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Convenient Formation of Triarylphosphines by Nickel-Catalyzed C–P Cross-Coupling with Aryl Chlorides

Meng Sun,*[a] Yu-Shi Zang,[a] Le-Kai Hou,[a] Xiang-Xiang Chen,[a] Wei Sun,[a] and Shang-Dong Yang[b]

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A convenient strategy has been developed for the preparation of various phosphine ligands in good to excellent yields through a nickel-catalyzed C–P bond-forming step. This reaction proceeded smoothly and tolerated a variety of functional groups to provide a new method for the synthesis of important phosphine ligands through the direct cleavage of a C–Cl bond.

Introduction

As one of the most useful ligands, tertiary phosphines as well as their derivatives have applications in many reactions that are catalyzed by transition metals.[1] In addition, phosphines and phosphonate derivatives are fundamental building blocks that are widely used in the fields of medicinal[2] and materials chemistry.[3] With regard to the development of the synthesis of phosphine ligands, direct C–P cross-coupling reactions that are catalyzed by transition metals are one of the most valuable and highly efficient procedures. Since the pioneering work of Stelzer and co-workers[4] in 1996, most researchers have focused on the development of palladium-,[5] copper-,[6] and nickel-catalyzed[7] phosphinations of aryl bromides/iodides or aryl triflates to synthesize tertiary phosphines. In addition, Merck Research Laboratories developed a Ni-catalyzed method for the synthesis of BINAP [2,2′-bis(diphenylphosphino)-1,1′-binaphthyl].[8a] Recently, in studies of C–Cl bond functionalization, some groups reported the use of aryl chlorides in the direct C–P cross-coupling reaction, the idea of which was a significant advance in this field.[8] For example, Han and co-workers[9] developed the nickel-catalyzed cross-coupling reaction of an aryl chloride with diphenylphosphine oxide, which demonstrated a new and convenient method to synthesize phosphine derivatives. Similarly, a few related protocols based on diphenylphosphine oxide were developed by Zhao[10] and Wu's group[11] to construct C–P bonds. Although great progress has been achieved in this field over the past decades, studies of the direct synthesis of tertiary phosphines ligands by using aryl chloride derivatives as the substrate are rare.[12] Very recently, our group discovered a highly efficient protocol for the preparation of various diphenylphosphoryl ligands by employing a nickel-catalyzed C–CN bond cleavage.[13] Considering the small difference between the bond-dissociation energies (BED) of the C–Cl (79 kcal mol^{-1}) and C–CN bond (83 kcal mol^{-1}),[14] we hypothesize that aryl chlorides can be cleaved under the similar conditions. Following our interest in organic phosphine chemistry,[15] we herein report a convenient, new, and efficient approach with wide substrate scope to synthesize a number of different phosphine ligands through the nickel-catalyzed activation of the C–Cl bond.

Results and Discussion

Our initial investigation focused on the model reaction of chlorobenzene (**1a**, 0.5 mmol) and Me_3SiPPh_2[16,17a] (**2a**, 1.0 mmol) with *t*BuOK (1.5 equiv.) in the presence of $NiCl_2(PPh_3)_2$ (10 mol-%) in dioxane at 90 °C for 12 h (see Table 1, Entry 1). To our delight, the desired product **3a** was obtained in high yield, and further screening of the solvent showed no improvement to this result (see Table 1, Entries 2–5). In addition, different Ni catalysts and $PdCl_2(PPh_3)_2$ were also investigated, the results of which show that $NiCl_2(PCy_3)_2$ (Cy = cyclohexyl) had the same catalytic activity as $NiCl_2(PPh_3)_2$ (see Table 1, Entries 6–8). Considering the high price of $NiCl_2(PCy_3)_2$ compared with $NiCl_2(PPh_3)_2$ and other less efficient Ni catalysts, we selected $NiCl_2(PPh_3)_2$ as the best choice. To show the significance of the base, we employed *t*BuONa in this transformation, which also afforded a good yield of product (see Table 1, Entry 9). Other bases such as MeONa, Cs_2CO_3, and K_3PO_4 were less effective or impeded the reaction (see

[a] Key Laboratory of Synthetic and Natural Functional Molecule Chemistry of Ministry of Education, Department of Chemistry & Materials Science, Northwest University, Xi'an 710069, P. R. China
E-mail: sunmeng@nwu.edu.cn
http://chem.nwu.edu.cn
[b] State Key Laboratory of Applied Organic Chemistry, Lanzhou University, Lanzhou 730000, P. R. China

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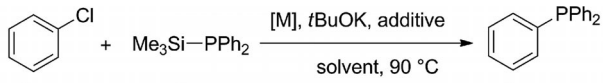
Table 1, Entries 10–12). It should be noted that this transformation only worked well in the presence of both $NiCl_2(PPh_3)_2$ and *t*BuOK (see Table 1, Entries 13 and 14). Decreasing the amount of $NiCl_2(PPh_3)_2$ was worthwhile, as a loading of only 3% effectively catalyzed the reaction (see Table 1, Entries 15–17). Meanwhile, the stoichiometry of the reaction also served an important role, and more or less of the base did affect the yield of the product (see Table 1, Entries 18 and 19). A further increase or decrease to the reaction temperature suppressed the efficiency of the reaction, and decreasing the temperature to 70 °C resulted in a distinct reduction of yield (see Table 1, Entries 20 and 21). In addition, different sources of fluoride such as KF, Bu_4NF, CuF_2, and AgF were examined, but no obvious positive effect was observed (see Table 1, Entries 22 and 23). Finally, the optimized conditions for the Ni-catalyzed C–P cross-coupling reaction included 3 mol-% $NiCl_2(PPh_3)_2$ as the catalyst, 1.5 equiv. of *t*BuOK as the base, and 2.0 equiv. of Me_3SiPPh_2 as the phosphine reagent in the solvent dioxane at 90 °C for 12 h.

Table 1. Optimization of the reaction conditions.[a]



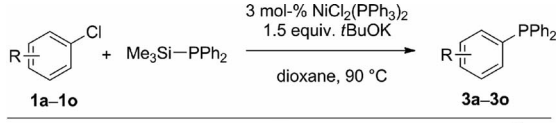
1a 2a 3a

Entry	Catalyst (mol-%)	Base, equiv.	Solvent	Yield [%][b]
1	$NiCl_2(PPh_3)_2$ (10)	*t*BuOK, 1.5	dioxane	95%
2	$NiCl_2(PPh_3)_2$ (10)	*t*BuOK, 1.5	toluene	71%
3	$NiCl_2(PPh_3)_2$ (10)	*t*BuOK, 1.5	DMF	54%
4	$NiCl_2(PPh_3)_2$ (10)	*t*BuOK, 1.5	THF	22%
5	$NiCl_2(PPh_3)_2$ (10)	*t*BuOK, 1.5	NMP	23%
6	$NiCl_2(PCy_3)_2$ (10)	*t*BuOK. 1.5	dioxane	97%
7	$NiCl_2$ (10)	*t*BuOK, 1.5	dioxane	46%
8	$PdCl_2(PPh_3)_2$ (10)	*t*BuOK, 1.5	dioxane	n.r.
9	$NiCl_2(PPh_3)_2$ (10)	*t*BuONa, 1.5	dioxane	81%
10	$NiCl_2(PPh_3)_2$ (10)	CH_3ONa, 1.5	dioxane	34%
11	$NiCl_2(PPh_3)_2$ (10)	Cs_2CO_3, 1.5	dioxane	n.r.
12	$NiCl_2(PPh_3)_2$ (10)	K_3PO_4, 1.5	dioxane	n.r.
13	$NiCl_2(PPh_3)_2$ (10)		dioxane	<5%
14		*t*BuOK, 1.5	dioxane	n.r.
15	$NiCl_2(PPh_3)_2$ (5)	*t*BuOK, 1.5	dioxane	95%
16	**$NiCl_2(PPh_3)_2$ (3)**	**tBuOK, 1.5**	**dioxane**	**93%**
17	$NiCl_2(PPh_3)_2$ (2)	*t*BuOK, 1.5	dioxane	68%
18	$NiCl_2(PPh_3)_2$ (3)	*t*BuOK, 2.0	dioxane	88%
19	$NiCl_2(PPh_3)_2$ (3)	*t*BuOK, 1.0	dioxane	63%
20	$NiCl_2(PPh_3)_2$ (3)	*t*BuOK, 1.5	dioxane	90%[c]
21	$NiCl_2(PPh_3)_2$ (3)	*t*BuOK, 1.5	dioxane	34%[d]
22	$NiCl_2(PPh_3)_2$ (3)	*t*BuOK, 1.5	dioxane	78%[e]
23	$NiCl_2(PPh_3)_2$ (3)	*t*BuOK, 1.5	dioxane	82%[f]

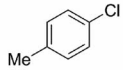
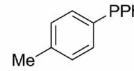
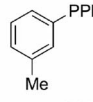
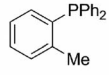
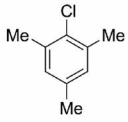
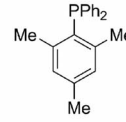
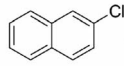
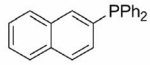
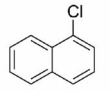
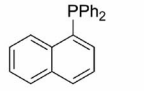
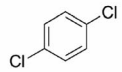
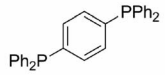
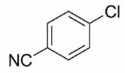
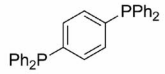
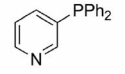
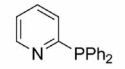
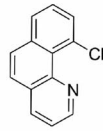
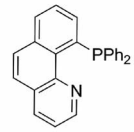
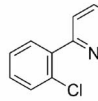
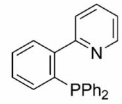
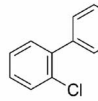
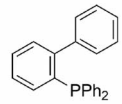
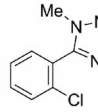
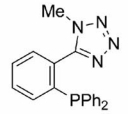
[a] All the reactions were carried out in the presence of **1a** (0.5 mmol) and **2a** (1.0 mmol) in different solvents (5.0 mL) at 90 °C for 12 h under Ar; DMF = *N*,*N*-dimethylformamide, THF = tetrahydrofuran, NMP = *N*-methyl-2-pyrrolidone, n.r.: no reaction. [b] Yield of isolated product. [c] The reaction was carried out at 110 °C. [d] The reaction was carried out at 70 °C. [e] KF (2.0 equiv.) was added. [f] CuF_2 (2.0 equiv.) was added.

With the optimized reaction conditions in hand, the scope of different aryl chlorides was investigated, and the results are summarized in Table 2. Moderate to excellent

Table 2. The scope of different aryl chloride compounds.[a]



1a–1o 3a–3o

Entry	R-Cl		Products		Yield [%][b]
1		1a		3a	93%
2		1b		3b	90%
3		1c		3c	82%
4		1d		3d	49%[c]
5		1e		3e	trace
6		1f		3f	88%
7		1g		3g	76%
8		1h		3h	65%[d]
9		1i		3h	60%[d]
10		1j		3j	54% (34)[e]
11		1k		3k	48% (32)[e]
12		1l		3l	75%
13		1m		3m	79%
14		1n		3n	n.r.
15		1o		3o	62%

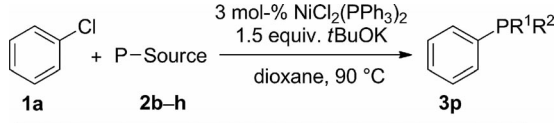
[a] All the reactions were carried out under the optimized conditions for 12 h. [b] Yield of isolated product. [c] Yield determined by ^1H NMR spectroscopic analysis. [d] The corresponding product was obtained by using *t*BuOK (3.0 equiv.), Me_3SiPPh_2 (4.0 equiv.), and $NiCl_2(PPh_3)_2$ (10 mol-%) at 90 °C under argon. [e] Yield in parentheses corresponds to reaction performed in the absence of the catalyst.

yields were isolated for most cases. Generally, the aryl chloride derivatives that contained electron-donating groups gave better yields than those with electron-withdrawing groups. 4-Chloro- and 3-chlorotoluene provided the corresponding products in excellent yields (see Table 2, Entries 2 and 3). Nevertheless, 2-chlorotoluene, which was sterically hindered, afforded a lower yield, and the increased steric hindrance of 2-chloromesitylene proved to have a negative effect on the reaction (see Table 2, Entries 4 and 5). It is satisfying that chloronaphthalene also showed high compatibility for the reaction, and the corresponding tertiary phosphines were obtained in 88 and 76% yield, respectively (see Table 2, Entries 6 and 7). In addition, the chlorobenzene derivatives that contained electron-withdrawing groups, for example, 4,4′-dichlorobenzene and 4-chlorobenzonitrile were successfully coupled[18] to Me_3SiPPh_2, and the bidentate phosphine ligands were smoothly obtained in good yields (see Table 2, Entries 8 and 9). However, aryl chlorides with other substituents, such as those that contained F, Br, I, or OTf (trifluoromethanesulfonate), were not compatible under these conditions. Further exploration disclosed that some heteroaromatic chlorides could be favorably employed under our new reaction conditions. Indeed, 3-chloro- and 2-chloropyridine afforded the corresponding products in moderate yields. In the absence of the catalyst, these heterocyclic compounds also gave the nucleophilic aromatic substitution products in relatively lower yields (see Table 2, Entries 10 and 11). Moreover, **3l**, **3m**, and **3o** were prepared in good yields compared with the reaction of 2-chlorobiphenyl (**1n**), which remained unreactive under the best conditions. The nitrogen atom directing group may be the reason for these different results (see Table 2, Entries 12–15).

Next, we examined the scope of the phosphine derivatives in this reaction with chlorobenzene under our best conditions. The first attempt proceeded successfully, and the corresponding methyldiphenylphosphine ligand, which is very important in transition-metal-catalyzed reactions, was obtained in good yield (see Table 3, Entry 1). In addition, Ph_2PH, Ph_2PK, and Ph_2PPPh_2 also worked well to give the corresponding products in moderate to high yields (see Table 3, Entries 2–4). However, other phosphine sources such as chlorodiisopropylphosphine, chlorodiphenylphosphine, and diethyl chlorophosphite failed to participate in the reaction (see Table 3, Entries 5–7).

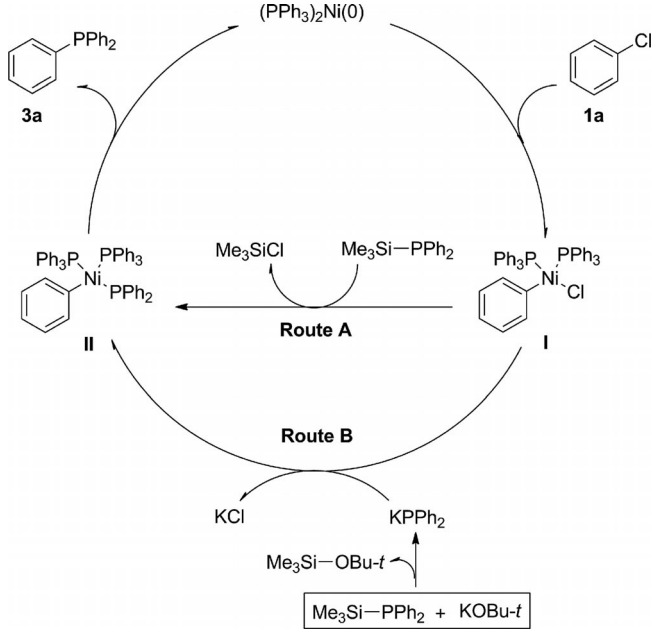
On the basis of our experimental results and those previously reported in the literature,[17] a plausible mechanistic pathway is outlined in Scheme 1. First, it is reasonable to assume that the oxidative addition of the C–Cl bond to highly active Ni^0 generates intermediate **I**. Then, intermediate **I** undergoes a reaction with Me_3SiPPh_2 and then a ligand exchange to give intermediate **II**, which liberates the tertiary phosphine moieties by a subsequent reductive elimination. Finally, the released Ni^0 is reoxidized by the aryl chloride to continue the catalytic cycle. On the other hand, it could be that the Me_3SiPPh_2 first undergoes a reaction with *t*BuOK to form the ionic $KPPh_2$ salt, which then takes part in a ligand exchange or transmetalation procedure.

Table 3. The scope of different phosphine sources.[a]



Entry	P–Source	Yield [%][b]
1	Me_3Si–PMePh	69%
2	Ph_2PH	60%
3	Ph_2PK	77%
4	Ph_2PPPh_2	41%
5	iPr_2PCl	n.r.
6	Ph_2PCl	n.r.
7	$(EtO)_2PCl$	n.r.

[a] All reactions were carried out under the optimized conditions for 12 h. [b] Yield of isolated products; n.r.: no reaction.



Scheme 1. The proposed mechanisms of nickel-catalyzed C–P bond formation.

Conclusions

In summary, we have developed a new, efficient catalytic system for synthesis of tertiary phosphine ligands by employing a C–Cl bond functionalization reaction. The availability of the aryl chloride compounds and the apparent broad scope that was observed might make this strategy attractive to synthetic chemists. Further applications of this approach and an asymmetric synthesis of phosphine ligands are ongoing in our laboratory.

Experimental Section

General Methods: All reactions involving air- and moisture-sensitive reagents were carried out under nitrogen. Toluene, DMF, 1,2-dichloroethane, dimethyl sulfoxide (DMSO), 1,4-dioxide, and CH_3CN were distilled from the appropriate drying agents prior to

use. All chemicals were purchased from Aldrich and used without further purification. Me_3SiPPh_2 was purchased from Aldrich or prepared from PPh_3 and TMSCl according to Stille's method.[17a] Thin-layer chromatography was performed by using silica gel plates (60 mesh), and the developed plates were visualized by short wavelength UV light (254 nm). Silica gel 60 (230–400 mesh) was used for column chromatography. IR spectra were recorded with an FTIR spectrometer by using KBr plates and thin films of the sample, and the bands are reported in cm^{-1}. Only representative absorptions are provided. The ^1H and ^{13}C NMR spectroscopic data were recorded with a Bruker INOVA-400 and a Bruker AC-250. The NMR spectrosocopic data were recorded with a 400 MHz instrument (400 MHz for ^1H NMR and 100 MHz for ^{13}C NMR). Chemical shifts (δ) are reported in ppm relative to TMS (δ = 0 ppm) as the internal standard for ^1H NMR and chloroform (δ = 77.0 ppm) as the internal standard for ^{13}C NMR. Data are reported in the order of chemical shift, multiplicity [singlet (s), doublet (d), triplet (t), quartet (q), and multiplet (m)], coupling constants (J) in Hertz, and number of protons. Mass spectrometry data were measured with a Thermo Scientific DSQ II mass spectrometer. Caution: Me_3SiPPh_2 is highly pyrophoric and therefore should be used under Ar.

Triphenylphosphine (3a):[13a] White solid (122 mg, 93%). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.36 (s, 15 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 128.47 (d, J = 7 Hz), 128.70, 133.70 (d, J = 20 Hz), 137.03 (d, J = 11 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –5.34 ppm. IR (neat): $\tilde{\nu}$ = 694.77, 742.52, 1025.59, 1089.59, 1432.41, 1477.18, 3054.38 cm^{-1}. MS (ESI): m/z = 263.2 $[M + 1]^+$.

Diphenyl(*p*-tolyl)phosphine (3b):[13a] White solid (124 mg, 90%). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.35 (s, 3 H), 7.14–7.24 (m, 4 H), 7.28–7.33 (m, 10 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.30, 128.39, 128.45, 128.55, 128.60 (d, J = 19 Hz), 129.34 (d, J = 8 Hz), 133.59 (d, J = 19 Hz), 133.63, 133.91 (d, J = 20 Hz), 137.54 (d, J = 10 Hz), 138.83 ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –6.29 ppm. IR (neat): $\tilde{\nu}$ = 808.86, 1117.79, 1191.45, 1435.30, 1479.32, 1599.59, 2863.69, 2920.00, 3017.25, 3052.46 cm^{-1}. MS (ESI): m/z = 277.3 $[M + 1]^+$.

Diphenyl(*m*-tolyl)phosphine (3c):[13a] White solid (113 mg, 82%). ^1H NMR (400 MHz, $CDCl_3$): δ = 2.29 (s, 3 H), 7.05–7.23 (m, 4 H), 7.31–7.32 (m, 10 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.4, 128.34, 128.40, 128.46, 128.64, 128.69, 129.60, 130.73 (d, J = 17 Hz), 133.69 (d, J = 20 Hz), 134.44 (d, J = 22 Hz), 137.18 (d, J = 10 Hz), 138.02 (d, J = 8 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –5.39 ppm. IR (neat): $\tilde{\nu}$ = 696.33, 745.05, 1115.91, 1222.90, 1434.07, 1477.48, 1588.05, 2919.61, 3051.95 cm^{-1}. MS (ESI): m/z = 277.3 $[M + 1]^+$.

Diphenyl(*o*-tolyl)phosphine (3d):[13a] White solid (68 mg, 49%). The title compound could not be isolated from the mixture of the diphenyl(*o*-tolyl)phosphine and triphenylphosphine. ^1H NMR (400 MHz, $CDCl_3$): δ = 2.38 (s, 3 H), 6.75–6.78 (m, 1 H), 7.03–7.07 (m, 1 H), 7.15–7.30 (m, 12 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 21.17 (d, J = 20 Hz), 125.94, 128.39, 128.46, 128.59 (d, J = 15 Hz), 128.64, 130.00 (d, J = 4 Hz), 132.66, 133.66 (d, J = 20 Hz), 133.93 (d, J = 19 Hz), 135.87 (d, J = 12 Hz), 136.16 (d, J = 10 Hz), 137.07 (d, J = 11 Hz), 142.09 (d, J = 26 Hz) ppm. IR (neat): $\tilde{\nu}$ = 696.19, 743.93, 780.38, 1091.53, 1433.24, 1477.69, 1586.39, 2920.62, 3053.06 cm^{-1}. MS (ESI): m/z = 277.3 $[M + 1]^+$.

Naphthalen-2-yldiphenylphosphine (3f):[13a] White solid (137 mg, 88%). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.41–7.57 (m, 13 H), 7.79–7.81 (d, J = 8 Hz, 1 H), 7.85–7.91 (m, 3 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 126.44 (d, J = 43 Hz), 127.84 (d, J = 41 Hz), 127.91 (d, J = 6 Hz), 128.47, 128.53, 128.74, 129.97 (d, J = 18 Hz), 133.21 (d, J = 8 Hz), 133.30, 133.75 (d, J = 20 Hz), 134.15 (d, J = 23 Hz), 137.04 (d, J = 11 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –4.81 ppm. IR (neat): $\tilde{\nu}$ = 1071.01, 1188.84, 1432.62, 1477.03, 1587.59, 3049.82, 3384.73 cm^{-1}. MS (ESI): m/z = 313.3 $[M + 1]^+$.

Naphthalen-1-yldiphenylphosphine (3g):[13a] White solid (118 mg, 76%). ^1H NMR (400 MHz, $CDCl_3$): δ = 6.99–7.02 (m, 1 H), 7.24–7.32 (m, 11 H), 7.35–7.43 (m, 2 H), 7.76–7.81 (t, J = 20 Hz, 2 H), 8.41–8.44 (t, J = 12 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 125.55 (d, J = 1 Hz), 125.98, 126.25 (t, J = 2 Hz), 128.56 (d, J = 24 Hz), 128.52, 128.59, 128.81, 129.43, 132.01, 133.40 (d, J = 5 Hz), 133.73 (d, J = 19 Hz), 134.17 (d, J = 20 Hz), 134.53 (d, J = 14 Hz), 135.29 (d, J = 22 Hz), 136.33 (d, J = 10 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –14.21 ppm. IR (neat): $\tilde{\nu}$ = 1117.90, 1186.36, 1435.13, 1710.74, 3052.96, 3389.58 cm^{-1}. MS (ESI): m/z = 313.3 $[M + 1]^+$.

1,4-Bis(diphenylphosphino)benzene (3h):[13a] White solid (145 mg, 65%). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.20–7.24 (m, 4 H), 7.30–7.31 (d, J = 4 Hz, 20 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 128.49 (d, J = 7 Hz), 128.50, 128.82, 133.35 (d, J = 25 Hz), 133.40 (d, J = 13 Hz), 133.81 (d, J = 20 Hz), 136.75 (d, J = 10 Hz), 137.98 (d, J = 13 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –5.68 ppm. IR (neat): $\tilde{\nu}$ = 1118.77, 1182.90, 1436.50, 2857.73, 2924.06, 3055.67, 3353.39 cm^{-1}. MS (ESI): m/z = 447.3 $[M + 1]^+$.

3-(Diphenylphosphino)pyridine (3j):[13a] White solid (71 mg, 54%). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.06–7.08 (m, 1 H), 7.15–7.18 (m, 1 H), 7.34–7.42 (m, 10 H), 7.52–7.57 (m, 1 H), 8.72–8.73 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 122.11, 127.71 (d, J = 15 Hz), 128.52, 128.59, 129.00, 134.10 (d, J = 20 Hz), 135.67 (d, J = 2 Hz), 136.05 (d, J = 10 Hz), 150.25 (d, J = 13 Hz), 163.89 (d, J = 5 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –4.16 ppm. IR (neat): $\tilde{\nu}$ = 695.09, 737.01, 1118.31, 1192.51, 1436.33, 1571.77, 3054.45, 3408.58 cm^{-1}. MS (ESI): m/z = 264.2 $[M + 1]^+$.

2-(Diphenylphospino)pyridine (3k):[13a] White solid (63 mg, 48%). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.21–7.24 (m, 1 H), 7.29–7.36 (m, 10 H), 7.52–7.57 (m, 1 H), 8.52–8.56 (m, 2 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 123.42 (d, J = 4 Hz), 128.60, 128.67, 129.06, 133.45, 133.50, 133.61, 133.70, 135.62 (d, J = 10 Hz), 140.85 (d, J = 16 Hz), 149.54, 154.10 (d, J = 24 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –11.96 ppm. IR (neat): $\tilde{\nu}$ = 698.29, 745.55, 800.02, 1023.81, 1191.93, 1400.04, 1434.23, 1475.09, 1566.64, 3051.49, 3398.08 cm^{-1}. MS (ESI): m/z = 264.2 $[M + 1]^+$.

10-(Diphenylphosphino)benzo[*h*]quinoline (3l):[13a] White solid (136 mg, 75%). ^1H NMR (400 MHz, $CDCl_3$): δ = 6.95–6.98 (m, 1 H), 7.50–7.54 (m, 2 H), 7.62–8.00 (m, 11 H), 8.14–8.16 (m, 1 H), 9.02–9.03 (m, 1 H), 9.33–9.35 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 120.09, 121.72, 124.34, 125.05, 125.29, 126.36, 126.46, 126.48, 127.03, 127.71, 127.77, 128.15, 128.46, 128.59, 130.85 (d, J = 125 Hz), 133.87 (d, J = 60 Hz), 134.50, 135.75, 145.83, 146.50, 146.54, 147.26, 148.77 ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –40.35 ppm. IR (neat): $\tilde{\nu}$ = 727.28, 748.58, 805.91, 834.60, 1325.08, 1400.28, 1443.22, 1510.94, 1565.35, 1590.33, 1619.68, 1937.63, 2944.61, 3045.27 cm^{-1}. MS (ESI): m/z = 363.2, $[M + 1]^+$.

2-[2-(Diphenylphosphino)phenyl]pyridine (3m):[13a] White solid (140 mg, 79%). ^1H NMR (400 MHz, $CDCl_3$): δ = 7.08–7.13 (m, 2 H), 7.22–7.28 (m, 11 H), 7.38–7.44 (m, 2 H), 7.53–7.61 (m, 2 H), 8.51–8.53 (d, J = 4.8 Hz, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 121.78, 124.06 (d, J = 5 Hz), 128.19, 128.26, 128.67, 129.48 (d, J = 4 Hz), 133.77 (d, J = 20 Hz), 134.47, 135.55, 136.08 (d, J = 18 Hz), 138.03 (d, J = 11 Hz), 145.66 (d, J = 24 Hz), 148.41, 158.67 (d, J = 2 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –11.13 ppm.

IR (neat): $\tilde{\nu}$ = 698.74, 729.40, 747.87, 794.95, 910.71, 1112.56, 1187.63, 1431.79, 1457.63, 1478.14, 1585.10, 2217.49, 2931.58, 3054.00, 3384.08 cm^{-1}. MS (ESI): *m/z* = 340.4 $[M + 1]^+$.

5-[2-(Diphenylphosphino)phenyl]-1-methyl-1*H*-tetrazole (3o):[13a] White solid (107 mg, 62%). ^1H NMR (400 MHz, $CDCl_3$): δ = 4.24 (s, 3 H), 7.02–7.05 (m, 1 H), 7.25–7.37 (m, 11 H), 7.44–7.48 (m, 1 H), 8.05–8.08 (m, 1 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 39.34, 128.36, 128.44, 128.63, 129.80, 129.87 (d, *J* = 4 Hz), 131.66 (d, *J* = 23 Hz), 133.90, 134.10, 134.31, 137.17 (d, *J* = 11 Hz), 137.56 (d, *J* = 23 Hz), 164.93 ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –7.95 ppm. IR (neat): $\tilde{\nu}$ = 542.95, 697.42, 748.23, 1035.91, 1120.51, 1191.89, 1363.35, 1431.32, 3055.19 cm^{-1}. MS (ESI): *m/z* = 345.3 $[M + 1]^+$. HRMS: calcd. for $C_{20}H_{18}PN_4$ 345.1264; found 345.1260.

Methyldiphenylphosphine (3p):[19] Pale yellow liquid (69 mg, 69%). ^1H NMR (400 MHz, $CDCl_3$): δ = 1.57–1.58 (d, *J* = 4 Hz, 3 H), 7.24–7.29 (m, 6 H), 7.36–7.40 (m, 4 H) ppm. ^{13}C NMR (100 MHz, $CDCl_3$): δ = 12.40 (d, *J* = 14 Hz), 128.19, 128.25, 131.94 (d, *J* = 18 Hz), 140.06 (d, *J* = 12 Hz) ppm. ^{31}P NMR (162 MHz, $CDCl_3$): δ = –26.82 ppm. IR (neat): $\tilde{\nu}$ = 510.00, 682.13, 651.28, 920.46, 1012.36, 1081.66, 1127.35, 1300.74, 1498.54, 2920.12, 3052.23, 3068.30 cm^{-1}. MS (ESI): *m/z* = 201.3 $[M + 1]^+$.

Supporting Information (see footnote on the first page of this article): Copies of the ^1H and ^{13}C NMR spectra for the isolated products.

Acknowledgments

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[18] The bidentate phosphine ligand was obtained by using *t*BuOK (3.0 equiv.), Me_3SiPPh_2 (4.0 equiv.), and $NiCl_2(PPh_3)_2$ (10 mol-%) at 90 °C under argon. The bidentate phosphine ligand was accompanied by the single C–Cl bond cleavage product by using 1 or 2 equiv. of Me_3SiPPh_2. These observations proved that the C–Cl bond underwent the reaction faster than the C–CN bond, under these conditions.

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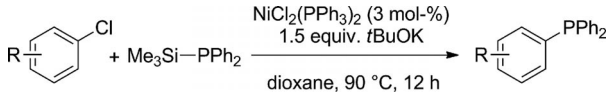
Cross-Coupling Reaction



A convenient strategy has been developed for the preparation of various phosphine ligands in good to excellent yields through a nickel-catalyzed C–P bond-forming step. This reaction proceeded smoothly and tolerated a variety of functional groups to provide a new method for the synthesis of important phosphine ligands through the direct cleavage of a C–Cl bond.

Keywords: Synthetic methods / Homogeneous catalysis / Cross-coupling / Phosphane ligands / Nickel / Arenes

