobenzene remained almost untouched under the otherwise identical conditions. When 0.1 mol% palladium loading was used bromobenzene could be smoothly converted and gave biphenyl in 93% isolated yield. The electronic factor from aromatic halides exerted a significant influence on the coupling. The reactions of unactivated (electron-neutral) arylbromides employing the $PdCl_2$–**2**–K_2CO_3 catalyst system proceeded in good yields while deactivated (electron-rich) arylbromides with electron-donating groups, such as MeO, reacted slowly and the yield decreased to 76% (Table 2, entry 5). In contrast, activated (electron-poor) arylbromides with electron-withdrawing groups, such as CH_3CO and NO_2, reacted fast and provided cross-coupling product in high yields (Table 1, entry 3 and Table 2, entry 6). For an aromatic bromide with modest steric hindrance, 2,5-dibromoxylene, the coupling still went well, giving diarylation product, in 90% yield (Table 2, entry 7). Even, the sterically demanding di-*ortho*-substituted-2-bromomesitylene also reacted well providing the cross-coupling product in 94% yield with an increased loading of palladium (3 mol%) (Table 2, entry 10).

The usually unreactive aromatic chlorides were further explored as the coupling partner using the $PdCl_2$–**2**–K_2CO_3 catalyst system. The low reactivity of aromatic chlorides has been attributed to their resistance to the oxidative addition to Pd(0) species because of a large C_{sp^2}–Cl bond dissociation energy.[16] Due to the low cost of aromatic chlorides and the challenge to activate the C_{sp^2}–Cl bond, it has attracted much attention from both the industry and academic communities to couple aromatic chlorides with arylboronic acids.[15,16] Electron-rich phosphine ligands, such as tri(*tert*-butylphosphine), and *N*,*N*′-diarylsubstituted imidazolium–palladium systems have been reported to be suitable for the Suzuki coupling of aromatic chlorides. Using the $PdCl_2$–**2**–K_2CO_3 catalyst system, which worked well for the coupling of aromatic bromides, only trace amount of the activated chloride, 4-chloroacetophone, was converted. A stronger base $Ba(OH)_2$, a higher loading of palladium (0.5 mol%) and higher reaction temperature (130–140 °C) were required for the reaction to proceed to completion (Table 2, entries 11 and 12). The yields of the cross-coupling increased from 70 to 82% with the increase of the loading of $PdCl_2$ from 0.5 to 2 mol%. However, palladium black was observed on the wall of the reaction vessel with 2 mol% palladium loading, indicating the true catalytic species should be less than 2 mol% and ratio of palladium to benzimidazolium should be lower than 1:2. Further increasing the loading of palladium did not increase the yield of the cross-coupling. When Cs_2CO_3 was used instead of $Ba(OH)_2$, the yield of cross-coupling product reached 88% under the otherwise identical conditions (Table 2, entry 13). Using the $PdCl_2$–**2**–Cs_2CO_3 catalyst system, the cross-coupling of unactivated aromatic chlorides, such as chlorobenzene and 4-chlorotoluene, with arylboronic acids also gave the biaryl products in good yields (Table 2, entries 14–16). In contrast to the electronic effect from aromatic halides, the electronic factor from arylboronic acids showed a negligible influence on the coupling. Sterically hindered 2-chlorotoluene was equally reactive producing the cross-coupling product in 70% yield (Table 2, entry 17).

3. Conclusion

In summary, five representative benzimidazolium salts have been studied in constructing palladium catalyst systems for the Suzuki coupling, from which a practical and highly active palladium catalyst system has been developed from the simplest palladium source $PdCl_2$ and readily available *N*,*N*′-dibenzylbenzimidazolium chloride **2** for the Suzuki coupling of aromatic halides with arylboronic acids. A different substitutent effect has been uncovered with respect to nitrogen substituents of benzimidazolium salts from the imidazolium salt analogs. The $PdCl_2$–**2** catalyst system has proven to be highly efficient for the coupling of a wide array of aromatic halides including chlorides with arylboronic acids. The effective palladium loading could be as low as 0.0001 mol% and 0.01–0.1 mol% for iodide and bromide substrates, respectively. The coupling of aromatic chlorides with arylboronic acids also gave good results using the $PdCl_2$–**2** catalyst system with 2 mol% palladium loading and Cs_2CO_3 as the base. Electron-deficient aromatic halides reacted faster and gave higher yields than the electron-rich ones, indicating electronic factor from aromatic halides exerted a significant influence on the Suzuki coupling catalyzed by the palladium–benzimidazolium system while the electronic effect from the arylboronic counterparts is almost negligible. The obvious advantages of the $PdCl_2$–**2** system lie in its ready availability and yet high catalytic activity. These results suggest that the *N*-heterocyclic carbenes from benzimidazolium salts are promising ligands for the homogenous transition metal catalysts. Further modification of the benzimidazolium salts and applications in transition metal catalyzed organic transformations are in progress in our laboratory.

4. Experimental

4.1. General

All reactions and manipulations were performed in air unless otherwise indicated. All the commercially available chemicals, reagents and solvents, were used as received with an exception of iodobenzene that was distilled prior to use. ^1H and ^{13}C NMR spectra were recorded on a Bruker 500 spectrometer using the residue of deuterated solvents as the internal standard. GC and Mass analyses were performed using a Hewlett Packard Model HP 6890 Series with HP-5 column. Elemental analysis was performed at the Center of Analysis and Structure Determination of ECNU.

4.2. Synthesis of benzimidazolium salts

4.2.1. *N,N′*-Dibutylbenzimidazolium bromide 1. To a 50 mL flask charged with benzimidazole (1.18 g, 10 mmol) was added 10 mL 30% NaOH(aq) and 1.5% equiv $Bu_4N^+Br^-$ (TBAB) (50 mg, 0.15 mmol) followed by 1.2 equiv 1-bromobutane (1.3 mL, 12 mmol) at room temperature. The mixture was stirred at 55 °C for 3 h before being poured into 50 mL water and extracted with toluene (20 mL×3). The toluene extracts was dried with Na_2SO_4, filtrated and added to a solution of 1-bromobutane (2.3 mL, 20 mmol) in a 100 mL flask. The mixture was refluxed for 6 h and slowly cooled to room temperature giving *N,N′*-dibutylbenzimidazolium bromide **1** as a white powder, which was further purified by recrystallization from CH_2Cl_2 to give **1** as colorless crystals 1.9 g (61%, two steps), mp: 140–142 °C. ^{1}H NMR ($CDCl_3$, 25 °C), δ, ppm: 11.33 (1H, s, H2), 7.77–7.80 (2H, m, H4, H7), 7.67–7.70 (m, 2H, H5, H6), 4.67 (4H, t, J=7.0 Hz, CH_2), 2.24 (2H, s, H_2O), 2.05–2.10 (4H, m, CH_2), 1.45–1.52 (4H, m, CH_2), 0.98–1.01 (6H, t, J=7 Hz, CH_3). ^{13}C NMR ($CDCl_3$, 25 °C), δ, ppm: 142.5, 131.3, 127.2, 113.2, 47.5, 31.4, 19.8, 13.6. Anal. Calcd for $C_{15}H_{25}N_2OBr$ (**1**·H_2O): C, 54.71; H, 7.65; N, 8.51. Found: C, 54.86; H, 7.55; N, 8.28.

4.2.2. *N,N′*-Dibenzylbenzimidazolium chloride 2. A similar procedure to that for the preparation of **1** was adopted employing benzimidazole (5.9 g, 50 mmol) to provide **2** as colorless microcrystals 10.2 g (61%), mp: 210–212 °C. ^{1}H NMR (DMSO, 25 °C), δ, ppm: 10.36 (1H, s, H2), 7.98–8.01 (2H, m, H4, H7), 7.63–7.65 (m, 2H, H5, H6), 7.56 (4H, d, J=7.2 Hz, Ph), 7.35–7.45 (6H, m, Ph), 5.84 (4H, s, CH_2Ph). ^{13}C NMR (DMSO, 25 °C), δ, ppm: 142.8, 133.9, 130.9, 128.8, 128.5, 128.2, 126.6, 113.9, 49.8. Anal. Calcd for $C_{21}H_{21}N_2OCl$ (**2**·H_2O): C, 71.48; H, 6.00; N, 7.94. Found: C, 71.24; H, 5.87; N, 7.68.

4.2.3. *N,N′*-Bis-ethoxycarbonylmethyl benzimidazolium bromide 3. A similar procedure to that for the preparation of **1** was adopted employing benzimidazole (1.18 g, 10 mmol) to provide **3** as colorless microcrystals 3.2 g (86%), mp: 157–159 °C. ^{1}H NMR (DMSO, 25 °C), δ, ppm: 9.80 (1H, s, H2), 8.08–8.10 (2H, m, H4, H7), 7.71–7.73 (2H, m, H5, H6), 5.70 (4H, s, CH_2CO_2Et), 4.23 (4H, q, J=7.2 Hz, CH_2), 1.26 (6H, t, J=7.2 Hz, CH_3). ^{13}C NMR (DMSO, 25 °C), δ, ppm: 166.4, 144.3, 131.0, 126.9, 113.9, 62.0, 47.7, 13.9. Anal. Calcd for $C_{21}H_{21}N_2OCl$ (**3**·H_2O): C, 46.29; H, 5.44; N, 7.20. Found: C, 46.08; H, 5.23; N, 6.88.

4.2.4. *N,N′*-Dibenzhydrylbenzimidazolium chloride 4. To a 100 mL flask charged with 1,2-diaminobenzene (1.08 g, 10 mmol) was added 20 mL 30% NaOH(aq) and 1.5% equiv $Bu_4N^+Br^-$ (TBAB) (50 mg, 0.15 mmol) followed by 2.5 equiv benzhydryl chloride (5.0 g, 25 mmol) at room temperature. The mixture was stirred at 55 °C for 8 h before being poured into 50 mL water and extracted with ether (20 mL×3). The ether extracts were dried over Na_2SO_4 and concentrated. The resulting residue was purified by flash chromatography through a short pad of silica gel (eluent: ethyl acetate/petroleum ether=1:50 v/v). Spectroscopically pure *N,N′*-dibenzhydryl-1,2-diaminobenzene was obtained as a yellow powder (2.5 g, 57%). To the yellow powder in 100 mL flask was added 50 mL $HC(OEt)_3$, 0.50 mL HCl(con. aq) and two drops of HCO_2H. The resulting mixture was stirred under nitrogen at 80 °C for 2 h. A white fine powder formed was collected by filtration. Recrystallization of the residue from EtOH gave *N,N′*-dibenzhydrylbenzimidazolium chloride **4**, 2.39 g (86%), mp: 245–247 °C. ^{1}H NMR (DMSO, 25 °C), δ, ppm: 9.15 (1H, s, H2), 7.56–7.60 (6H, m, overlapping), 7.41–7.50 (20H, m, overlapping). ^{13}C NMR (CD_3OD, 25 °C), δ, ppm: 142.1, 136.9, 133.7, 130.7, 130.7, 129.5, 128.6, 116.3, 67.6. Anal. Calcd for $C_{33}H_{27}N_2Cl$: C, 81.38; H, 5.59; N, 5.75. Found: C, 80.88; H, 5.63; N, 5.58.

4.2.5. *N,N′*-Diphenylbenzimidazolium chloride 5. To a 100 mL flask charged with 1,2-diaminobenzene (1.08 g, 10 mmol) in 30 mL DMSO was added 0.2 equiv CuI (0.39 g, 2.0 mmol), 0.4 equiv L-proline (0.46 g, 4.0 mmol), 5 equiv iodobenzene (5.6 mL, 50 mmol) and 4.1 equiv K_2CO_3 (5.7 g, 41 mmol) under nitrogen at room temperature. The mixture was stirred at 80 °C for 18 h before being cooled and poured into 50 mL water and extracted with ethyl acetate (30 mL×3). The extracts were dried with Na_2SO_4 and solvents were removed under reduced pressure. The residue was purified by flash chromatography through a short pad of silica gel (eluent: ethyl acetate/petroleum ether=1:50 v/v). *N,N′*-Diphenyl-1,2-diaminobenzene was obtained as a slight yellow powder containing about 2–3% isomers (0.78 g, 30%). To the powder in 50 mL flask was added 20 mL $HC(OEt)_3$, 0.30 mL HCl(con.) and two drops of HCO_2H. The resulting mixture was stirred under nitrogen at 80 °C for 2 h. After removal of solvents, the slight yellow residue was purified by recrystallization from EtOH to provide slight yellow microcrystals 0.83 g (90%), mp: 241–243 °C (dehydrolyze 127–131 °C). ^{1}H NMR ($CDCl_3$, 25 °C), δ, ppm: 11.19 (1H, s, H2), 8.10 (4H, d, J=7.0 Hz, Ph), 7.79–7.81 (2H, m, H4, H7), 7.62–7.72 (6H, m, Ph), 7.29–7.35 (2, m, H5, H6). ^{13}C NMR ($CDCl_3$), δ, ppm: 141.9, 132.8, 131.6, 131.1, 130.7, 128.3, 125.5, 114.1. Anal. Calcd for $C_{19}H_{17}N_2ClO$ (**5**·H_2O): C, 70.26; H, 5.28; N, 8.62. Found: C, 69.80; H, 5.05; N, 8.46.

4.3. General procedure for Suzuki coupling of aromatic halides with arylboronic acids

Under an atmosphere of nitrogen to a 25 mL Schlenk flask charged with 1.0 mmol arylhalide, 1.1–1.2 mmol arylboronic acid and a base (3 equiv) in DMF (10 mL)–H_2O (0.5 mL) were added stock solutions of $PdCl_2$ and benzimidazolium salts in DMF, respectively. The flask was placed and stirred in an oil bath at the temperature as required. The progress of the reactions was monitored by TLC or GC. After be cooled to room temperature, the mixture was poured into water and extracted with ether. Removal of solvents gave the crude products, which were purified either by flash chromatography or by recrystallization.

4.4. Data for biaryls

4.4.1. 4-Acetylbiphenyl. Mp: 121–123 °C (lit.[17] 120–121 °C). ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 8.00 (2H, d, J=8.3 Hz), 7.69 (2H, d, J=8.3 Hz), 7.63 (2H, dd, J_1=7.2 Hz, J_2=1.1 Hz), 7.46 (2H, t, J=7.5 Hz), 7.39 (1H,

t, 7.3 Hz), 2.62 (s, 3H, $COCH_3$. EI-MS: *m/z* (relative intensity) 196 (99%, M^+), 181 (100%).

4.4.2. 4-Methylbiphenyl. Mp: 48–50 °C (lit.[18] 44–46 °C, 49–50 °C). ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 7.58 (2H, dd, $J_1=8.0$ Hz, $J_2=1.0$ Hz), 7.50 (2H, d, $J=$ 7.5 Hz), 7.38–7.44 (2H, m), 7.29–7.33 (1H, m), 7.24 (2H, d, $J=8.0$ Hz), 2.38 (s, 3H, CH_3). EI-MS: *m/z* (relative intensity) 168 (100%, M^+).

4.4.3. Biphenyl. Mp: 69–70 °C (lit.[18b] 69–72 °C). ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 7.60 (4H, dd, $J_1=$ 7.5 Hz, $J_2=1.0$ Hz), 7.42–7.46 (4H, m), 7.32–7.36 (2H, m). EI-MS: *m/z* (relative intensity) 154 (100%, M^+).

4.4.4. 4-Nitrobiphenyl. Mp: 112–113 °C (lit.[17,19] 102–103 °C, 114–114.5 °C). ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 8.29 (2H, d, $J=8.5$ Hz), 7.93 (2H, d, $J=8.5$ Hz), 7.62 (2H, d, $J=7.5$ Hz), 7.49 (2H, t, $J=7.5$ Hz), 7.44 (1H, t, $J=7.5$ Hz). EI-MS: *m/z* (relative intensity) 199 (99%, M^+), 169 (59%), 152 (100%).

4.4.5. 1,4-Diphenyl-2,5-dimethylbenzene. Mp: 180–182 °C (lit.[20] 180 °C). ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 7.38–7.44 (4H, m), 7.31–7.36 (6H, m), 7.15 (2H, s), 2.27 (6H, s, CH_3). EI-MS: *m/z* (relative intensity) 258 (100%, M^+).

4.4.6. 1-Phenyl-2,4,6-trimethylbenzene.[21] Colorless oil. ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 7.35–7.50 (2H, m), 7.30–7.35 (1H, m), 7.15 (2H, d, $J=7.5$ Hz), 6.95 (2H, s), 2.33 (3H, s), 2.00 (6H, s). EI-MS: *m/z* (relative intensity): 196 (98%, M^+), 181 (100%).

4.4.7. 2-Methylbiphenyl.[22] Slight yellow oil. ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 7.35–7.40 (2H, m), 7.26–7.33 (3H, m), 7.20–7.25 (4H, m), 2.25 (3H, s, CH_3). EI-MS: *m/z* (relative intensity) 168 (100%, M^+).

4.4.8. 4-Methoxybiphenyl. Mp: 87–88 °C (lit.[18a,23] 83–84 °C, 87 °C). ^{1}H NMR ($CDCl_3$, 500 MHz, 25 °C), δ, ppm: 7.52–7.56 (4H, m), 7.35–7.50 (2H, m), 7.30 (1H, t, $J=$ 7.5 Hz), 7.00 (2H, d, $J=8.5$ Hz), 3.85 (3H, s, CH_3O). EI-MS: *m/z* (relative intensity) 184 (84%, M^+), 169 (53%), 141 (88%), 115 (100%).

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