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Highly Active Well-Defined Palladium Precatalysts for the Efficient Amination of Aryl Chlorides

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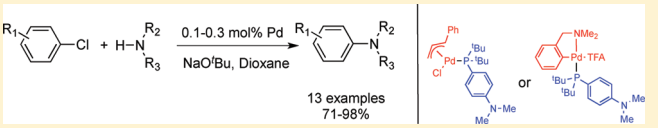
Supporting Information

ABSTRACT: The efficient preparation of [Pd(Amphos)(cinnamyl)Cl)] and [Pd(Amphos)(TFA)(κ^2-*N*,C-C_6H_4-CH_2-NMe_2)] (Amphos = 4-(di-*tert*-butylphosphino)-*N*,*N*-dimethylaniline and TFA = trifluoroacetate), two new well-defined palladium precatalysts, is reported. These complexes prove highly active in the Buchwald−Hartwig amination reaction, allowing the coupling of a wide range of (hetero)aryl chlorides, including unactivated, neutral, and sterically hindered substrates, with a wide range of amines, including primary and secondary amines. Finally, the catalytic systems have proven efficient at low catalyst loadings ranging from 0.1 to 0.3 mol %.



INTRODUCTION

Since its discovery in 1983,[1] the palladium-catalyzed aryl amination reaction, most commonly known as the Buchwald−Hartwig reaction, has emerged as one of the most powerful methods for the formation of C−N bonds.[2,3] During the past decades, in order to increase the versatility and the potential of amination reactions, most efforts have been devoted to the development of new Pd-based precatalysts. The nature of the ligand in these systems appears crucial since its ligation to the metal center dictates the catalytic properties. In this context, a wide range of ligands has been studied, including bulky electron-rich trialkylphosphines,[4] biaryldialkylphosphines,[5] bidentate diphosphines,[6] and N-heterocyclic carbenes (NHCs).[7] The stability of palladium complexes bearing such ligands comes from the strong σ-donating effect of the ligand. The high catalytic activity of these Pd/L systems can be explained by the formation of a highly reactive monoligated [Pd^0L] species,[8] and the facile delivery of such a reactive species can be modulated by ancillary ligand (non L ligands) selection. Most often, the active species is generated *in situ* by mixing a palladium source (oxidation state 0 or +2) with an excess of the ligand L. Nevertheless, in order to better understand the mechanism of the catalytic process and most often increase catalytic performance, the use of a well-defined precatalyst is preferred.

Among the large number of palladium precatalysts described in the literature, [Pd(NHC)(cinnamyl)Cl][7d,e] derivatives (NHC: IPr = *N*,*N*′-bis(2,6-diisopropylphenyl)imidazol-2-ylidene, SIPr = *N*,*N*′-bis(2,6-diisopropylphenyl)-4,5-dihydroimidazol-2-ylidene) and [$Pd(PR_3)(X)(\kappa^2$-*N*,C-C_6H_4-CH_2NMe_2)] palladacycles[9] (X = TFA, OTf, Cl, Br, and I) have proven to be excellent precatalysts in aryl amination reactions, allowing the coupling of unactivated aryl chlorides with catalyst loadings as low as 100 and 1000 ppm, respectively. These two architectures were selected for the present study in view of the ease with which the palladium sheds them to generate the putative [Pd^0L] species.[10,11] Additionally, among the large number of possible phosphine ligands, the 4-(di-*tert*-butylphosphino)-*N*,*N*-dimethylaniline (Amphos) has recently demonstrated good efficiency in Suzuki−Miyaura[12] coupling and moderate reactivity in amination reactions.[13] We thus report here the preparation of two new well-defined Pd-based precatalysts by combining the Amphos ligand with a palladium cinnamyl and a palladacycle moiety (Figure 1). The reactivity of these systems in amination reactions was then examined.

RESULTS AND DISCUSSION

The preparation of two new precatalysts, [Pd(Amphos)(cinnamyl)Cl)] (**1**) and [Pd(Amphos)(TFA)(κ^2-*N*,C−C_6H_4-CH_2NMe_2)] (**2**), is straightforward and makes use of a simple fragmentation of the corresponding palladium dimer[14,15]using the Amphos ligand (Scheme 1). In the case of **1**, the process requires a stoichiometric amount of phosphine and is complete in 1.5 h in THF at room temperature. This synthesis affords the desired complex with an excellent 95% isolated yield after recrystallization. In the case of **2**, a slight excess of phosphine was used (2.1 equiv), and the complex is obtained at room temperature in CH_2Cl_2 with a very good 82% yield in 1 h. Finally, it is noteworthy that both Pd complexes are air- and moisture-stable.

For **1** and **2**, crystals suitable for X-ray diffraction were grown by slow diffusion of hexane into a saturated $CDCl_3$ solution of the complex.[16] In both cases, the bond lengths between palladium and the phosphine are similar (2.3291(15) and 2.3110(13) Å for **1** and **2**, respectively). These values are also comparable to those found for complexes described in the literature.[17] We can note that in the case of **1** the distance between the palladium and the cinnamyl group is comparable to [Pd(NHC)(cinnamyl)Cl] complexes.[7d] The structure of **2** adopts a slightly distorted square-planar geometry, and the bond lengths are similar to

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literature values (within 0.05 Å).[14b] Finally, the percent buried volume of Amphos in both systems was calculated using the web application SambVca.[18] Similar results were obtained for both complexes (**1**: $\%V_{bur}$ = 34.7; **2**: $\%V_{bur}$ = 34.3), showing that the Amphos ligand is quite bulky in comparison to reported tertiary phosphine congeners.[19]

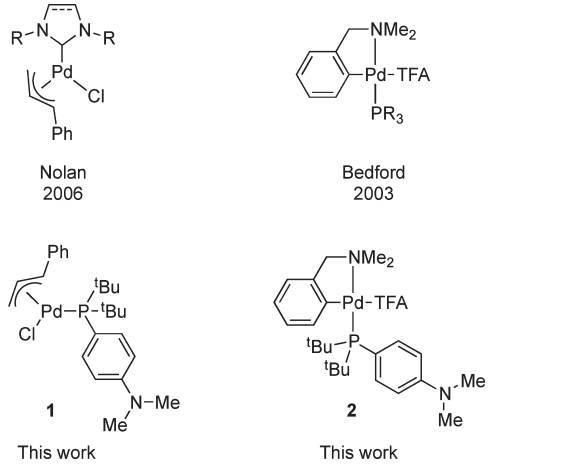
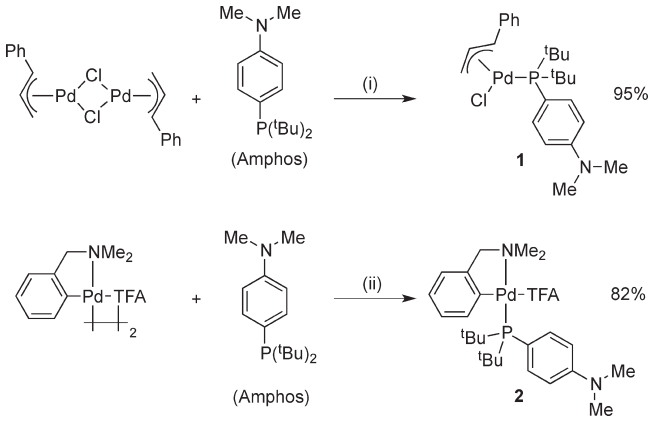


Figure 1. Design of the new palladium/Amphos precatalysts.

Scheme 1. Synthesis of the Two New Well-Defined Palladium Precatalysts 1 and 2[a,b]



[a] Reagents and conditions: (i) [Pd(cinnamyl)(μ-Cl)]$_2$ (1 equiv), Amphos (2 equiv), THF, rt, 1.5 h; (ii) [{Pd(μ-TFA)-(κ^2-*N*,*C*-C_6H_4-CH_2NMe_2)}$_2$] (1 equiv), Amphos (2.1 equiv), CH_2Cl_2, rt, 1 h. [b] Isolated yields.

One of the current challenges in amination reactions is to achieve the coupling of unactivated chlorides at low catalyst loadings. In order to perform a rapid optimization of reaction conditions using a challenging aryl halide, the reactivity of 4-chloroanisole with morpholine was examined. At first, 0.1 mol % of the palladacycle **2** was used, using conditions previously described by Bedford and Cazin,[9] using sodium *tert*-butoxide (NaO^tBu) as the base in toluene for 17 h at 110 °C (Table 1, entry 1). Under these conditions, the desired product **3** is obtained in 50% conversion of the starting 4-chloroanisole. In order to favor the formation of **3**, several bases and solvents were next screened. It was found that weaker bases such as NaOH, KOH, K_3PO_4, or carbonate bases (Table 1, entries 3−8) did not prove as efficient as the stronger NaO^tBu. Surprisingly, under these conditions, it was shown that KO^tBu as base led to poor conversion (10%, Table 1, entry 2) in comparison to reactions conducted using NaO^tBu. Several

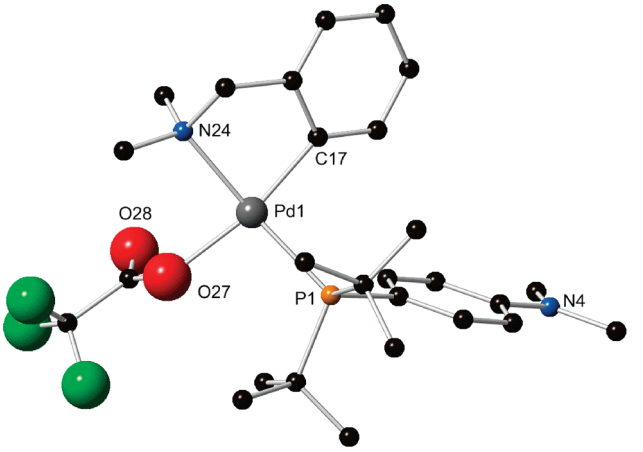


Figure 3. Graphical representation of **2**. Hydrogens have been omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd1−C17, 2.015(5); Pd1−O27, 2.141(3); Pd1−N24, 2.181(4); Pd1−P1, 2.3110(13); C17−Pd1−N24 81.32(18), O27−Pd1−N24 87.56(15), C17−Pd1−P1 95.36(15), O27−Pd1−P1 96.16(10).

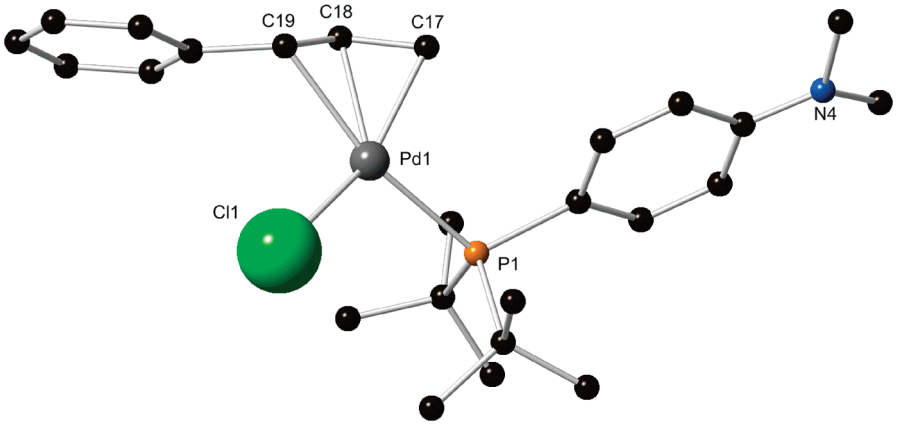


Figure 2. Graphical representation of **1**. Hydrogens have been omitted for clarity. Selected bond lengths (Å) and angles (deg): Pd1−C17, 2.115(6); Pd1−C18, 2.154(6); Pd1−C19, 2.273(6); Pd1−P1, 2.3291(15); Pd1−Cl1, 2.3672(15); C17−Pd1−C19, 67.0(2); C17−Pd1−P1, 97.29(18); C19−Pd1−Cl1, 93.56(16); P1−Pd1−Cl1, 102.68(5).

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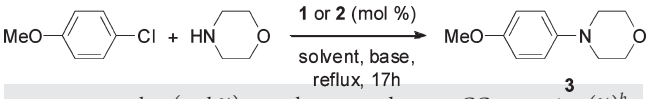
Table 1. Optimization of the Reaction Conditions[a]



entry	precatalyst (mol %)	solvent	base	GC conversion (%)[b]
1	**2** (0.1)	toluene	NaO^{t}Bu	50
2	**2** (0.1)	toluene	KO^{t}Bu	10
3	**2** (0.1)	toluene	NaOH	2
4	**2** (0.1)	toluene	KOH	4
5	**2** (0.1)	toluene	K_3PO_4	6
6	**2** (0.1)	toluene	Na_2CO_3	0
7	**2** (0.1)	toluene	K_2CO_3	0
8	**2** (0.1)	toluene	Cs_2CO_3	4
9	**2** (0.1)	1,4-dioxane	NaO^{t}Bu	90
10	**2** (0.1)	DME	NaO^{t}Bu	12
11	**2** (0.1)	THF	NaO^{t}Bu	2
12	**1** (0.1)	1,4-dioxane	NaO^{t}Bu	95
13	**1** (0.15)	1,4-dioxane	NaO^{t}Bu	99 (85)[c]
14	**1** (0.1)	1,4-dioxane	KO^{t}Bu	16[d]
15	**1** (0.1)	1,4-dioxane	NaOH	0
16	**1** (0.1)	1,4-dioxane	KOH	2
17	**1** (0.1)	1,4-dioxane	K_3PO_4	0
18	**1** (0.1)	1,4-dioxane	Cs_2CO_3	0
19	**1** (0.05)	1,4-dioxane	NaO^{t}Bu	82
20	**2** (0.05)	1,4-dioxane	NaO^{t}Bu	65

[a] Reagents and conditions: 4-chloroanisole (1 equiv), morpholine (1.26 equiv), Pd precatalyst **1** or **2** (mol %), solvent, base (1.40 equiv), reflux, 17 h. [b] Conversion to coupling product based on 4-chloroanisole determined by GC. [c] Isolated yield after chromatography on silica gel, average of two runs. [d] The formation of **3** and another unidentified product is observed by GC.

solvents were next screened. While 1,2-dimethoxyethane (DME) and tetrahydrofuran (THF) gave poor conversions (Table 1, entries 10 and 11), 1,4-dioxane gave the best result, affording the desired product with conversions up to 90% (Table 1, entry 9). This result can probably be explained by the stabilization of the [Pd^0-L] active species by the high-boiling and donating 1,4-dioxane.

The activity of the second palladium cinnamyl precatalyst **1** was next studied under similar conditions to those optimized for **2**. The reaction proved very efficient when using the NaO^{t}Bu/1,4-dioxane combination, permitting a 95% conversion of the starting 4-chloroanisole (Table 1, entry 12). Other bases gave no or poor conversions (Table 1, entries 14−18). Finally, complete conversion can be obtained by using 1.4 equivalents of NaO^{t}Bu, refluxing the 1,4-dioxane during 17 h with 0.15 mol % **1** (99%, Table 1, entry 13). To compare the efficiency of both **1** and **2**, the catalyst loading was further decreased. The reaction was then performed using 0.05 mol % Pd, showing that **1** provided an improved conversion over that obtained with **2** (82% vs 65%, Table 1, entry 19 vs entry 20). For this reason, the scope of the reaction was next explored using **1** as precatalyst in the presence of 1,4-dioxane and NaO^{t}Bu.

The results are summarized in Table 2. The system displays good efficiency for the coupling of nonactivated (Table 2, entries 1 and 2) and deactivated chlorides (Table 2, entry 3) with cyclic dialkylamines, yielding the expected compounds in excellent isolated yields (82−93%). If steric hindrance is increased about the coupling partner reaction site, such as in the case of 2-chlorotoluene, the amount of palladium necessary to reach completion had to be slightly increased (0.3 mol %). The case of the more challenging *N*-methylaniline (Table 2, entries 4 and 5) was next explored, and using 0.3 mol % of **1**, the expected aniline derivatives were obtained in very good yields (84−89%). The reactivity of some primary amines with some sterically hindered aryl chlorides was next studied. Excellent results were obtained in these instances, and the corresponding secondary amines were isolated in high yields (Table 2, entries 6−9, 86−98%). It is noteworthy here that the necessary amount of palladium to reach completion appears dependent on the bulkiness of the amine. However, the reaction requires only 0.2 mol % of **1** to allow the coupling of 2,6-dimethylchlorobenzene with the bulkiest 2,6-diisopropylaniline (Table 2, entry 9). 1-Chloronaphthalene could be successfully coupled to piperidine (Table 2, entry 10). Despite the fact that a significant amount of the dehydrohalogenated product (naphthalene) was detected by GC (<10%), the formation of the desired product was obtained with a good, 71% isolated yield. Finally, the compatibility of the catalytic system with heterocycles was demonstrated, and very good results were obtained for the coupling of 2-chloropyridine, but also for the more challenging deactivated 3-chloropyridine (Table 2, entries 11−13, 77−85%).

CONCLUSION

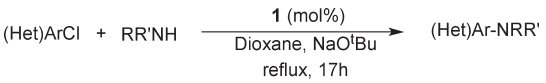
In summary, we have disclosed a facile and efficient access to two new, well-defined palladium precatalysts containing the Amphos ligand. These complexes have shown excellent catalytic activities in the Buchwald−Hartwig reaction, allowing for coupling of various (hetero)aryl chlorides with a wide range of amines in very good yields (71−98%) and using low catalyst loadings (0.1−0.3 mol %). The use of these systems in flow chemistry is presently being examined in our laboratories.

EXPERIMENTAL SECTION

Synthesis of [Pd(Amphos)(cinnamyl)Cl)], 1. In a glovebox, in a 100 mL round-bottom flask equipped with a magnetic bar, [Pd(cinnamyl)(μ-Cl)]$_2$ (1.04 g, 2 mmol) and Amphos (1.06 g, 4 mmol) were added to THF (30 mL). The reaction mixture was stirred at room temperature during 1.5 h. After this time, outside the glovebox, THF was concentrated, and the complex was precipitated with pentane and collected by filtration. The complex was recrystallized from DCM and pentane, yielding the title compound as a yellow powder, 2.0 g (95%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.56−7.51 (m, 4H, H_{Ar}), 7.37−7.27 (m, 3H, H_{Ar}), 6.67 (dd, J_{HH} = 9.0 Hz, J'_{HH} = 1.1 Hz, 2H, H_{Ar}), 5.90−5.82 (m, 1H, H_{Cin}), 5.21−5.15 (m, 1H, H_{Cin}), 3.30 (dd, J_{HH} = 6.5 Hz, J'_{HH} = 1.5 Hz, 1H, H_{Cin}), 3.01 (s, 6H, NCH_3), 2.71 (d, J_{HH} = 11.6 Hz, 1H, H_{Cin}), 1.47 (d, J_{HP} = 14 Hz, 9H, CCH_3), 1.38 (d, J_{HP} = 13.9 Hz, 9H, CCH_3). ^{13}C{^{1}H} NMR (100 MHz, $CDCl_3$): δ 151.0 (d, J_{CP} = 1.5 Hz, C_{Ar}), 137.0 (d, J_{CP} = 5.9 Hz, C_{Ar}), 136.7 (d, J_{CP} = 12.5 Hz, C_{Ar}), 128.8 (d, J_{CP} = 1.0 Hz, C_{Ar}), 128.1 (d, J_{CP} = 2.9 Hz, C_{Ar}), 127.9 (d, J_{CP} = 2.2 Hz, C_{Ar}), 117.1 (d, J_{CP} = 36.0 Hz, C_{Ar}), 110.5 (d, J_{CP} = 10.3 Hz, C_{Ar}), 108.9 (d, J_{CP} = 5.9 Hz, C_{Cin}), 99.7 (d, J_{CP} = 26.4 Hz, C_{Cin}), 55.2 (C_{Cin}), 40.1 (NCH_3), 36.3 (d, J_{CP} = 13.9 Hz, CMe_3), 36.2 (d, J_{CP} = 13.2 Hz, CMe_3), 30.7 (d, J_{CP} = 5.9 Hz, $C(CH_3)_3$), 30.2 (d, J_{CP} = 5.1 Hz, $C(CH_3)_3$). ^{31}P{^{1}H} NMR (162 MHz, $CDCl_3$): δ 67.0 (s) Anal. Calcd for $C_{25}H_{37}ClNPPd$: C, 57.26; H, 7.11; N, 2.67. Found: C, 57.36; H, 6.93; N, 2.79.

Synthesis of [Pd(Amphos)(TFA)(κ^2*N*,C-C_6H_4-CH_2NMe_2)], 2. In a glovebox, a 50 mL Schlenk flask equipped with a magnetic bar

Table 2. Scope of the Amination Reaction[a]



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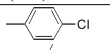
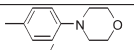
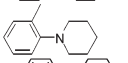
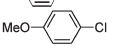
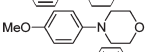
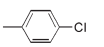
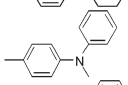
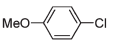
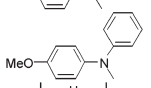
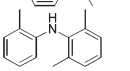
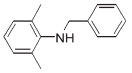
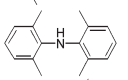
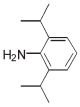
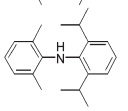
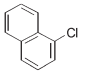
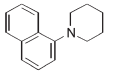
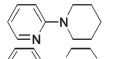
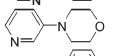
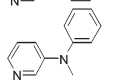
1			0.1		93
2			0.3		82
3			0.15		85
4			0.3		89
5			0.3		84
6			0.15		86
7			0.1		88
8			0.15		98
9			0.2		94
10			0.1		71[c]
11			0.2		85
12			0.2		77
13			0.1		80

[a] Reagents and conditions: (Het)ArCl (1 equiv), amine (1.2−1.3 equiv), **1** (mol %), base (1.4 equiv), 1,4-dioxane, reflux, 17 h. [b] Isolated yield after chromatography on silica gel, average of two runs. [c] Hydrodehalogenation side-product observed by GC (<10%).

was charged with $[Pd(TFA)(\kappa^2\text{-}N,C\text{-}C_6H_4\text{-}CH_2NMe_2)]_2$ (0.283 mmol, 0.200 g), Amphos (0.595 mmol, 0.157 g), and 1,2-dichloromethane (DCM) (11 mL). The reaction mixture was stirred at room temperature during 1 h. After this time, outside the glovebox, the solvent was concentrated to ca. 1 mL *in vacuo*, and ethanol (10 mL) was added. The solution was concentrated, leading to the precipitation of a yellow solid. The supernatant was removed, and the solvents were evaporated *in vacuo*, yielding the title compound as a yellow powder, 0.286 g (82%). ^{1}H NMR (400 MHz, CD_2Cl_2): δ 7.47−7.41 (m, 2H, H_{Ar}), 6.87 (dd, J_{HH} = 7.3 Hz, J'_{HH} = 1.4 Hz, 1H, H_{Ar}), 6.74 (td, J_{HH} = 7.3 Hz, J'_{HH} = 1.4 Hz, 1H, H_{Ar}), 6.47 (dd, J_{HH} = 9.0 Hz, J'_{HH} = 1.4 Hz, 2H, H_{Ar}), 6.40−6.29 (m, 2H, H_{Ar}), 3.94 (s, 2H, CH_2), 2.93 (s, 6H, NCH_3), 2.62 (s, 6H, NCH_3), 1.47 (d, J_{CP} = 13.8 Hz, 18H, CCH_3). ^{13}C {^{1}H} NMR (100 MHz, $CDCl_3$): δ 151.1 (d, J_{CP} = 2.1 Hz, C=O), 147.5 (d, J_{CP} = 2.1 Hz, C_{Ar}), 146.0 (d, J_{CP} = 2.1 Hz, C_{Ar}), 139.3 (d, J_{CP} = 6.9 Hz, C_{Ar}), 137.1 (d, J_{CP} = 9.7 Hz, C_{Ar}), 124.5 (d, J_{CP} = 4.2 Hz, C_{Ar}), 123.5 (C_{Ar}), 122.2 (C_{Ar}), 113.9 (C_{Ar}), 113.4 (C_{Ar}), 110.4 (d, J_{CP} = 10.4 Hz, C_{Ar}), 72.4 (d, J_{CP} = 2.8 Hz, CH_2), 49.7 (d, J_{CP} = 2.1 Hz, NCH_3), 40.1 (NCH_3), 37.4 (CMe_3), 37.1 (CMe_3), 30.8 (d, J_{CP} = 4.2 Hz, $C(CH_3)_3$). ^{31}P{^{1}H} NMR (162 MHz, CD_2Cl_2): δ 67.2 (s). Anal. Calcd for $C_{27}H_{40}F_3N_2O_2PPd$: C, 52.39; H, 6.51; N, 4.53. Found: C, 52.51; H, 6.60; N, 4.47.

Buchwald−Hartwig Cross-Coupling of Aryl Halides with Primary and Secondary Amines: General Procedure. In a glovebox, a vial equipped with a stirring bar and sealed with a screw cap fitted with a septum was charged with NaO^{t}Bu (0.136 g, 1.4 mmol) and the necessary amount of 1,4-dioxane to bring the total solvent volume to 3 mL. Outside the glovebox, the aryl chloride (1.0 mmol), the amine (1.2 −1.3 mmol), and finally the precatalyst solution were added. The reaction mixture was stirred at reflux during 17 h. The reaction mixture was cooled, quenched with $HCl_{(aq)}$ (5 mL, 2.3 M), and neutralized with $NaOH_{(aq)}$ (5 mL, 5 M), and the aqueous layer was extracted with DCM (3 × 10 mL). The combined organic layers were dried over $MgSO_4$, and the solvents were evaporated *in vacuo*. The crude product was finally purified by flash chromatography on silica gel. The reported yields are the average of two reactions.

■ ASSOCIATED CONTENT

Supporting Information. Crystallographic data for **1** and **2**, procedure for the amination reactions, and NMR spectra for all complexes and cross coupling products. This material is available free of charge via the Internet at http://pubs.acs.org.

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REFERENCES

(1) Kosugi, M.; Kameyama, M.; Migita, T. *Chem. Lett.* **1983**, 927.

(2) For early references on amination reactions see: (a) Guram, A. S.; Rennels, R. A.; Buchwald, S. L. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1348. (b) Louie, J.; Hartwig, J. F. *Tetrahedron Lett.* **1995**, *36*, 3609.

(3) For reviews on amination reactions see: (a) Hartwig, J. F. *Handbook of Organopalladium Chemistry for Organic Synthesis*; 2002; Vol. 1, p 1051. (b) Muci, A. R.; Buchwald, S. L. *Top. Curr. Chem.* **2002**, *219*, 131. (c) Bedford, R. B.; Cazin, C. S. J.; Holder, D. *Coord. Chem. Rev.* **2004**, *248*, 2283.(d) Jiang, L.; Buchwald, S. L. *Metal-Catalyzed Cross-Coupling Reactions*, 2nd Ed.; 2004; Vol. 2, p 699. (e) Hartwig, J. F. *Acc. Chem. Res.* **2008**, *41*, 1534.

(4) (a) Littke, A. F.; Dai, C.; Fu, G. C. *J. Am. Chem. Soc.* **2000**, *122*, 4020. (b) Hill, L. L.; Smith, J. M.; Brown, W. S.; Moore, L. R.; Guevera, P.; Pair, E. S.; Porter, J.; Chou, J.; Wolterman, C. J.; Craciun, R.; Dixon, D. A.; Shaughnessy, K. H. *Tetrahedron* **2008**, *64*, 6920. (c) Fleckenstein, C. A.; Plenio, H. *Chem. Soc. Rev.* **2010**, *39*, 694.

(5) (a) Surry, D. S.; Buchwald, S. L. *Angew. Chem., Int. Ed.* **2008**, *47*, 6338. (b) Surry, D. S.; Buchwald, S. L. *Chem. Sci.* **2011**, *2*, 27.

(6) (a) Wolfe, J. P.; Wagaw, S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 7215. (b) Driver, M. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 7217. (c) Wolfe, J. P.; Buchwald, S. L. *J. Org. Chem.* **2000**, *65*, 1144. (d) Shen, Q.; Shekhar, S.; Stambuli, J. P.; Hartwig, J. F. *Angew. Chem., Int. Ed.* **2005**, *44*, 1371. (e) Shen, Q.; Ogata, T.; Hartwig, J. F. *J. Am. Chem. Soc.* **2008**, *130*, 6586.

(7) (a) Viciu, M. S.; Kissling, R. M.; Stevens, E. D.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 2229. (b) Navarro, O.; Marion, N.; Scott, N. M.; Gonzalez, J.; Amoroso, D.; Bell, A.; Nolan, S. P. *Tetrahedron* **2005**, *61*, 9716. (c) Marion, N.; Ecarnot, E. C.; Navarro, O.; Amoroso, D.; Bell, A.; Nolan, S. P. *J. Org. Chem.* **2006**, *71*, 3816. (d) Marion, N.; Navarro, O.; Mei, J.; Stevens, E. D.; Scott, N. M.; Nolan, S. P. *J. Am. Chem. Soc.* **2006**, *128*, 4101. (e) Navarro, O.; Marion, N.; Mei, J.; Nolan, S. P. *Chem.—Eur. J.* **2006**, *12*, 5142. (f) Esposito, O.; Gois, P. M. P.; Lewis, A. K. d. K.; Caddick, S.; Cloke, F. G. N.; Hitchcock, P. B. *Organometallics* **2008**, *27*, 6411. (g) Organ, M. G.; Abdel-Hadi, M.; Avola, S.; Dubovyk, I.; Hadei, N.; Kantchev, E. A. B.; O'Brien, C. J.; Sayah, M.; Valente, C. *Chem.—Eur. J.* **2008**, *14*, 2443. (h) Jin, Z.; Guo, S.-X.; Gu, X.-P.; Qiu, L.-L.; Song, H.-B.; Fang, J.-X. *Adv. Synth. Catal.* **2009**, *351*, 1575. (i) Fortman, G. C.; Nolan, S. P. *Chem. Soc. Rev.* **2011**, DOI: 10.1039/C1CS15088J.

(8) Christmann, U.; Vilar, R. *Angew. Chem., Int. Ed.* **2005**, *44*, 366.

(9) Bedford, R. B.; Cazin, C. S. J.; Coles, S. J.; Gelbrich, T.; Horton, P. N.; Hursthouse, M. B.; Light, M. E. *Organometallics* **2003**, *22*, 987.

(10) (a) For the first mechanistic details involving imines: Bedford, R. B.; Cazin, C. S. J.; Hursthouse, M. B.; Light, M. E.; Pike, K. J.; Wimperis, S. *J. Organomet. Chem.* **2001**, *633*, 173. (b) For the first use of dmba to such an end see: Bedford, R. B.; Cazin, C. S. J. *Chem. Commun.* **2001**, 1540.

(11) (a) Viciu, M. S.; Germaneau, R. F.; Nolan, S. P. *Org. Lett.* **2002**, *4*, 4053. (b) Viciu, M. S.; Germaneau, R. F.; Navarro, O.; Stevens, E. D.; Nolan, S. P. *Organometallics* **2002**, *21*, 5470. (c) Viciu, M. S.; Kelly, R. A., III; Stevens, E. D.; Naud, F.; Studer, M.; Nolan, S. P. *Org. Lett.* **2003**, *5*, 1479. (d) Cämmerer, S.; Viciu, M. S.; Stevens, E. D.; Nolan, S. P. *Synlett* **2003**, 1871. (e) Viciu, M. S.; Navarro, O.; Germaneau, R. F.; Kelly, R. A., III; Sommer, W.; Marion, N.; Stevens, E. D.; Cavallo, L.; Nolan, S. P. *Organometallics* **2004**, *23*, 1629.

(12) Guram, A. S.; King, A. O.; Allen, J. G.; Wang, X.; Schenkel, L. B.; Chan, J.; Bunel, E. E.; Faul, M. M.; Larsen, R. D.; Martinelli, M. J.; Reider, P. J. *Org. Lett.* **2006**, *8*, 1787.

(13) Lundgren, R. J.; Sappong-Kumankumah, A.; Stradiotto, M. *Chem.—Eur. J.* **2010**, *16*, 1983.

(14) $[Pd(cinnamyl)(\mu\text{-}Cl)]_2$ is commercially available from Umicore. $[\{Pd(\mu\text{-}TFA)\text{-}(\kappa^2\text{-}N,C\text{-}C_6H_4CH_2NMe_2)\}_2]$ is prepared in a two-step literature procedure.[9]

(15) For recent use of $[Pd(cinnamyl)(\mu\text{-}Cl)]_2$ as a palladium source in catalysis, see: (a) Watson, D. A.; Su, M.; Teverovskiy, G.; Zhang, Y.; Garcia-Fortanet, J.; Kinzel, T.; Buchwald, S. L. *Science* **2009**, *325*, 1661. (b) Dumrath, A.; Wu, X.-F.; Neumann, H.; Spannenberg, A.; Jackstell, R.; Beller, M. *Angew. Chem., Int. Ed.* **2010**, *49*, 8988. (c) Wu, X.-F.; Sundararaju, B.; Neumann, H.; Dixneuf, P. H.; Beller, M. *Chem.—Eur. J.* **2011**, *17*, 106.

(16) CCDC-830310 (**1**) and CCDC-830311 (**2**) contain the supplementary crystallographic data for this contribution. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

(17) (a) As a comparison for **1** see for example the case of $[Pd(\eta^3\text{-}allyl)(PNSO)]$: Achard, T.; Benet-Buchholz, J.; Escudero-Adan, E. C.; Riera, A.; Verdaguer, X. *Organometallics* **2011**, *30*, 3119. (b) As a comparison for **2** see for example the cases of $[Pd(PR_3)(X)(\kappa^2\text{-}N,C\text{-}C_6H_4\text{-}CH_2NMe_2)]$ palladacycles: Bedford, R. B.; Cazin, C. S. J.; Coles, S. J.; Gelbrich, T.; Horton, P. N.; Hursthouse, M. B.; Light, M. E. *Organometallics* **2003**, *22*, 987.

(18) (a) https://www.molnac.unisa.it/OMtools/sambvca.php. (b) Poater, A.; Cosenza, B.; Correa, A.; Giudice, S.; Ragone, F.; Scarano, V.; Cavallo, L. *Eur. J. Inorg. Chem.* **2009**, 1759. (c) Clavier, H.; Correa, A.; Cavallo, L.; Escudero-Adan, E. C.; Benet-Buchholz, J.; Slawin, A. M. Z.; Nolan, S. P. *Eur. J. Inorg. Chem.* **2009**, 1767.

(19) Among 13 tertiary phosphines, only $P(C_6F_5)_3$, $P(o\text{-}Tol)_3$, and $P(Mes)_3$ have a bigger buried volume than Amphos for a M—P length of 2.28 Å: Clavier, H.; Nolan, S. P. *Chem. Commun.* **2010**, *46*, 841.