A recyclable triethylammonium ion-tagged diphenylphosphine palladium complex for the Suzuki–Miyaura reaction in ionic liquids†

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Suzuki-Miyaura reactions of aryl bromides and arylboronic acids proceed in good to excellent yields in a pyrrolidinium ionic liquid by using a preformed air stable and easily handled triethylammonium-tagged diphenylphosphine palladium(II) complex (**2**). The reaction requires short reaction times and mild temperature conditions and does not show any tendency towards the formation of palladium black. After extraction of the product, the catalyst containing ionic liquid phase is easily recycled for 6 times, with no significant loss of catalytic activity.

Introduction

The use of the Suzuki-Miyaura (SM) reaction[1] in the challenging field of the synthesis of biaryls and of natural and bioactive products characterized by the presence of Csp^2–Csp^2 single bonds, has recorded a huge growth over the last few years.[2] An attractive feature of the SM reaction is that a large number of forms of palladium can be used as precatalyst.[3–7] A further element of flexibility of the SM reaction is the wide choice of solvent/base combinations available,[3,5] including solvent-free protocols under microwave irradiation.[8] Despite the tolerance of a broad range of functional groups and reaction conditions, the cost of palladium and environmental regulations urge to develop procedures which minimize metal loading and leaching.

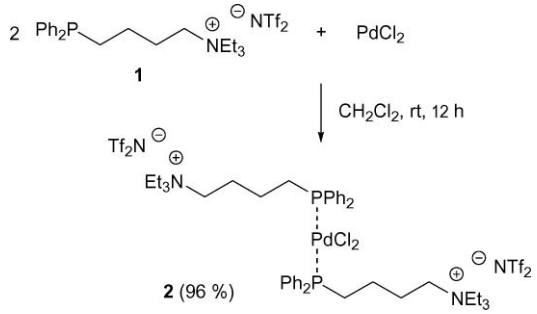
Catalyst recyclability and metal leaching issues can be addressed in two ways. The first one involves metal immobilization on a solid support,[5–7] a strategy that not only reduces product contamination but also allows the use of inherently less wasteful flow-through technologies.[9]

The second approach makes use of extremely low loadings of metal. The "active form of palladium" is considered to be a mononuclear Pd(0) entity which originates from the precatalyst. However, on heating, the mononuclear Pd(0) species tends to cluster and, eventually, to precipitate as inactive palladium black, unless highly diluted conditions are used.[10] Active Pd nanoparticles can also be produced in environments capable of stabilizing them *via* coordination or electrostatic interactions that inhibit their aggregation.[11] Task-specific ionic liquids (TSILs), for example nitrile-functionalized imidazolium salts, have been proposed by Dyson *et al.* as excellent nanoparticles stabilizers.[12] TSIL-stabilized nanoparticles are supposed to act as a reservoir of catalytically active mononuclear Pd(0) species.[13]

As solvents for the SM reaction, ionic liquids (ILs) have been extensively used for Pd-catalyzed cross coupling reactions.[14] In particular, enhanced reactivity and an increased catalyst stability were recorded in imidazolium based ILs, compared to conventional molecular solvents.[15]

Results and discussion

Within this field we committed ourselves to the design of a multiphase homogeneous catalytic system for the SM reaction, and focused the attention to the thermoregulated biphasic system consisting of 1-butyl-1-methyl-pyrrolidinium bis(trifluoro methylsulfonyl)imide ([bmpy][NTf_2]) and water. This system is heterogeneous at 25 °C, and when heated at 65 °C, it becomes a homogeneous phase where the SM reaction can be carried out. Eventually, upon cooling the mixture to rt, the system turns heterogeneous. In principle, the IL phase can be extracted, delivering the coupling product, for instance, in pentane. Then, it could be washed with water to remove the inorganic salts. If palladium is confined into the IL phase thanks to the ion-tagged ligand, an efficient multiphase homogeneous catalytic protocol will become available. The rational approach adopted was to incorporate a tetralkyl ammonium tag on a phosphine capable of binding the Pd catalyst and to confine it into the IL phase.[16] After a preliminary screening of the carbon chain length, we chose ligand **1** to prepare the air stable Pd complex **2**, which could be directly used as the pre-catalyst of the SM reaction (Scheme 1).[17]



Scheme 1

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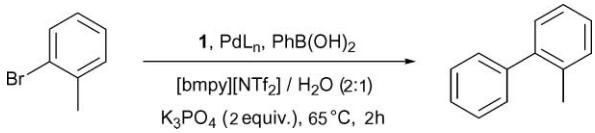
† Electronic supplementary information (ESI) available: ^{1}H-NMR, ^{13}C-NMR and GC-MS spectra for all compounds reported. See DOI: 10.1039/b815568b

Table 1 Effect of palladium source and metal/ligand ratio



Entry	PdL$_n$, mol%	**1** (mol%)	Yield (%)[a]
1	Pd$_2$(dba)$_3$, 1	2	—
2	Pd(OAc)$_2$, 1	2	79
3	PdCl$_2$, 1	2	92
4	PdCl$_2$, 1	1	60
5	PdCl$_2$, 1	3	—

[a] Isolated yields after purification by flash-chromatography on silica.

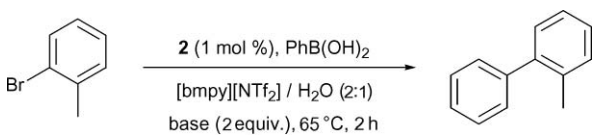
Using the cross-coupling of *o*-bromotoluene and phenyl boronic acid as the benchmark reaction, a preliminary optimization study was carried out. The effect of the palladium source and the palladium/ligand ratio on reactivity was evaluated using [bmpy][NTf$_2$] as the solvent (Table 1).

The catalytically active species is efficiently stabilized using a 1 : 2 palladium/ligand ratio, since the formation of Pd black, even after prolonged heating at 65 °C, is never observed. While Pd$_2$(dba)$_3$ failed to afford the desired product, PdCl$_2$ revealed itself as a better source of Pd than Pd(OAc)$_2$ (Table 1, Entries 1–3). By changing the metal/ligand ratio to 1 : 1, the formation of Pd black was rapidly observed and the yield dropped significantly (Entry 4). Using a 1 : 3 palladium/ligand ratio did not result in formation of Pd black, but the catalytic system became totally inactive (Entry 5). These results are in good agreement with the observation that the active catalyst in many palladium mediated transformations is a monoligated species derived from the initial loss of a phosphine ligand from the precatalyst.[18]

PdCl$_2$ and the ligand can be directly mixed in 1 : 2 ratio in the reaction flask. However, essentially the same results are obtained using the preformed L$_2$·PdCl$_2$ complex **2**. We continued the optimization study using the preformed complex **2**, since it is more practical to handle than the free ligand **1**.

In Table 2 the results obtained with different inorganic bases are reported. Yields strongly depended on the base used, K$_3$PO$_4$ being more effective as a base than K$_2$CO$_3$ and Na$_2$CO$_3$ (Table 2, Entries 1–3). This order of reactivity can be possibly ascribed to the greater solubility of K$_3$PO$_4$ in H$_2$O.

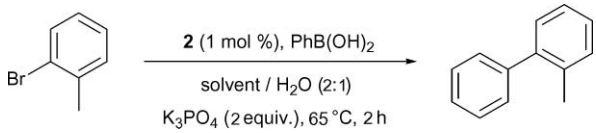
Table 2 Effect of the base



Entry	Base	Yield (%)[a]
1	Na$_2$CO$_3$	57
2	K$_2$CO$_3$	79
3	K$_3$PO$_4$	94

[a] Isolated yields after purification by flash-chromatography on silica.

Table 3 Effect of the solvent



Entry	Solvent	Yield (%)[a]
1	THF	—
2	CH$_3$CN	12
3	[mC$_1$CNpy][NTf$_2$][b]	—
4	[P(6,6,6,14)][Cl][c]	—
5	[bmpy][OTf][d]	39
6	[bmpy][NTf$_2$][e]	93
7	[bmim][NTf$_2$][f]	87

[a] Isolated yields after purification by flash-chromatography on silica. [b] 1-Cyanomethyl-pyridinium bis(trifluoromethylsulfonyl) imide. [c] Trihexyl-tetradecyl-phosphonium chloride. [d] 1-Butyl-1methyl-pyrrolidinium triflate. [e] 1-Butyl-1methyl-pyrrolidinium bis(trifluoromethylsulfonyl) imide. [f] 1-Butyl-3-methyl-imidazolium bis(trifluoromethylsulfonyl) imide.

Using these preliminary optimized conditions, we tested several organic solvents and ionic liquids (Table 3). At 65 °C the reaction mixture is a single-phase homogeneous system, even in the case of ILs insoluble in water (Table 3, Entries 3,6,7).

THF and CH$_3$CN afforded disappointing results (Table 3, Entries 1,2). While the complex **2** is only sparingly soluble in THF, it dissolves completely in CH$_3$CN. In both cases, however, formation of Pd black is observed after heating the reaction mixture at 65 °C.

The reactivity of the catalytic system is completely suppressed if a nitrile-functionalized ionic liquid (Entry 3) or an ionic liquid with a coordinating counter anion (Entry 4) is used. Using 1-butyl-1-methyl-pyrrolidinium ionic liquids, the effect of the counter anion on the reactivity is apparent (Entries 5,6), with bis(trifluoromethylsulfonyl) imide giving much better results than triflate. When the 1-butyl-3-methyl-imidazolium cation is used (Entry 7), a slightly lower yield is obtained.

From these results, [bmpy][NTf$_2$] was selected as the solvent of choice, also considering that imidazolium-based ILs could produce mixed phosphine/*N*-heterocyclic carbene complexes (NHC).[11] Moreover, NTf$_2^-$, chosen as the anion of both the catalyst and the IL, confers them the lowest solubility in H$_2$O and in pentane, a property necessary to separate biaryls and water soluble co-products from the catalyst-containing IL phase.

The effect of the temperature on the catalytic system under the conditions used in Entry 6 of Table 3 is reported in Fig. 1. To obtain good conversion in short reaction times a temperature above 40 °C is needed, while the product is formed only very slowly at room temperature (25 °C).

Finally, we tested different aryl electrophiles with boronic acids and, surprisingly, the order of reactivity was ArBr > ArI ≫ ArOTf, while ArCl are not reactive under the reaction conditions tested (Fig. 2).

Initial slopes in Fig. 2 suggest the presence of an induction effect, particularly for aryl triflates and iodides. Since the aromatic electrophile is added pure as the last reagent to the reaction mixture, the induction time observed reflects, in our

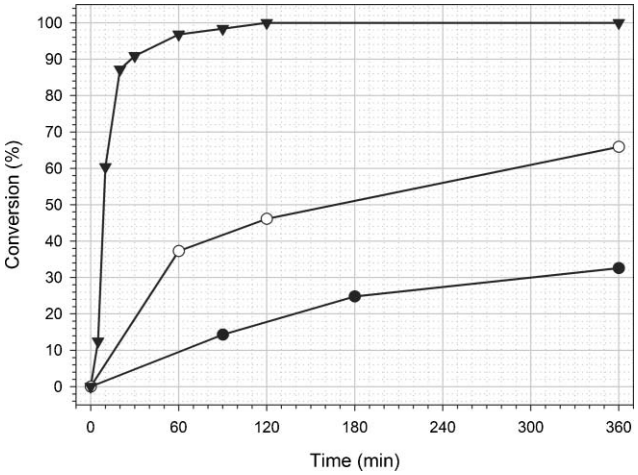


Fig. 1 Effect of temperature on conversion. ▼: 65 °C; ○: 40 °C; ●: 25 °C using reaction conditions reported in Table 3, Entry 6.

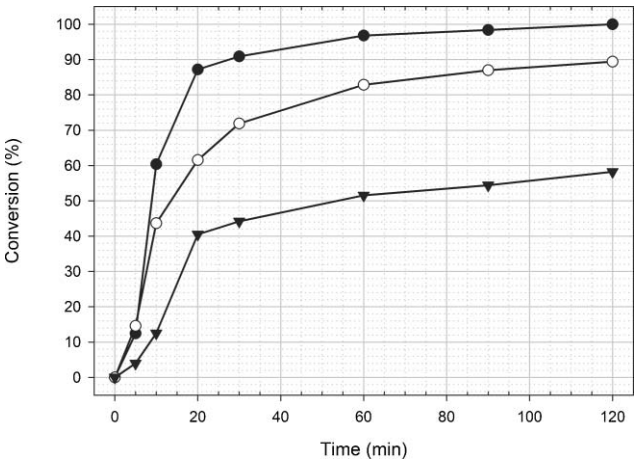


Fig. 2 Comparison of reactivity between aryl bromides (●), iodides (○) and triflates (▼) using reaction conditions reported in Table 3, Entry 6.

opinion, a slow mass transfer rate of the aryl triflate or halide in this viscous reaction medium.

In order to evaluate the possible effect of anion exchange with [bmpy][NTf_2] on reaction rates, we performed a series of experiments using the same conditions reported in Entry 6 of Table 3, but adding 1 equivalent of different potassium salts to the reaction mixtures. The results obtained are reported in Fig. 3.

The addition of 1 equivalent of KI considerably reduced the reaction rate, while a much smaller effect is observed in the case of KBr. Thus, the lower reactivity of aryl iodides with respect to bromides can be explained by considering that the corresponding potassium halide salts are formed during the course of the reaction. Conversely, the decrease of reaction rate due to the addition of 1 equivalent of KOTf cannot alone explain the much lower reactivity of triflates. Moreover, no trace of [bmpy][OTf] deriving from anion exchange was apparent by NMR analyses of the ionic liquid after the reaction work-up.

On the basis of these observations, a reference protocol was derived based on the use of 1 mol% of Pd in the form of $L_2{\cdot}PdCl_2$ complex **2**, which was applied to a number of aryl bromide/aryl

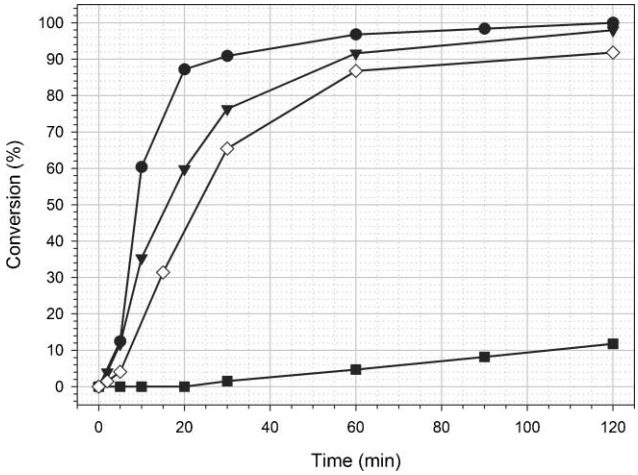


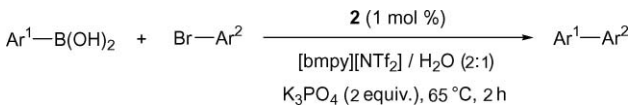
Fig. 3 Comparison of reaction rates without adding salts (●), by adding 1 equiv. of KBr (▼), 1 equiv. of KOTf (◇) and 1 equiv. of KI (■) using reaction conditions reported in Table 3, Entry 6.

boronic acid pairs in [bmpy][NTf_2] as the solvent at 65 °C for 2 h, as outlined in Table 4.

Good to excellent results were confirmed for aryl bromides and boronic acids containing electron-withdrawing or electron-donating groups. In particular, *o*-bromobenzonitrile and *p*-methyl phenylboronic acid (Table 4, Entry 6) afforded 97% of a coupled product which is a known intermediate for the synthesis of angiotensin II receptor antagonists.[19] The time dependence study of the reaction conversions shows that the highest rates are recorded at the beginning of the reaction, in contrast to other catalytic Pd systems in ILs which present induction periods.[20] Irrespective of the true identity of the catalyst, a point of strength of this reaction protocol is the catalyst recyclability, which is ensured by the strong interaction between the ligand **1** and the IL, both being quaternary ammonium ions. Fig. 4 shows the results of six consecutive cycles carried out under identical conditions reported in Table 4, Entry 1, and no significant change in the catalytic activity and the reaction rates is observed.

Lowering the Pd loading is a further way to check catalyst activity. The reaction reported in Entry 1 of Table 4 was carried

Table 4 Suzuki coupling using ligand **2**



Entry	Ar^1	Ar^2	Yield (%)[a]
1	Ph	2-Me-Ph	92
2	Ph	4-MeO-Ph	89
3	2-Me-Ph	2-Me-Ph	89
4	2-Me-Ph	1-Naphthyl	99
5	2-Me-Ph	4-Ph-Ph	99
6	4-Me-Ph	2-CN-Ph	97
7	3-NO_2-Ph	2-Me-Ph	86
8	4-MeO-Ph	1-Naphthyl	98
9	4-MeO-Ph	4-MeO-Ph	93
10	4-MeO-Ph	4-Ph-Ph	84
11	4-MeO-Ph	2-Me-Ph	89
12	4-MeO-Ph	2-CN-Ph	92

[a] Isolated yields after purification by flash-chromatography on silica.

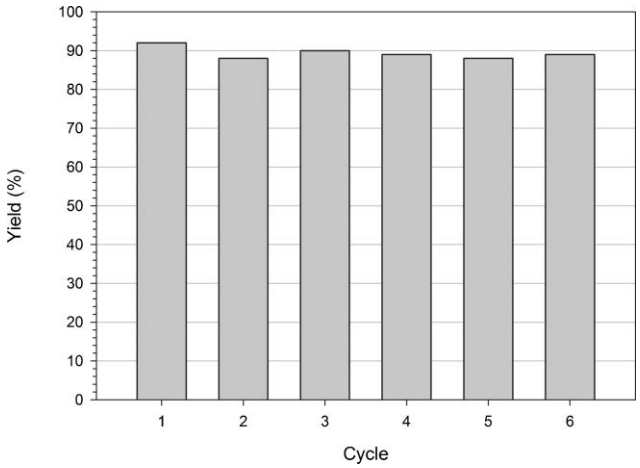


Fig. 4 Results of six consecutive cycles adopting conditions described in Table 4, Entry 1.

out using two different catalyst loadings, 0.1 and 0.01 mol% of Pd, respectively. The first reaction, run for 6 h at 65 °C, gave an 81% yield, with a TON of 810 and a TOF of 135 h^{-1}. In the second reaction, after 1.5 h at 95 °C, a 78% yield was recorded, corresponding to a TON of 7800 and a TOF of 5200 h^{-1}.

Finally, preliminary analyses of palladium contents in the organic phase extracts by atomic-absorption spectroscopy (AAS), showed that <10 ppb of the metal was released from the IL into the product during recycling. This value is very promising in terms of metal leaching and more detailed studies will be published in due course.

Conclusions

In conclusion, we showed that the triethylammonium tagged complex **2** provides a highly active catalyst for the SM reaction of aryl bromides in an IL. Formation of Pd black was never observed and the catalyst-containing IL phase could be recycled six times without substantial decrease of catalytic activity.

Experimental

Synthesis of the ionic liquids

All ionic liquids used were synthesized and purified according to known procedures.[21]

Synthesis of the catalyst

4-Bromobutyl-triethyl-ammonium bromide. Triethylamine (2.8 mL, 20 mmol) is added to 1,4-dibromobutane (7.1 mL, 60 mmol) and the solution is stirred for 2–3 h at 70–80 °C. The resulting suspension is cooled to 0 °C, the solid is collected by filtration and washed with EtOAc. 4-Bromobutyl-triethyl-ammonium bromide is obtained as an hygroscopic white solid (5.91 g, 18.7 mmol, 93%). ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 1.40 (t, J = 7.2 Hz, 9 H), 1.86–1.99 (m, 2 H), 1.99–2.11 (m, 2 H), 3.43–3.60 (m, 10 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 7.1, 19.4, 27.9, 32.0, 52.4, 55.4. Anal. Calcd for $C_{10}H_{23}Br_2N$ (317.10): C, 37.88; H, 7.31; N, 4.42. Found: C, 37.76; H, 7.33; N, 4.41.

4-Diphenylphosphinobutyl-triethyl-ammonium bromide. *n*-BuLi (1 mL, 2.5 M in cyclohexane) is slowly added at 0 °C to a solution of Ph_2PH (350 µl, 2.48 mmol) in THF (1 mL). The orange solution is allowed to reach room temperature and further stirred for 30 min. The solution of Ph_2PLi is slowly added *via* syringe at 0 °C to a suspension of 4-bromobutyl-triethyl-ammonium bromide (0.66 g, 2.07 mmol) in THF (2 mL). The colorless suspension is allowed to reach room temperature and further stirred for 2 h. The reaction is quenched by adding water (2 mL), the organic solvent is evaporated the residue is extracted with CH_2Cl_2. The combined organic phases are washed with water, dried (Na_2SO_4) and evaporated under reduce pressure. The solid obtained is washed with Et_2O to afford the title compound as a white solid (0.753 g, 1.78 mmol, 86%). ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 1.36 (t, J = 7.2 Hz, 9 H), 1.48–1.66 (m, 2 H), 1.78–1.94 (m, 2 H), 2.16 (t, J = 7.4 Hz, 2 H), 3.19–3.30 (m, 2 H), 3.49 (q, J = 7.2 Hz, 6 H), 7.24–7.57 (m, 10 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 7.3, 22.2, 26.3, 26.5, 52.7, 56.2, 127.5, 127.6, 127.8, 127.8, 128.0, 129.8, 129.9, 130.0, 130.0, 130.9, 131.0, 131.7, 131.8, 132.0, 137.1, 137.3. Anal. Calcd for $C_{22}H_{33}BrNP$ (422.38): C, 62.56; H, 7.87; N, 3.32. Found: C, 62.68; H, 7.85; N, 3.31.

4-Diphenylphosphinobutyl-triethyl-ammonium bis(trifluoromethylsulfonyl) imide (1). $LiNTf_2$ (0.474 g, 1.65 mmol) is added to a solution of 4-diphenylphosphinobutyl-triethyl-ammonium bromide (0.633 g, 1.5 mmol) in water (1 mL) and the reaction mixture is vigorously stirred at room temperature for 12 h. The solution is extracted with CH_2Cl_2 and the combined organic phases are washed with water until no bromide is detected by the $AgNO_3$ test. The combined organic phases are dried (Na_2SO_4) and CH_2Cl_2 is removed at reduced pressure to afford the title compound as a viscous liquid (0.793 g, 1.28 mmol, 85%). **1** can be further purified through a short pad of neutral alumina and of decolorizing charcoal, eluting with CH_2Cl_2. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 1.26 (t, J = 7.1 Hz, 9 H), 1.36–1.64 (m, 2 H), 1.64–1.92 (m, 2 H), 2.12 (t, J = 7.5 Hz, 2 H), 2.92–3.12 (m, 2 H), 3.21 (q, J = 7.1 Hz, 6 H), 7.28–7.86 (m, 10 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 7.4, 22.7, 26.9, 27.1, 53.1, 56.8, 117.7, 122.0, 128.6, 128.6, 128.7, 128.8, 128.9, 129.0, 130.6, 130.8, 132.5, 132.6, 132.6, 132.8, 137.7, 137.9. Anal. Calcd for $C_{24}H_{33}F_6N_2O_4PS_2$ (622.62): C, 46.30; H, 5.34; N, 4.50. Found: C, 46.42; H, 5.35; N, 4.52.

Complex 2. $PdCl_2$ (0.044 g, 0.25 mmol) is added to a solution of ligand **1** (0.311 g, 0.5 mmol) in CH_2Cl_2 (1 mL) and the suspension is stirred at room temperature for 12 h, until a clear solution is obtained. The solution is filtered through a short pad of Celite® and the solvent is evaporated at reduced pressure to afford **2** as a yellow solid (0.338 g, 0.24 mmol, 95%). ^{1}H-NMR (300 MHz, CD_3CN) δ = 1.16 (t, J = 6.4 Hz, 18 H), 1.46–1.83 (m, 8 H), 2.43–2.54 (m, 4H), 2.88–3.04 (m, 4 H), 3.04–3.17 (m, 12 H), 7.29 (t, J = 7.0 Hz, 2 H), 7.39–7.59 (m, 12 H),7.67–7.77 (m, 6 H). ^{13}C-NMR (75 MHz, CD_3CN) δ = 7.8, 22.4, 23.3, 23.4, 23.4, 23.6, 23.7, 23.7, 24.9, 25.1, 25.3, 53.8, 57.2, 118.9, 123.1, 129.4, 129.5, 129.6, 129.7, 129.7, 129.9, 130.2, 130.3, 130.6, 130.9, 131.2, 131.5, 131.7, 132.0, 132.4, 132.8, 132.8, 134.2, 134.3, 134.4, 134.5, 134.6, 134.7. Anal. Calcd for $C_{50}H_{72}Cl_2F_{12}N_4O_8P_2PdS_4$ (1452.64): C, 41.34; H, 5.00; N, 3.86. Found: C, 41.37; H, 5.04; N, 3.88.

Optimized general procedure for the Suzuki coupling (Table 4, Entry 1)

Reactions have to be conducted under argon. In the presence of air, biphenyl, the homocoupling product of boronic acid, is formed up to ~15%, while in the absence of air it is limited to less than 2%.[22] Complex **2** (14.5 mg, 0.01 mmol) is added to [bmpy][NTf_2] (1 mL) and the yellow solution is stirred at 65 °C for a few minutes. Phenylboronic acid (0.183 g, 1.5 mmol), K_3PO_4 (0.424 g, 2 mmol) and degassed water (0.5 mL) are added to the solution. After a few minutes, an orange homogeneous solution is formed. 2-Methyl-bromobenzene (0.12 mL, 1 mmol) is added to the reaction mixture and the solution is stirred at 65 °C for 2 h. After cooling to room temperature, the reaction mixture is directly charged onto a silica gel column and the desired product is isolated by elution with cyclohexane (0.155 g, 0.92 mmol, 92%).

2-Methylbiphenyl (Table 4, Entry 1). GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 14.1 min; *m/z* 168. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 2.32 (s, 3 H), 7.25–7.50 (m, 10 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 20.4, 125.7, 126.7, 127.2, 128.0, 129.10, 129.13, 129.7, 130.3, 135.2, 141.89, 141.92. Anal. Calcd for $C_{13}H_{12}$ (168.23): C, 92.81; H, 7.19. Found: C, 92.55; H, 7.20.

4-Methoxybiphenyl (Table 4, Entry 2). m.p. = 85–86 °C. GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 17.6 min; *m/z* 184. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 3.87 (s, 3 H), 7.00 (d, J = 8.5 Hz, 2 H,), 7.32 (t, J = 7.3 Hz, 1 H), 7.43 (t, J = 7.6 Hz, 2 H), 7.49–7.62 (m, 4 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 55.3, 114.2, 126.6, 126.7, 128.1, 128.7, 133.7, 140.8, 159.1. Anal. Calcd for $C_{13}H_{12}O$ (184.23): C, 84.75; H, 6.57. Found: C, 84.53; H, 6.58.

2,2′-Dimethylbiphenyl (Table 4, Entry 3). GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 14.4 min; *m/z* 182. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 2.07 (s, 6 H), 7.08–7.15 (m, 2 H), 7.18–7.33 (m, 6 H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ = 19.8, 125.5, 127.1, 129.2, 129.8, 135.8, 141.6. Anal. Calcd for $C_{14}H_{14}$ (182.26): C, 92.26; H, 7.74. Found: C, 92.43; H, 7.72.

1-*o*-Tolylnaphthalene (Table 4, Entry 4). m.p. = 69–70 °C. GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 19.6 min; *m/z* 218. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 2.04 (s, 3 H), 7.17–7.57 (m, 9 H), 7.90 (dd, *J* = 8.1/11.5 Hz, 2 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 20.0, 125.3, 125.6, 125.7, 126.0, 126.1, 126.6, 127.4, 127.5, 128.2, 129.8, 130.3, 132.0, 133.5, 136.8, 139.8, 140.2. Anal. Calcd for $C_{17}H_{14}$ (218.29): C, 93.54; H, 6.46. Found: C, 93.57; H, 6.44.

2-Methyl-4′-phenylbiphenyl (Table 4, Entry 5). m.p. = 88–89 °C. GC-MS (100 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 17.2 min; *m/z* 244. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 2.32 (s, 3 H), 7.33–7.52 (m, 9 H), 7.56–7.71 (m, 4 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 20.5, 125.8, 126.7, 127.0, 127.2, 127.3, 128.8, 129.6, 129.8, 130.4, 135.3, 139.6, 140.8, 140.9, 141.4. Anal. Calcd for $C_{19}H_{16}$ (244.33): C, 93.40; H, 6.60. Found: C, 93.31; H, 6.58.

4′-Methylbiphenyl-2-carbonitrile (Table 4, Entry 6). m.p. = 49–51 °C. GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 18.6 min; *m/z* 193. ^{1}H-NMR (200 MHz, $CDCl_3$) δ = 2.41 (s, 3 H), 7.26–7.34 (m, 2 H) 7.35–7.54 (m, 4 H) 7.56–7.68 (m, 1 H) 7.74 (dd, *J* = 1.5/7.7Hz, 1 H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ = 21.1, 103.7, 111.0, 127.1, 128.4, 129.3, 129.8, 132.6, 133.5, 135.1, 138.5, 145.3. Anal. Calcd for $C_{14}H_{11}N$ (193.24): C, 87.01; H, 5.74; N, 7.25. Found: C, 86.67; H, 5.75; N, 7.27.

2-Methyl-3′-nitrobiphenyl (Table 4, Entry 7). GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 19.2 min; *m/z* 213. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 2.29 (s, 3 H), 7.21–7.36 (m, 4 H), 7.55–7.70 (m, 2 H), 8.19–8.25 (m, 2 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 20.1, 121.6, 123.8, 126.0, 128.2, 128.9, 129.4, 130.5, 135.0, 135.2, 139.1, 143.3, 147.9. Anal. Calcd for $C_{13}H_{11}NO_2$ (213.23): C, 73.23; H, 5.20; N, 6.57. Found: C, 73.16; H, 5.21; N, 6.55.

1-(4-Methoxyphenyl)naphthalene (Table 4, Entry 8). m.p. = 115–117 °C. GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 22.1 min; *m/z* 234. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 3.91 (s, 3 H), 7.02–7.08 (m, 2 H), 7.39–7.56 (m, 6 H), 7.79–7.97 (m, 3 H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ = 55.3, 113.7, 125.4, 125.7, 125.9, 126.0, 126.9, 127.3, 128.2, 131.1, 131.8, 133.1, 133.8, 139.9, 158.9. Anal. Calcd for $C_{17}H_{14}O$ (234.29): C, 87.15; H, 6.02. Found: C, 87.35; H, 6.00.

4,4′-dimethoxybiphenyl (Table 4, Entry 9). m.p. = 178–179 °C. GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 20.1 min; *m/z* 214. ^{1}H-NMR (200 MHz, $CDCl_3$) δ = 3.86 (s, 6 H), 6.97 (d, *J* = 8.9 Hz, 4 H), 7.49 (d, *J* = 8.9 Hz, 4 H). ^{13}C-NMR (50 MHz, $CDCl_3$) δ = 55.3, 114.1, 127.7, 133.4, 158.6. Anal. Calcd for $C_{14}H_{14}O_2$ (214.26): C, 78.48; H, 6.59. Found: C, 78.53; H, 6.58.

4-Methoxy-4′-phenylbiphenyl (Table 4, Entry 10). m.p. = 222–223 °C. GC-MS (100 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 19.8 min; *m/z* 260. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 3.88 (s, 3 H), 7.01 (d, *J* = 8.8 Hz, 2 H), 7.32–7.42 (m, 1 H) 7.43–7.52 (m, 2 H) 7.55–7.71 (m, 8 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 55.4, 114.3, 127.0, 127.0, 127.2, 127.5, 128.0, 128.8, 133.2, 139.5, 139.7, 140.8, 159.2. Anal. Calcd for $C_{19}H_{16}O$ (260.33): C, 87.66; H, 6.19. Found: C, 87.54; H, 6.17.

4′-Methoxy-2-methylbiphenyl (Table 4, Entry 11). GC-MS (50 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 17.3 min; *m/z* 198. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 2.31 (s, 3 H), 3.88 (s, 3 H), 6.98 (d, *J* = 8.8 Hz, 2 H), 7.22–7.33 (m, 6 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 20.5, 55.2, 113.4, 125.7, 126.9, 129.8, 130.2, 130.2, 134.3, 135.4, 141.5, 158.5. Anal. Calcd for $C_{14}H_{14}O$ (198.26): C, 84.81; H, 7.12. Found: C, 85.12; H, 7.15.

4′-Methoxybiphenyl-2-carbonitrile (Table 4, Entry 12). GC-MS (100 °C, 2 min → 280 °C, 10 °C min^{-1} → 280 °C, 10 min): t_R = 20.3 min; *m/z* 209. ^{1}H-NMR (300 MHz, $CDCl_3$) δ = 3.88 (s, 3 H), 7.03 (d, *J* = 8.8 Hz, 2 H), 7.25–7.28 (m, 1 H), 7.41 (t, *J* = 7.6 Hz, 1 H), 7.47–7.56 (m, 2 H), 7.63 (t, *J* = 7.7 Hz, 1 H), 7.75 (d, *J* = 7.7 Hz, 1 H). ^{13}C-NMR (75 MHz, $CDCl_3$) δ = 55.3, 111.0, 114.1, 118.9, 127.0, 129.8, 129.9, 130.5, 132.7, 133.7, 145.1, 160.0. Anal. Calcd for $C_{14}H_{11}NO$ (209.24): C, 80.36; H, 5.30; N, 6.69. Found: C, 80.27; H, 5.28; N, 6.71.

Optimized procedure for catalyst recycling (Fig. 4)

Reactions were carried out as described in the general procedure. After cooling to room temperature, the product is extracted with pentane (5 × 4 mL) and further purified by flash-chromatography on SiO_2. The ionic liquid is washed with degassed water (2 × 2 mL), dried under vacuum (~1 mmHg) for 6–8 h and directly reused for the next cycle.

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