

Use of Tunable Ligands Allows for Intermolecular Pd-Catalyzed C–O Bond Formation

Andrei V. Vorogushin, Xiaohua Huang, and Stephen L. Buchwald*

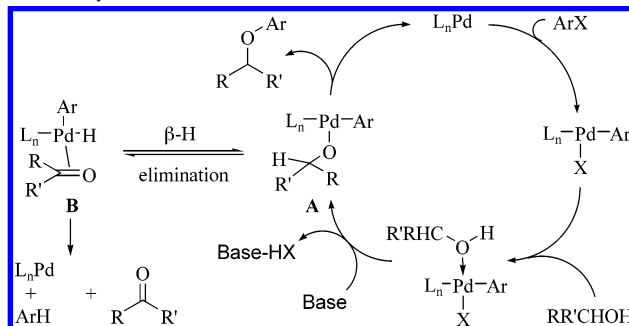
Contribution from the Department of Chemistry, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

Received January 24, 2005; E-mail: sbuchwal@mit.edu

Abstract: Bulky biaryl phosphine ligands facilitate Pd-catalyzed C–O coupling reactions of aryl halides with primary and secondary alcohols by promoting reductive elimination at the expense of β -hydride elimination. The key to their success is the ability to match the size of the ligand to that of the combination of substrates. The efficient coupling of a number of unactivated aryl chlorides and bromides with cyclic and acyclic secondary alcohols was achieved. This included the coupling of allylic alcohols for the first time in a Pd-catalyzed coupling process.

The Pd-catalyzed formation of C–N bonds has become a general method for the preparation of aniline derivatives from the reaction of aryl halides or sulfonates and amines.¹ The analogous process for the addition of alcohols to produce aromatic ethers has also been successfully accomplished.² However, except for intramolecular C–O bond-forming processes,^{2a,g} the success of the method greatly depends on the partitioning of the alkoxide intermediate **A** between aryl ether product or the product of β -hydride elimination, **B** (Scheme 1). Thus, while coupling with tertiary alcohols,^{2b,e,f,h} phenols,^{2c,d} and silanols^{2f} is not affected by this dichotomy, the reactions of primary and secondary alcohols often produce large amounts of arene byproduct. In 2001 we reported³ the first examples of Pd-catalyzed coupling of primary alcohols with unactivated aryl chlorides and bromides. Excellent results were obtained with aryl halides with one or two ortho-substituents, which facilitate the rate of reductive elimination from **A**. In the absence of such ortho-substitution, however, the reactions of unactivated aryl halides gave only poor to moderate yields. In all of these cases it was necessary to use **L2** to achieve satisfactory results. Unfortunately, we do not have an efficient synthesis of this ligand. Attempts to extend our method to include secondary alcohol substrates were successful only in reactions with ortho-, ortho'-disubstituted aryl halides.³ A mild catalytic method for the preparation of aryl *sec*-alkyl ethers would complement

Scheme 1. Pd-Catalyzed C–O Coupling of Primary and Secondary Alcohols



existing techniques including Mitsunobu processes⁴ and the copper-catalyzed coupling of aryl iodides and secondary alcohols,⁵ since the former is often complicated by formation of byproducts and the latter suffers from slow reaction rates. Precedent existed^{2,3} to indicate that bulky ligands could facilitate Pd-catalyzed C–O coupling reactions by promoting reductive elimination at the expense of β -hydride elimination. However, the need to accomplish this and yet accommodate coupling partners of various sizes has made the search for general ligands for these processes difficult. The general notion of devising modular syntheses of ligands that allow the tuning of steric and electronic properties to accommodate a given substrate combination has been used to advantage in many instances.⁶ Herein we disclose the development of such a ligand system for Pd-catalyzed C–O coupling of primary and secondary alcohols, including allylic alcohols, with unactivated aryl chlorides and bromides. The key to our success is the ability to match the size of the ligand to that of the combination of substrates.

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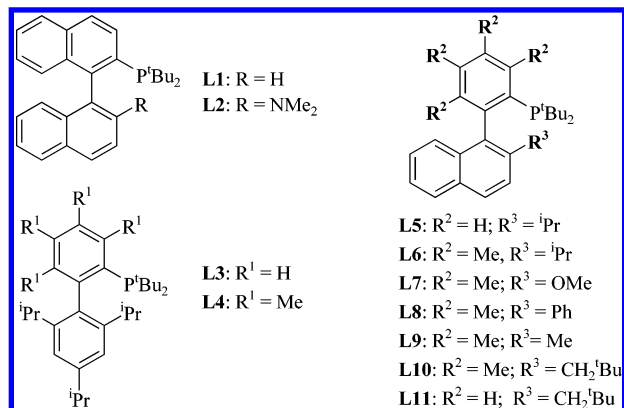


Figure 1. Ligands for Pd-catalyzed C–O coupling.

Table 1. Coupling of 5-Bromo-*m*-xylene with 2-Butanol^{a,b}

entry	ligand	1a, %	2a, %	3, %	4, %	5, %
1	L1	—	1	94	—	—
2	L2	—	48	42	4	2
3	L3	—	7	80	4	3
4	L4	26	4	14	31	12
5	L5	—	31	60	2	—
6	L6	—	42	27	19	6
7	L7	13	19	38	4	10
8	L8	16	25	26	15	7
9	L9	2	26	49	7	5
10	L10	—	53	31	7	5
11 ^c	L10	—	76	5	4	6

^a Conditions: 2 mol % of Pd(OAc)₂, 2.4 mol % of L, 2 equiv of 2-BuOH, 1.5 equiv of Cs₂CO₃, toluene, 90 °C, 24 h. ^b GC yields. ^c In Bu₃N.

An initial screen was performed using L1–L6 (Figure 1) for the coupling reaction of 1a and 2-BuOH. This produced, in addition to the desired coupling product (2a), side products: arene (3), diaryl ether⁷ (4), and biaryl (5) (Table 1).⁸ Use of ligands L1, L3, and L5 led to the extensive formation of 3 (entries 1, 3, 5). Presumably, these were insufficiently bulky to render reductive elimination faster than β-H elimination from A. The results with L4 (entry 4) were disappointing, and while employing L2 and L6 gave moderate yields of the coupling product 2a (entries 2 and 6), further modification of the ligand was obviously necessary. Having increased the size of the top ring by the addition of four methyl groups, we examined the effect of changing the size of R³. Ligands L7, L8, L9, with R³ = OMe, Ph, and Me, respectively, were prepared but found to be less efficient than L6 as supporting ligands (entries 7–9). Interestingly, replacement of isopropyl group as R³ of L6 by a methyl group in L9 led to the formation of a smaller amount of diaryl ether 4 (entry 6 vs 9). Unfortunately, the decreased steric bulk in L9 produced a lower ratio of 2a:3. This ratio was improved using L10, in which R³ = CH₂^tBu (entry 10). With L10 the formation of 3 can be almost completely suppressed if

(7) The mechanism for the formation of diaryl ether 4 is not completely understood. When ¹⁸O-labeled 1-phenylethanol was reacted with 1 using L4 as a ligand, ¹⁸O-2d (8%) and 4 (45%) were formed, the latter product without ¹⁸O enrichment. Therefore, it is likely that residual H₂O and/or Cs₂CO₃ are involved in this side reaction.

(8) See Supporting Information for the details

Table 2. Coupling of Aryl Halides with Secondary Alcohols^a

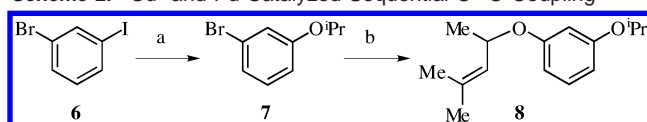
<p>2a, 74%</p>	<p>2b, 76%</p>	<p>2c, 68%^b</p>
<p>2d, 57%</p>	<p>2e, 81%^c</p>	<p>2f, 70%, 98% ee</p>
<p>2g, 72% (70%)^d</p>	<p>2h, 76%^c (79%)^{e,f}</p>	<p>2i, (80%)</p>
<p>2j, (82%)^{f,g,h}</p>	<p>2k, 62%</p>	<p>2l, 83%^c</p>
<p>2m, 63%</p>	<p>2n, 91%^{c,f}</p>	<p>2o, 63%^{e,i,j}</p>
<p>2p, 46%^{f,k}</p>	<p>2q, 60%^{i,k}</p>	<p>2r, 84%^l</p>
<p>2s, 81%</p>	<p>2t, 92%^{c,f}</p>	
<p>2u, 71%^c</p>	<p>2v, 76%^{c,r,f}</p>	

^a Isolated yields: X = Br (X = Cl). ^b 3% Pd, 3.6% L10. ^c 50 °C, 18 h. ^d 100 °C. ^e 5% Pd, 6% L10. ^f In toluene. ^g 50 °C, 8 h. ^h 1.2 equiv of Cs₂CO₃. ⁱ 70 °C, 18 h. ^j 1.2 equiv of alcohol. ^k With L11. ^l 70 °C, 24 h.

Bu₃N is used as a solvent⁹ instead of toluene (entry 11). Thus, simply changing R³ from isopropyl to neopentyl along with a solvent switch is enough to produce a synthetically useful catalyst system.

With the best conditions in hand, we examined the reaction of a number of unactivated aryl bromides and chlorides with cyclic and acyclic secondary alcohols (Table 2), which proceed in good yields. However, for more hindered 3,3-dimethylbutan-2-ol, less efficient coupling to afford 2d and 2k was realized. Of note, allylic alcohols, which previously were not viable substrates for these processes, are readily transformed to products, usually at a lower temperature and in higher yields

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Scheme 2. Cu- and Pd-Catalyzed Sequential C–O Coupling^a

^a Conditions: (a) 10 mol % of CuI, 20 mol % of 1,10-phenanthroline, 2 equiv of Cs₂CO₃, ⁱPrOH neat, 110 °C, 24 h, 81%; (b) 3 mol % of Pd(OAc)₂, 3.6 mol % of **L10**, 1.5 equiv of Cs₂CO₃, Bu₃N, 50 °C, 18 h, 84%.

than seen with saturated alcohols. This method avoids the regiochemical issues that arise in Pd-¹⁰ and Rh-catalyzed¹¹ allylic alkylation reactions of phenols. Yields were lower for the coupling of a monosubstituted allylic alcohol than for a trisubstituted one (compare **2n** and **2o**). Functional group tolerance for substituents on the aryl bromides was moderate and allowed for the formation of ester- and heterocycle-containing products **2s–v**. Although the reactions of most meta- and para-substituted aryl halides that we examined were well-behaved, little progress was realized with more electron-rich *o*- and *p*-bromoanisoles due to the extensive formation of arene and diaryl ether side products. Success with ortho-substituted aryl halides required the use of ligand **L11**, which is a less hindered analogue of **L10**. But even then the yields of **2p** and **2q** were only moderate, with the rest of the mass balance being **3** and **4**. Coupling of (*R*)-1-phenylethanol (98% ee) gave the product (*R*)-**2f** (98% ee) without racemization.

As was the case with C–N bond formation,¹² Pd- and Cu-catalyzed reactions can be used to advantage when performed in a tandem manner. Thus, the latter methodology allows for the selective coupling of bromide **6** with ⁱPrOH. The resulting bromide **7** can then be further transformed by treatment with secondary alcohol as shown (Scheme 2).

Major improvements in the coupling reaction of primary alcohols were achieved when the bulkier ligand, **L6**, was used in place of **L2**, which was previously the best ligand³ (Table 3). Reduction was suppressed, where necessary, by running the reactions in Bu₃N. For *ortho*-substituted aryl bromides, **L5** must be utilized (**12c**). The most challenging substrates, electron-rich *p*- and *o*-bromoanisole, gave good yields of the coupling products **12d** and **12e** using exceptionally hindered **L4**; poor yields had previously been seen³ with **L2**. With **L4**, the selective arylation of the primary hydroxyl of 1,3-dihydroxybutane was also possible (**12k**), without detectable coupling of the secondary hydroxyl.

The choice of ligand for Pd-catalyzed C–O bond formation is based on the nature of substrate combination being coupled (Table 4). Thus, as previously described,³ ortho,ortho'-disubstituted aryl halides can be easily coupled using **L1** as a supporting ligand (entry 1). Less hindered *ortho*-substituted aryl halides (except for R = EDG) require the bulkier ligands **L2** or **L5** for the successful reaction with primary alcohols and **L11** with secondary alcohols (entry 2). Electron-rich aryl halides are the most challenging substrates. Their coupling with primary alcohols works moderately well using **L4**. The analogous reaction, however, with secondary alcohols could not be achieved (entries 3, 4). For all other meta- and para-substituted aryl halides, the use of **L6** and **L10** is recommended, with primary and secondary alcohols, respectively (entry 5).

Table 3. Coupling of Aryl Bromides with Primary Alcohols^a

1	R ¹	2 mol % Pd(OAc) ₂ 2.4 mol % L6 1.5 equiv Cs ₂ CO ₃ toluene, 70 °C, 18 h.	12
			12a , 90% ^b
			12b , 96%
			12c , 80% ^c
			12d , 70% ^d
			12e , 73% ^{d,e}
			12f , 89% ^b
			12g , 86% ^b
			12h , 91% ^b
			12i , 90% ^f
			12j , 84% ^g
			12k , 66% ^{d,h,i}

^a Isolated yields. ^b In Bu₃N. ^c With **L5**. ^d With **L4**. ^e Pd₂(dba)₃ (1%) was used. ^f Slow addition of the alcohol. ^g 50 °C. ^h 24 h. ⁱ 5% Pd, 6% **L4**.

In summary, we have developed a tunable ligand system for the coupling of primary and secondary alcohols with aryl halides. These ligands, in combination with Bu₃N as a solvent, suppress the β-H elimination pathway, allowing for the first time for the efficient coupling of secondary, including allylic, alcohols. All of these ligands are accessible by variations of our benzyne route.¹³ The most general ligands **L6** and **L10** have been prepared on > 10 g scale without the need for chromatographic purification. We hope to have these as well as **L4** and **L5** commercially available soon.

Experimental Section

General Procedure for the Intermolecular Coupling of Alcohols with Aryl Halides. An oven-dried Schlenk tube was cooled in vacuo, back-filled with argon, and charged with Pd(OAc)₂, ligand, and Cs₂CO₃. The Schlenk tube was fitted with rubber septum, evacuated, and back-filled with argon. The aryl halide and alcohol were added through the septum via syringe, followed by the solvent. The septum was replaced with a Teflon screw cap under a counterflow of argon, and the tube was sealed and placed in an oil bath. The reaction was conducted under the conditions indicated in Tables 2 and 3. After the reaction mixture was allowed to cool to room temperature, it was filtered through a layer of Celite with the aid of ethyl acetate. In the cases where toluene was used as the solvent, the filtrate was concentrated in vacuo and the crude product was purified chromatographically (silica gel). In the cases where Bu₃N was used as the solvent, the filtrate was extracted with 10% HCl. The organic layer was isolated and the aqueous layer was back-extracted with diethyl ether. The combined organic extracts were dried over MgSO₄, and the crude product was purified chromatographically (silica gel). The yields of the coupling products are indicated in Tables 2 and 3. Three representative examples are shown below.

1-(1,3-Dimethylbut-2-enyloxy)-3,5-dimethylbenzene (2e). The general procedure was followed using Pd(OAc)₂ (4.5 mg, 0.02 mmol), **L10** (11.4 mg, 0.024 mmol), Cs₂CO₃ (489 mg, 1.5 mmol), 5-bromo-*m*-xylene

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Table 4. Choice of Ligand for C–O Bond Formation^a

entry	ArX	alcohol	
1			
2			
3			—
4			—
5			

^a EDG, electron-donating group; R ≠ EDG.

(185 mg, 1 mmol), and 4-methylpent-3-en-2-ol (200 mg, 2 mmol), with Bu₃N (2 mL) as solvent, for 18 h at 50 °C. The filtrate was extracted with 10% HCl (2 × 35 mL). Chromatographic purification (1% ethyl acetate in hexane) provided **2e** (colorless liquid, 165 mg, 81%): ¹H NMR (400 MHz, CDCl₃) δ 6.56 (s, 1H), 6.50 (s, 2H), 5.20–5.24 (m, 1H), 4.93–5.01 (m, 1H), 2.26 (m, 6H), 1.73 (d, 3H, *J* = 1.3 Hz), 1.72 (d, 3H, *J* = 1.3 Hz), 1.35 (d, 3H, *J* = 6.2 Hz); ¹³C NMR (100 MHz, CDCl₃) δ 158.0, 138.9, 134.0, 127.1, 122.1, 113.5, 70.7, 25.6, 21.4, 21.3, 18.2. IR (neat, cm⁻¹) 2975, 1595, 1448, 1292, 1155, 1067, 827, 688. Anal. Calcd for C₁₄H₂₀O: C, 82.30; H, 9.87. Found: C, 81.95; H, 9.84.

1-sec-Butoxy-3-methoxybenzene (2m). The general procedure was followed using Pd(OAc)₂ (4.5 mg, 0.02 mmol), **L10** (11.4 mg, 0.024 mmol), Cs₂CO₃ (489 mg, 1.5 mmol), 1-bromo-3-methoxybenzene (187 mg, 1 mmol), and 2-butanol (148 mg, 2 mmol), with Bu₃N (1 mL) as solvent, for 24 h at 90 °C. The filtrate was extracted with 10% HCl (2 × 20 mL). Chromatographic purification (2% ethyl acetate in hexane) provided **2m** (colorless liquid, 114 mg, 63%): ¹H NMR (400 MHz, CDCl₃) δ 7.16 (t, 1H), 6.45–6.51 (m, 3H), 4.28 (sextet, 1H, *J* = 6.2 Hz), 3.79 (s, 3H), 1.69–1.80 (m, 1H), 1.56–1.67 (m, 1H), 1.29 (d, 3H, *J* = 6.1 Hz), 0.97 (t, 3H, *J* = 7.5 Hz); ¹³C NMR (100 MHz, CDCl₃) δ 160.8, 159.4, 129.8, 107.9, 105.9, 102.2, 74.9,

55.1, 29.1, 19.2, 9.8; IR (neat, cm⁻¹) 2972, 1601, 1492, 1377, 1286, 1201, 1150, 1043, 1001, 837, 763, 688. Anal. Calcd for C₁₁H₁₆O₂: C, 73.30; H, 8.95. Found: C, 73.44; H, 9.11.

1-Butoxy-3,5-dimethylbenzene (12a). The general procedure was followed using Pd(OAc)₂ (4.5 mg, 0.02 mmol), **L6** (10.7 mg, 0.024 mmol), Cs₂CO₃ (489 mg, 1.5 mmol), 5-bromo-*m*-xylene (185 mg, 1 mmol), and butanol (148 mg, 2 mmol), with Bu₃N (2 mL) as solvent, for 18 h at 70 °C. The filtrate was extracted with 10% HCl (2 × 35 mL). Chromatographic purification (hexane, followed by 2% ethyl acetate in hexane) provided **12a**³ (colorless liquid, 161 mg, 90%). ¹H and ¹³C NMR data were consistent with those of the previously reported compound.

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Supporting Information Available: Full experimental details and characterization of products (PDF). This material is available free of charge via the Internet at <http://pubs.acs.org>.

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