Palladium-catalyzed aminations of aryl halides with phosphine-functionalized imidazolium ligands†

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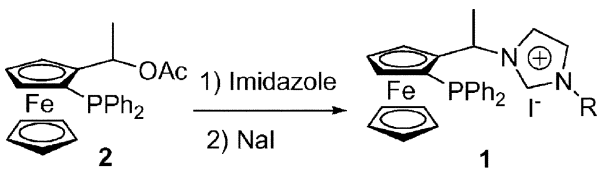
A series of 1-(2-diphenylphosphinoferrocenyl)ethyl-3-substituted imidazolium iodides [3-substituent = methyl (**1a**); isopropyl (**1b**); *tert*-butyl (**1c**); 1-adenosyl (**1d**); cyclohexyl (**1e**); 2,6-dimethylphenyl (**1f**); 2,4,6-trimethylphenyl (**1g**); 2,6-diisopropylphenyl (**1h**)] have been prepared and evaluated as ligands in the palladium-catalyzed aminations of aryl halides with various amines. The scope of the coupling process was carried out for various aryl bromides and chlorides with the catalysts generated *in situ* from a mixture of $Pd(OAc)_2$ and **1** in the presence of a base. NaO^{t}Bu was found the choice of base in combination with dioxane, toluene, or DME as solvent, although NaOH or Cs_2CO_3 promoted the coupling of 4-bromotoluene with morpholine in moderate conversion. The steric hindrance from the 3-substituent of imidazolium in the hybrid-bidentate chelating system was found to be only beneficial to the substrates without *ortho*-substituents. The more sterically hindered **1d** or **1h** promoted the coupling of bromobenzene with morpholine in nearly quantitative conversion with 0.2 mol% of palladium loading in the presence of NaO^{t}Bu at 110 °C, and 94% of conversion was afforded with the less sterical demanding **1a** for a longer time. However, for the substrates with *ortho*-substituents, higher conversions were achieved with **1a**. The $Pd(OAc)_2$/**1d** catalytic system was also active for deactivated aryl chloride, and 71% isolated yield for the desired product was realized for coupling of 4-chloroanisole with morpholine at 2 mol% of catalyst loading. The developed catalyst system has been applied successfully to the synthesis of a key building block for a type of functional polymers.

Introduction

Recently, the chemistry of *N*-heterocyclic carbenes (NHCs) and their transition-metal complexes has received much attention because these carbenes impact significantly on the catalytic performances of their ligating complexes for several organic transformations.[1] Exploring various NHCs as supporting ligands in transition-metal catalyzed reactions,[2] including asymmetric syntheses,[3] has been one of the current focuses in catalysis. For palladium-catalyzed cross-coupling reactions, monodentate NHCs with high steric demands as supporting ligands have allowed to employ deactivated aryl chlorides as substrates under mild reaction conditions.[4] The large steric demand of monodentate NHCs realises the possibility of a 12-electron Pd(0) species as a genuine catalyst and the readily available coordination sites of such a 12-e species greatly facilitates the oxidative addition of palladium to aryl chlorides. After oxidative addition of the 12e species with aryl halides, the catalytic species in the following steps should involve three-coordinate palladium complexes which are believed to be beneficial for reductive elimination.[5] Bidentate ligands containing NHCs have found widespread applications.[6] Theoretical calculations indicated that certain bidentate chelating ligands could favor the oxidative-addition process[7] and improve the stability of the catalyst which may exclude the side pathway of β-H elimination. Hybrid bidentate phosphine/NHC ligands have been explored in the Heck[6g] and the Suzuki–Miyaura[6h] reactions and found to be effective.

In the palladium-catalyzed cross-coupling, the optimal bite angle (*ca.* 102°) induced by the chelating ligand plays a crucial role on the activity and selectivity.[8] Chung and co-workers found that the bite angle of an NHC/phosphine Rh complex derived from 1-(2-diphenylphosphinoferrocenyl)ethyl-3-methylimidazolium iodide (**1a**, see Scheme 1) is 97.2°.[9] This value of the bite angle, close to 102°, has prompted us to evaluate the performance of this type of diphenylphosphinoferrocenyl-functionalized NHCs in palladium-catalyzed Suzuki–Miyaura cross-coupling reactions. The $Pd(OAc)_2$/**1d** catalyst system exhibits high efficiency and stability, indicated by the up to 20 000 turnover numbers (TONs) for coupling 4-bromotoluene with phenylboronic acid.[10]



R = Me (**1a**), ^{i}Pr (**1b**), ^{t}Bu (**1c**), 1-Ad (**1d**), Cy (**1e**), 2,6-dimethylphenyl (**1f**), 2,4,6-trimethylphenyl (**1g**), 2,6-diisopropylphenyl (**1h**)

Scheme 1 Phosphine-functionalized imidazolium salts **1**.

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The *N*-aryl moiety is often observed in natural products and pharmaceutical and medicinal compounds,[11] as well as being an important functional unit in materials.[12] Remarkable advances have been achieved in palladium-catalyzed aminations of aryl halides or halide equivalents.[13] Since the phosphine-functionalized imidazolium salts **1** have been effective in the palladium-catalyzed Suzuki–Miyaura reaction,[10] it would be of interest to explore their potential in the aminations of aryl halides. There have been no reports applying phosphine-functionalized *N*-heterocyclic carbenes in palladium-catalyzed amination reactions so far.

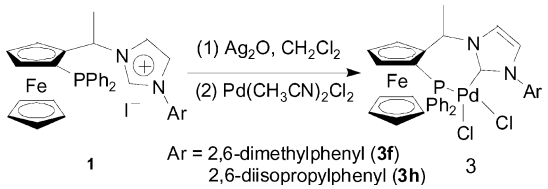
Results and discussion

Preparation of phosphinoferrocenyl-functionalized imidazolium salts

Since the bite angle of the rhodium(I) complex derived from **1a** is 97.2°,[9] it is reasonable to predict the bite angle of the palladium(II) complex derived from **1** would be close to this value since they are both d^8 with square-planar structure. Steric hindrance around the palladium center contributes to the catalytic activity when using unactivated aryl chlorides as substrates.[4] However, the rigid steric bulkiness may disfavor the couplings between the substrates with *ortho*-substituents. Recently, Glorius and co-workers introduced the notion of the *flexible* steric bulkiness, which could be varied: to be large to meet steric hindrance required for the high activity of catalyst; to be small to favor the couplings with sterically hindered substrates.[4b] Therefore, a series of 1-(2-diphenylphosphinoferrocenyl)ethyl-3-substituted imidazolium iodides with different size of 3-substituents were synthesized to reveal steric effects in the hybrid phosphine/NHC system for palladium-catalyzed amination. From the readily available racemic ferrocenyl derivative **2** the desired phosphine-functionalized imidazolium salts **1** were prepared *via* the substitution reaction of the OAc group with imidazoles in 79–87% yields (Scheme 1). The imidazolium salts, which are stable under nitrogen but slowly oxidized in air in solution, were characterized by ^{1}H, ^{13}C and ^{31}P NMR spectroscopy and HRMS or elemental analysis. A singlet $^{31}P\{^1H\}$ NMR peak observed around δ −26 for **1** is expected for diphenylferrocenylphosphines and consistent with the known compound **1a**.[9] The carbenic protons of **1** observed in the range of δ 9.2–10.2 reflect the high acidity of the 2-proton of the imidazolium ions.

Syntheses of phosphine/NHC palladium complexes

The free carbene route has been used to prepare the phosphine/NHC rhodium complex derived from the imidazolium salt **1a**.[9] We then tried another protocol to enrich the coordination chemistry of the phosphine/NHC bidentate ligands, *e.g.* the silver carbene transfer path, to attain the square-planar complex.[14] Treating the salt **1f** or **1h** with half of equiv. of Ag_2O in dichloromethane for 2 h at room temperature, and then adding $Pd(NCMe)_2Cl_2$ directly to the mixture led to the palladium complexes **3f** and **3h** in 34 and 41% yields, respectively (Scheme 2). Compared to the ligand, the $^{31}P\{^1H\}$ NMR peaks for **3f** and **3h** were shifted downfield to δ 8.0 and 7.7, respectively, as expected upon metal coordination. The ^{1}H NMR signals at δ 9.91 and 10.22 for H-2 of imidazolium **1f** and **1h**, respectively, disappeared



Scheme 2 Synthesis of complexes **3**.

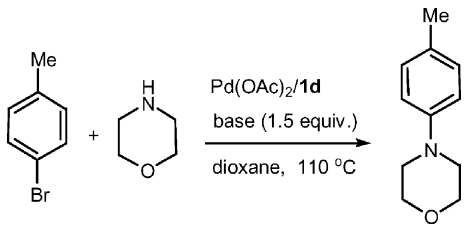
in complexes **3f** and **3h**, indicating the successful deprotonation of the salts into the carbenes. The HRMS data for **3f** and **3h** were in good agreement with their elemental compositions and suggested that they are monomeric palladium complexes.

Since the isolated yields for the palladium complexes are moderate and their activities for Suzuki–Miyaura cross-coupling reactions were found to be comparable to those generated *in situ*,[10] we decided to take advantage of generating the catalysts *in situ* in evaluating their catalytic performance.

Effect of the base on the amination of 4-bromotoluene with morpholine

A survey of bases for the palladium-catalyzed amination of 4-bromotoluene with morpholine using **1d** as ligand, which shows high activity combined with $Pd(OAc)_2$ for Suzuku–Miyaura cross-couplings,[10] is provided in Table 1. The catalytic reactions were all set up on the benchtop and the solid components were weighed in the air. Cs_2CO_3, which is a highly effective base for the $Pd(OAc)_2$/**1d**-catalyzed Suzuki–Miyaura coupling of aryl bromides with phenylboronic acid, showed moderate activity for amination of 4-bromotoluene and morpholine (Table 1, entry 1). A remarkable increasing in activity was observed with NaO^{t}Bu as base: >99% conversion of 4-bromotoluene with 94% isolated yield was achieved within 1 h with 1 mol% catalyst loading at 110 °C (Table 1, entry 2). The performances of NaOH and K_3PO_4 as bases for the phosphine-functionalized NHC ligands are also moderate,

Table 1 Effect of the base on the rate of the $Pd(OAc)_2$/**1d** catalyzed aminations of 4-bromotoluene with morpholine[a]



Entry	Base	*t*/h	Yield[b] (%)
1	Cs_2CO_3	16	32 (22)
2	NaO^{t}Bu	1	99 (94)
3[c]	NaO^{t}Bu	2	99 (93)
4	K_2CO_3	16	18
5	NaOH	16	41 (28)
6	K_3PO_4	16	30
7	KF	16	<5

[a] *General conditions*: 5 mmol of 4-bromotoluene, 1.2 equiv. of morpholine, 1.5 equiv. of base, 10 mL of dioxane, 1 mol% of $Pd(OAc)_2$/**1d** (1 : 1). [b] GLC conversion calibrated *via* internal standard. Isolated yields in parentheses. [c] Toluene used as solvent.

and other inorganic bases such as K_2CO_3 and KF resulted in lower yields. The choice of base for the hybrid phosphine/NHC as ligand in the palladium-catalyzed aminations of aryl halides is consistent with literature work on other ligands such as bidentate phosphines,[15] monodentate phosphines,[16] and mono-NHCs.[4,17]

Influence of the imidazolium salts on the amination of bromobenzene with morpholine

An investigation of the activity of the synthesized phosphine-functionalized imidazolium salts was carried out with NaO^{t}Bu as base and $Pd(OAc)_2$ as palladium source at 110 °C. Since 1 mol% of palladium loading resulted in complete conversion of 4-bromotoluene in the amination with morpholine within 1 h, catalyst loading was decreased to 0.2 mol% for differentiating the substituent size effects. The results are summarized in Table 2. The phosphine-functionalized imidazolium salts **1** are comparably effective ligands in the above reaction conditions for amination of bromobenzene with morpholine, although **1c**, **1d**, **1g** and **1h** are a little better. The results indicate: (1) the large bite angle created by the ferrocenyl backbone and the electronic properties of the coordinating atoms play an importance role in the catalytic performance of the hybrid phosphine/NHC systems **1** as supporting ligands for the palladium-catalyzed coupling of 4-bromobenzene with morpholine; (2) high steric demand of the system **1** also benefits the aminations of the aryl bromides without *ortho*-substituents such as 4-bromotoluene or bromobenzene with morpholine in a minor way. Herein it should pointed out that much better results have been obtained so far by the groups of Hartwig,[15] Buchwald,[17] Beller,[5a] Nolan,[18] *etc.*

Amination with the prepared palladium complexes

Although no differences were observed for palladium-catalyzed Suzuki–Miyaura cross-coupling reactions using the catalysts generated *in situ* or the prepared palladium complexes **3**,[10] we were still interested in the situation in the Hartwig–Buchwald amination reactions. Under the same reaction conditions as indicated above, the amination of 4-bromotoluene with morpholine with the palladium complexes was complete in 12 h (Table 3, entries 3 and 4). Considering the induction time and the probable experimental error, the prepared palladium complexes **3** are also comparable

Table 2 Influence of imidazolium salts on $Pd(OAc)_2$-catalyzed amination of 4-bromotoluene with morpholine[a]

Entry	Ligand	*t*/h	Yield[b] (%)
1	**1a**	24	94 (88)
2	**1b**	24	96 (89)
3	**1c**	16	99 (93)
4	**1d**	16	99 (96)
5	**1e**	24	96 (91)
6	**1f**	24	98 (93)
7	**1g**	16	99 (95)
8	**1h**	16	99 (94)
9[c]	**1d**	16	99 (94)
10[d]	**1d**	18	98 (92)

[a] *General conditions*: 5 mmol of bromobenzene, 1.2 equiv. of morpholine, 1.5 equiv. of NaO^{t}Bu, 10 mL of dioxane, 0.2 mol% of $Pd(OAc)_2$/**1** (1 : 1). [b] GLC conversion calibrated *via* internal standard. Isolated yields in parentheses. [c] Toluene used as solvent. [d] DME used as solvent.

Table 3 Comparison of the catalysts generated *in situ* with isolated samples for the amination of 4-bromotoluene with morphine[a]

Entry	Catalyst	*t*/h	Yield[b] (%)
1	$Pd(OAc)_2$/**1f**[c]	24	98 (93)
2	$Pd(OAc)_2$/**1h**[c]	16	>99 (94)
3	**3f**	12	>99 (95)
4	**3h**	12	>99 (97)

[a] *General conditions*: 5 mmol of 4-bromotoluene, 1.2 equiv. of morpholine, 1.5 equiv. of NaO^{t}Bu, 10 mL of dioxane, 0.2 mol% of catalyst. [b] GLC conversion calibrated *via* internal standard. Isolated yields in parentheses. [c] $Pd(OAc)_2$/**1** (1 : 1).

with the catalysts generated *in situ* for the aminations of aryl bromides with amines. Two steps are needed for preparing the complexes **3** with moderate isolated yields, so further evaluation of the synthesized phosphine/NHC system as supporting ligands was carried out with the advantage of generating catalysts *in situ*.

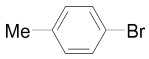
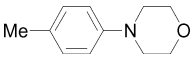
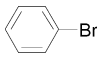
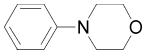
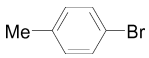
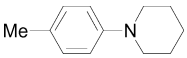
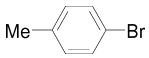
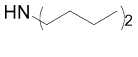
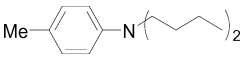
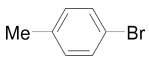
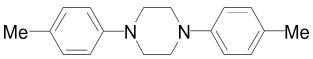
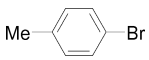
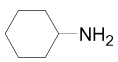
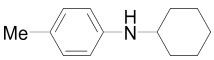
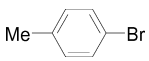
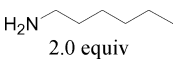
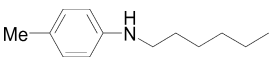
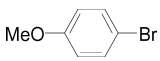
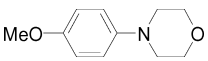
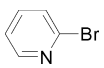
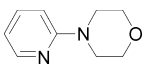
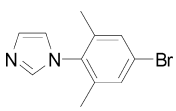
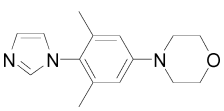
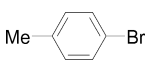
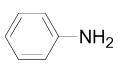
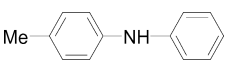
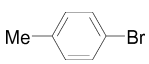
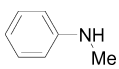
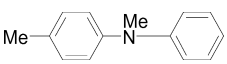
Extended scope and application of aminations of aryl bromides

As shown in Table 4, the procedure employing the catalyst system $Pd(OAc)_2$/**1d** is effective in aminations of aryl bromides with various amines. For amination of bromobenzene with morpholine the catalyst loading could be further decreased to 0.1 mol% and the reaction was complete within 24 h with 95% isolated yield for the desired product (Table 4, entry 2). The catalyst system $Pd(OAc)_2$/**1d** is also applicable to heteroaryl bromides. Using 2-bromopyridine and morpholine as substrates leads to a 94% isolated yield at 0.2% loading of catalyst (entry 10). The weakly binding effect from heterocyclic nitrogen to depress the coupling reactions was not observed for the catalyst system $Pd(OAc)_2$/**1d** as well for another case (entry 11).[18] The catalytic system is very effective for cyclic secondary amines: deactivated aryl bromide could be used as substrate (entry 9) and double arylation of piperazine could be achieved with an excess of aryl bromide (entry 6) in 88% yield at 0.5 mol% loading of catalyst. Entry 5 shows the catalyst system could couple an acyclic secondary amine with an aryl bromide in high yield. Primary alkylamine coupling with aryl bromide required a longer time, but 83–87% yields of the desired products were still realized with 2 equiv. of amines and at 1 mol% loading of catalyst (entries 7 and 8). The catalyst system $Pd(OAc)_2$/**1d** is not suitable for coupling aniline with aryl bromides. The supporting ligand **1d** is effective, however, in combination with $Pd_2(dba)_3$ at higher reaction temperature and 1% loading of catalyst (entries 12 and 13).

Aminations of aryl chlorides

Aryl chlorides are attractive coupling partners because they are widely available and inexpensive. With the optimal conditions for amination of aryl bromides, the catalyst systems were tested using aryl chlorides with morpholine. 2-Chloropyridine couples with morpholine smoothly in 94% yield in 16 h at 1 mol% of loading of $Pd(OAc)_2$/**1d** (Table 5, entry 4). Activated aryl chloride as substrate leads to a 87% isolated yield (entry 3). This system is also applicable to deactivated aryl chlorides in higher (2 mol%) catalyst loading and only minimal dehalogenation products were observed. However, no activity of the present system was found

Table 4 $Pd(OAc)_2$/**1d**-catalyzed aminations of aryl bromides with amines[a]

Entry	ArBr	Amine	Product	Pd (mol%)	*t*/h	Yield (%)
1				0.2	6	96
2				0.1	24	95
4				0.5	6	93
5				0.5	6	92
6	 2.4 equiv			0.5	6	88
7		 2.0 equiv		1	16	87[a]
8		 2.0 equiv		1[b]	16	83
9				1	16	89
10				1	16	94
11		 1.5 equiv		0.2	16	71
12				2[b]	24[c]	58
13				2[b]	24[c]	70

[a] *General conditions*: 1 mmol of ArBr; 1.2 equiv. of amine; 1.5 equiv. of NaO^{t}Bu; 2 mL of dioxane; $Pd(OAc)_2$/**1d** (1 : 1), 110 °C (oil bath). [b] $Pd_2(dba)_3$ was used as the palladium source; toluene as solvent. [c] 120 °C.

for aryl tosylates as an aryl halide equivalent or for indole and imidazole as amine (data not shown).

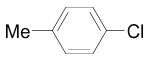
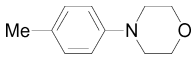
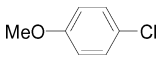
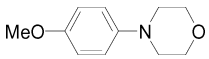
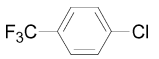
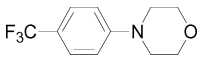
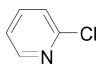
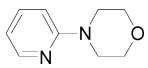
Aminations of aryl halides with *ortho*-substituents

For the present phosphine/NHC chelating ligands, it has been found that increasing steric demand of substituents on the imidazole provides little benefit for the catalytic activities of their supported palladium catalysts for coupling the aryl bromides without *ortho*-substituents such as 4-bromotoluene and bromobenzene with morpholine. The bite angles and election character of the ligating atoms are likely the major factors for the catalytic activity. For coupling aryl halides with *ortho*-substituents, the steric demand of ligands may retard reaction owing to steric repulsion between the substrate and the catalyst. Therefore a notion of a flexible steric demand has been introduced in the ligand design for coupling reactions.[4b] We suspect that the effect from the steric repulsion becomes more obvious in the chelating system and carried out experiments to compare the catalytic performance between the ligand **1a** with the smallest 3-substituent and **1d** with the largest one for palladium-catalyzed aminations of *ortho*-substituted aryl halides. Table 6 shows that the performance of **1d** is indeed worse than that of **1a**. In the case of aryl bromide with two *ortho*-substituents, the effect becomes more profound (Table 6, entry 4).

Synthesis of a building block

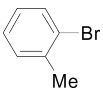
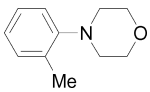
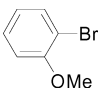
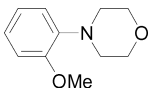
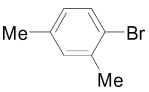
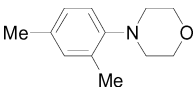
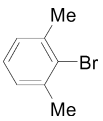
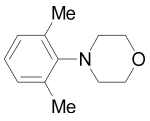
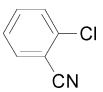
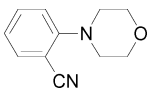
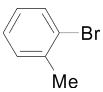
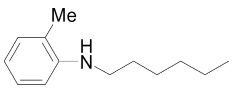
Aryl piperazines are an important type of medicinal compounds and have been pursued through palladium-catalyzed amination

Table 5 $Pd(OAc)_2$/**1d**-catalyzed amination of aryl chlorides with morphine[a]

Entry	ArCl	Product	Pd (mol%)	T/°C	t/h	Yield (%)
1[b]			2	120	24	79[c]
2[b]			2	120	24	71[d]
3			1	110	16	87
4			1	110	16	94

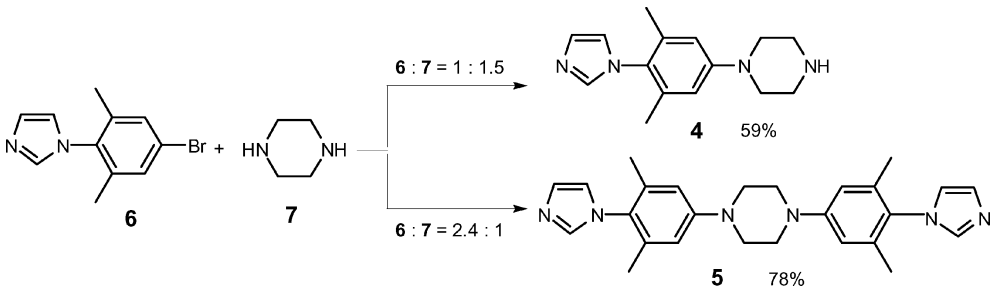
[a] *General conditions*: 1 mmol of ArCl; 1.2 mmol of morphine; 1.5 mmol of NaO^{t}Bu; 2 mL of dioxane; Pd/**1d** (1 : 1). [b] 1.5 Equiv. of amine; 2.0 equiv. of NaO^{t}Bu. [c] $Pd_2(dba)_3$ was used as the palladium source; toluene as solvent. [d] 2% of the dehalogenation product was observed.

Table 6 Palladium catalyzed amination aryl halides with *ortho*-substituents with supporting ligands **1a** and **1d**[a]

Entry	ArX	Product	Ligand	Yield [b,c] (%)
1			**1a** **1d**	>99 (93) 96 (91)
2			**1a** **1d**	>99 (91) 91 (87)
3			**1a** **1d**	>99 (90) 83 (81)
4			**1a** **1d**	84 (72) 62 (46)
5			**1a** **1d**	>99 (90) 94 (83)
6			**1a** **1d**	>99 (89) 97 (84)

[a] *General conditions*: 1 mmol of ArX; 1.2 equiv. of amine; 1.5 equiv. of NaO^{t}Bu; 2 mL of dioxane; 2 mol% $Pd(OAc)_2$; $Pd(OAc)_2$/**1** (1 : 1); 16 h; 110 °C. [b] GLC conversion calibrated *via* internal standard. Isolated yield in parentheses. [c] Around 3% of the dehalogenation product was observed.

reactions.[19] The present catalytic system is effective for preparing aryl piperazines. We are pursuing a new type of imidazoliun polymer and have designed the building block **5**. Imidazolium salts are important compounds as ligands and reaction media. The ratio of aryl bromide to piperazine determines the mono- or di-arylation of piperazine (see Scheme 3). We were pleased that the present catalyst system worked well to reach the building block in 78% yield with 0.5 mol% of catalyst loading.



Scheme 3 Arylation of piperazine.

Conclusions

In summary, diphenylferrocenylphospine-functionalized imidazolium salts are effective ligands for palladium-catalyzed Hartwig–Buchwald aminations involving aryl bromides and aryl chlorides. The $Pd(OAc)_2$–**1**–NaO^{t}Bu system was found to be very efficient for amination of aryl bromides with a variety of primary and secondary cyclic and acyclic alkyl amines. The bulkiness of the 3-substituents on the imidazole-ring of the hybrid phosphine/NHC chelating ligands was found to benefit the coupling of aryl halides without *ortho*-substituents, but retard those with *ortho*-substituents. This is an interesting clarification for palladium-catalyzed coupling reactions supported by chelating ligands. The developed system has been successfully applied to the synthesis of a new building block for a functional polymer.

Experimental

General considerations

All amines, aryl bromides and chlorides (Aldrich or Acros) were used as received. 3-Methyl-1-[(2-diphenylphosphinoferrocenyl)-ethyl]-3*H*-imidazolium iodide (**1a**) was prepared according to the literature method.[9] Palladium acetate and tris-(dibenzylideneactone)dipalladium(0) were purchased from Strem Chemical Company. 1,4-Dioxane, toluene and THF were distilled under nitrogen from sodium benzophenone ketyl prior to use. Cs_2CO_3, K_2CO_3, KF, NaOBu^t, K_3PO_4 and NaOH were used as received. All reactions and manipulations involving air- and/or moisture-sensitive compounds were carried out using standard Schlenk techniques under nitrogen. NMR spectra were recorded on a BRUKER DRX 400 MHz or Varian INOVA 400 MHz (^{1}H 400 MHz; ^{13}C 100 MHz; ^{31}P 162 MHz) spectrometers. Elemental analyses were obtained on an Elementar Vario EI analyzer. High-resolution mass spectra (HRMS, ESI) were obtained on a Micromass Q-Tof Micro (Micromass Inc., Manchester, England).

Synthesis

3-(Isopropyl)-1-[(2-diphenylphosphinoferrocenyl)ethyl]-3*H*-imidazolium iodide (1b). *Representative procedure*: Under nitrogen, 6.0 mL of CH_3CN and 3.0 mL of H_2O was added to a Schlenk tube charged with racemic PPFOAc **2** (1.2 mmol, 550 mg) and 1-methyl-1*H*-imidazole (1.5 mmol, 186 mg). The mixture was allowed to stir at 25 °C for 3 days to give a clear orange solution. After addition of benzene (10 mL) the organic phase was separated and concentrated in vacuum. The residue was dissolved together with NaI (3.0 mmol, 450 mg) in ethanol (10 mL) and the mixture was stirred at 25 °C for 4 h. After evaporating the solvent the crude product was chromatographed on a silica gel column by a eluting first with hexane–ethyl acetate (5 : 1), then with CH_2Cl_2–MeOH (95 : 5) to give a orange solid (529 mg, 87% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.31 (t, J = 7.6 Hz, 6H), 2.07 (d, J = 7.2 Hz, 3H), 3.89 (s, 1H), 4.01 (s, 5H), 4.42–4.47 (m, 2H), 4.96 (s, 1H), 5.99–6.02 (m, 1H), 6.69–6.75 (m, 3H), 6.87 (s, 1H), 6.99–7.08 (m, 3H), 7.31–7.42 (m, 5H), 9.59 (s, 1H). ^{31}P NMR (162 MHz, $CDCl_3$): δ −27.7 (s). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.5, 22.4, 22.7, 29.5, 52.7, 56.2, 56.3, 70.0, 70.2, 70.9, 72.7, 90.1, 118.3, 119.5, 128.0, 128.2, 128.3, 129.6, 131.4, 131.6, 134.2, 134.7, 134.9, 135.5, 138.8. HRMS (ESI) m/z: calc. for $C_{30}H_{32}FeN_2P$: 507.1652 [M$^+$ − I]; found: 507.1646.

3-(*tert*-Butyl)-1-[(2-diphenylphosphinoferrocenyl)ethyl]-3*H*-imidazolium iodide (1c). Yield: 81%. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.36 (s, 9H), 2.14 (d, J = 2.5 Hz, 3H), 3.98 (s, 1H), 4.04 (s, 5H), 4.54 (s, 1H), 5.04 (s, 1H), 6.23 (m, 1H), 6.75 (m, 2H), 6.85 (s, 1H), 7.05–7.13 (m, 4H), 7.37–7.41 (m, 3H), 7.47 (s, 2H), 9.52 (s, 1H). ^{31}P NMR (162 MHz, $CDCl_3$): δ −25.7 (s). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.4, 29.7, 56.1, 60.2, 70.3, 70.8, 71.1, 72.8, 90.1, 90.4, 118.9, 119.5, 128.2, 128.3, 129.9, 131.2, 131.4, 133.5, 134.9, 135.1. Anal. Calc. for $C_{31}H_{34}FeIN_2P$: C, 57.43; H, 5.28; N, 4.32. Found: C, 57.21; H, 5.66; N, 3.88%. HRMS (ESI) m/z: calc. for $C_{31}H_{34}FeN_2P$: 521.1809 [M$^+$ − I]; found: 521.1804.

3-(1-Admantyl)-1-[(2-diphenylphosphinoferrocenyl)ethyl]-3*H*-imidazolium iodide (1d). Yield: 82%. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.62 (s, 6H), 1.79 (s, 6H), 2.13 (d, J = 7.2 Hz, 6H), 3.94 (s, 1H), 4.01 (s, 5H), 4.49 (s, 1H), 4.98 (s, 1H), 6.16 (m, 1H), 6.70 (t, J = 7.0 Hz, 2H), 6.96 (s, 1H), 7.02–7.09 (m, 4H), 7.34–7.36 (m, 3H), 7.44–7.47 (m, 3H), 9.32 (s, 1H). ^{31}P NMR (162 MHz, $CDCl_3$): δ −26.75 (s). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.3, 29.2, 35.1, 42.0, 56.2, 60.3, 70.1, 70.3, 72.7, 90.6, 117.9, 119.3, 128.0, 128.1, 128.3, 129.8, 131.2, 131.4, 133.0, 135.0, 135.2. HRMS (ESI) m/z: calc. for $C_{37}H_{40}FeN_2P$: 599.2279 [M$^+$ − I]; found: 599.2272.

3-(2,6-Dimethylphenyl)-1-[(2-diphenylphosphinoferrocenyl)ethyl]-3*H*-imidazolium iodide (1f). Yield: 85%. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.96 (s, 6H), 2.15 (d, J = 7.2 Hz, 3H), 3.90 (s, 5H), 4.13 (s, 1H), 4.51 (s, 1H), 4.95 (s, 1H), 6.56 (m, 1H), 6.72–6.77 (m, 3H), 6.99–7.01 (m, 5H), 7.11–7.17 (m, 3H), 7.30–7.32 (m, 3H), 7.52 (t, J = 7.2 Hz, 2H), 9.91 (s, 1H). ^{31}P NMR (162 MHz, $CDCl_3$): δ −26.9 (s). HRMS (ESI) m/z: calc. for $C_{35}H_{34}FeN_2P$: 569.1809 [M$^+$ − I]; found: 569.1801.

3-(2,4,6-Trimethylphenyl)-1-[(2-diphenylphosphinoferrocenyl)-ethyl]-3*H*-imidazolium iodide (1g). Yield: 84%. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.96 (s, 6H), 2.15 (d, J = 7.2 Hz, 3H), 4.04 (s, 5H), 4.25 (s, 1H), 4.67 (s, 1H), 5.15 (s, 1H), 6.68–6.93 (m, 5H), 7.11–7.17 (m, 3H), 7.44–7.46 (m, 3H), 7.68 (t, J = 7.2 Hz, 2H), 10.08 (s, 1H). ^{31}P NMR (162 MHz, $CDCl_3$): δ −25.7 (s). HRMS (ESI) m/z: calc. for $C_{36}H_{34}FeN_2P$: 583.1966 [M^+ − I]; found: 583.1970.

3-(2,6-Diisopropylphenyl)-1-[(2-diphenylphosphinoferrocenyl)-ethyl]-3*H*-imidazolium iodide (1h). Yield: 80%. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.72 (d, J = 6.4 Hz, 3H), 0.97 (d, J = 6.8 Hz, 3H), 1.07 (d, J = 6.8 Hz, 3H), 1.22 (d, J = 6.8 Hz, 3H), 1.68 (sept, J = 6.6 Hz, 1H), 2.07 (sept, J = 6.8 Hz, 1H), 2.21 (d, J = 6.4 Hz, 3H), 3.92 (s, 5H), 4.21 (s, 1H), 4.56 (s, 1H), 5.01 (s, 1H), 6.78–6.84 (m, 4H), 7.11–7.27 (m, 6H), 7.41–7.45 (m, 4H), 7.69 (m, 2H), 10.22 (s, 1H). ^{31}P NMR (162 MHz, $CDCl_3$): δ −25.5 (s). ^{13}C NMR (100 MHz, $CDCl_3$): δ 22.9, 23.6, 24.0, 24.2, 24.6, 28.0, 28.2, 28.5, 56.5, 69.7, 70.4, 71.3, 73.4, 89.3, 89.6, 120.3, 123.6, 124.3, 124.4, 127.3, 127.8, 128.2, 129.7, 131.1, 131.2, 131.5, 135.4, 135.6, 136.2, 137.3, 140.7, 145.1. HRMS (ESI) m/z: calc. for $C_{39}H_{42}FeN_2P$: 625.2435 [M^+ − I]; found: 625.2429.

Synthesis of the palladium complex 3f. The imidazolium salt **1f** (320 mg, 0.46 mmol) and Ag_2O (63.6 mg, 0.27 mmol) suspended in CH_2Cl_2 solution (20 mL) was stirred for 2 h at room temperature. $Pd(NCMe)_2Cl_2$ (119 mg, 0.46 mmol) in CH_2Cl_2 (20 mL) was then added to the reaction mixture and was stirred for 2 h. During this period, white precipitates formed. The precipitates were filtered off, and the filtrate was evaporated to dryness and chromatographed on a silica gel column by eluting with CH_2Cl_2–MeOH (95 : 5) to give an orange solid (117 mg, 34% yield). ^{1}H NMR (400 MHz, CD_2Cl_2): δ 1.97 (s, 3H), 2.08 (d, J = 6.8 Hz, 3H), 2.93 (dd, J_1 = 6.8 Hz, J_2 = 14.0 Hz, 1H), 3.66 (s, 5H), 4.04 (s, 1H), 4.31 (s, 1H), 4.42 (s, 1H), 4.60 (s, 1H), 6.23 (m, 1H), 6.75 (m, 2H), 6.85 (s, 1H), 6.54–7.29 (m, 8H), 7.41 (s, 3H), 7.50–7.55 (m, 2H), 7.91 (m, 2H). ^{31}P NMR (162 MHz, CD_2Cl_2): δ 8.0 (s). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 21.4, 29.7, 56.1, 60.2, 70.3, 70.8, 71.1, 72.8, 90.1, 90.4, 118.9, 119.5, 128.2, 128.3, 129.9, 131.2, 131.4, 133.5, 134.9, 135.1. Anal. Calc. for $C_{35}H_{33}Cl_2FeN_2PPd$: C, 56.37; H, 4.46; N, 3.76. Found: C, 56.25; H, 4.66; N, 3.28%. HRMS (ESI) m/z: calc. for $C_{35}H_{33}ClFeN_2PPd$: 709.0454 [M^+ − Cl]; found: 709.0480.

Synthesis of the palladium complex 3h. Yield: 41%. ^{1}H NMR (400 MHz, CD_2Cl_2): δ 0.39 (d, J = 6.4 Hz, 3H), 0.58 (d, J = 6.8 Hz, 3H), 1.08 (d, J = 6.8 Hz, 3H), 1.37 (d, J = 6.8 Hz, 3H), 2.15–2.10 (m, 4H), 2.66 (m, 1H), 3.60 (s, 5H), 4.37 (s, 1H), 4.43 (s, 1H), 4.63 (s, 1H), 6.52 (m, 1H), 7.01–7.58 (m, 12H), 8.12–8.17 (m, 2H). ^{31}P NMR (162 MHz, CD_2Cl_2): δ 7.7 (s). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 92.2, 115.0, 123.6, 124.4, 127.5, 127.6, 128.0, 128.1, 128.6, 129.7, 130.4, 130.6, 132.0, 134.5, 134.6, 135.4, 135.5, 135.7, 139.4, 143.9, 147.2, 157.6. HRMS (ESI) m/z: calc. for $C_{39}H_{41}ClFeN_2PPd$: 765.1080 [M^+ − Cl]; found: 765.1089.

General procedure for aminations of aryl halides

An oven-dried round-bottom flask was cooled in vacuum, back-filled with nitrogen, and charged with $Pd(OAc)_2$, imidazolium salts, and NaO^{t}Bu (weighed in air). Then the flask was evacuated and back-filled with nitrogen (three times), and dioxane was added under nitrogen. The mixture was stirred at 50 °C for 0.5 h. After cooling to room temperature, the aryl halide and amine were added, and the vial was placed in an oil bath. The reaction was monitored by GLC. After cooling to room temperature, the reaction mixture was filtered through a layer of Celite with the aid of ethyl acetate. The filtrate was concentrated in vacuum and the crude product was purified chromatographically and the products were identified by ^{1}H NMR.

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Notes and references

1 (*a*) D. Bourissou, O. Guerret, F. P. Gabbaï and G. Bertrand, *Chem. Rev.*, 2000, **100**, 39; (*b*) T. M. Trnka and R. H. Grubbs, *Acc. Chem. Res.*, 2001, **34**, 18; (*c*) C. W. K. Gstöttmayr, V. P. Böhm, W. E. Herdtweck, M. Grosche and W. A. Herrmann, *Angew. Chem., Int. Ed.*, 2002, **41**, 1363; (*d*) O. Navarro, R. A. Kelly, III and S. P. Nolan, *J. Am. Chem. Soc.*, 2003, **125**, 16194; (*e*) I. E. Marko, S. Sterin, O. Buisine, G. Mignani, P. Branlard, B. Tinant and J.-P. Declercq, *Science*, 2002, **298**, 204.

2 (*a*) W. A. Herrmann, *Angew. Chem., Int. Ed.*, 2002, **41**, 1290; (*b*) A. C. Hiller, G. A. Grasa, M. S. Viciu, H. W. Lee, C. L. Yang and S. P. Nolan, *J. Organomet. Chem.*, 2002, **653**, 69; (*c*) H. Yu, J.-c. Shi, H. Zhang, P. Yang, X. Wang and Z. L. Jin, *J. Mol. Catal. A: Chem.*, 2006, **250**, 15.

3 (*a*) F. Glorius, G. Altenhoff, R. Goddard and C. Lehmann, *Chem. Commun.*, 2002, 2704; (*b*) L. H. Gade, V. César and S. Bellemin-Laponnaz, *Angew. Chem., Int. Ed.*, 2004, **43**, 1014; (*c*) J. J. Van Veldhuizen, D. G. Gillingham, S. B. Garber, O. Kataoka and A. H. Hoveyda, *J. Am. Chem. Soc.*, 2003, **125**, 12502; (*d*) J.-c. Shi, N. Lei, Q. Tong, Y. Peng, J. Wei and L. Jia, *Eur. J. Inorg. Chem.*, 2007, 2221.

4 (*a*) N. Marion, O. Navarro, J. Mei, E. D. Stevens, N. M. Scott and S. P. Nolan, *J. Am. Chem. Soc.*, 2006, **128**, 4101; (*b*) G. Altenhoff, R. Goddard, C. W. Lehmann and F. Glorius, *Angew. Chem., Int. Ed.*, 2003, **42**, 3690; (*c*) S. R. Stauffer, S. Lee, J. P. Stambuli, S. I. Hauck and J. F. Hartwig, *Org. Lett.*, 2000, **2**, 1423; (*d*) J.-c. Shi, X. Cao, Y. Zheng and L. Jia, L., *Chin. J. Org. Chem.*, 2007, **27**, 666; (*e*) J.-c. Shi, X. Cao, Y. Zheng and L. Jia, *Acta Chim. Sinica*, 2007, **65**, 1702.

5 (*a*) A. Zapf and M. Beller, *Chem. Commun.*, 2005, 431; (*b*) A. K. de K. Lewis, S. Cadick, F. G. N. Cloke, N. C. Billingham, P. B. Hitchcock and J. Leonard, *J. Am. Chem. Soc.*, 2003, **125**, 10066.

6 (*a*) J.-M. Becht, E. Bappert and G. Helmchen, *Adv. Synth. Catal.*, 2005, **347**, 1495; (*b*) M. C. Perry, X. Cui, M. T. Powell, D.-r. Hou, J. H. Reibenspies and K. Burgess, *J. Am. Chem. Soc.*, 2003, **125**, 113; (*c*) W. A. Herrmann, C. Köcher, L. J. Gooβen and G. R. J. Artus, *Chem.–Eur. J.*, 1996, **2**, 1627; (*d*) A. A. Danopoulos, S. Winston, T. Gelbrich, M. B. Hursthouse and R. P. Tooze, *Chem. Commun.*, 2002, 482; (*e*) S. Gischig and A. Togni, *Organometallics*, 2004, **23**, 2479; (*f*) H. Seo, B. Y. Kim, J. H. Lee, H.-J. Park, S. U. Son and Y. K. Chung, *Organometallics*, 2003, **22**, 4783; (*g*) C. Yang, H. M. Lee and S. P. Nolan, *Org. Lett.*, 2001, **3**, 1511; (*h*) A. Wang, J. Zhong, J. Xie, K. Li, K. and Q. Zhou, *Adv. Synth. Catal.*, 2004, **346**, 595.

7 M.-D. Su and S.-Y. Chu, *Inorg. Chem.*, 1988, **37**, 3400.

8 M. Kranenburg, P. C. J. Kamer and P. W. N. M. von Leeuwen, *Eur. J. Inorg. Chem.*, 1998, 155.

9 H. Seo, J. H. Kim, B. Y. Kim, H. J. Lee, S. U. Son and Y. K. Chung, *Organometallics*, 2003, **22**, 618.

10 J.-c. Shi, P. Yang, Q. Tong, Y. Wu and Y. Peng, *J. Mol. Catal. A: Chem.*, 2006, **259**, 7.

11 Y. P. Hong, G. J. Tanoury, H. S. Wilkinson, R. P. Bakale, S. A. Wald and C. H. Senanayake, *Tetrahedron Lett.*, 1997, **38**, 5663.

12 F. E. Goodson and J. F. Hartwig, *Macromolecules*, 1998, **31**, 1700.

13 (*a*) *Metal-Catalyzed Cross-coupling Reactions*, ed. A. de Meijere and F. Diederich, Wiley-VCH, New York, 2004; (*b*) N. Miyaura, Cross-Coupling Reactions: A Practical Guide, *Top. Curr. Chem.*, 2002, **219**, 11; (*c*) A. F. Littkle and G. C. Fu, *Angew. Chem., Int. Ed.*, 2002, **41**, 4176;

(*d*) *Handbook of Organopalladium Chemistry for Organic Synthesis*, ed. E.-i. Negishi, Wiley-Interscience, New York, 2002; (*e*) J. F. Hartwig, *Angew. Chem., Int. Ed.*, 1998, **37**, 2046; (*f*) B. Schlummer and U. Scholz, *Adv. Synth. Catal.*, 2004, **346**, 1599.
14 H. M. J. Wang and I. J. B. Lin, *Organometallics*, 1998, **17**, 972.
15 (*a*) B. C. Hamann and J. F. Hartwig, *J. Am. Chem. Soc.*, 1998, **120**, 7369; (*b*) J.-F. Marcoux, S. Wagaw and S. L. Buchwald, *J. Org. Chem.*, 1997, **62**, 1568.
16 S. Cacchi, G. Fabrizi, A. Goggiamani, E. Licandro, S. Maiorana and D. Perdicchia, *Org. Lett.*, 2005, **7**, 1497.
17 M. S. Viciu, R. M. Kissling, E. D. Stevens and S. P. Nolan, *Org. Lett.*, 2002, **4**, 2229.
18 J. P. Wolfe, H. Tomori, J. P. Sadighi, H. Yin and S. L. Buchwald, *J. Org. Chem.*, 2000, **65**, 1158.
19 S. Zhao, A. K. Miller, J. Berger and L. A. Flippin, *Tetrahedron Lett.*, 1996, **37**, 4463.