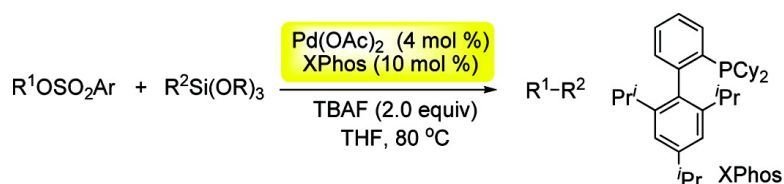


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J. Am. Chem. Soc., **2008**, 130 (37), 12250-12251 • DOI: 10.1021/ja804672m • Publication Date (Web): 21 August 2008

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Palladium-Catalyzed Hiyama Cross-Couplings of Aryl Arenesulfonates with Arylsilanes

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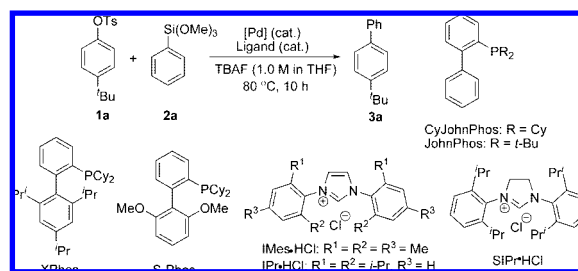
Pd-catalyzed Hiyama coupling of organosilicon compounds with organic electrophiles is an important method for C–C bond formation.^{1,2} Compared to some of the other organometallic reagents (Zn, Mg, Sn, etc.) utilized in cross-coupling processes, organosilicon compounds are attractive due to their ease of handling and/or low toxicity. Moreover, silicon compounds are more stable toward air/moisture than organomagnesium and organozinc reagents. In addition, organosilanes are becoming popular for industrial purposes, whereas organoboron compounds are difficult to purify due to the structural ambiguity (the formation of the boroxine) and some of them are unstable, losing boron readily to give rise to homocoupling products.³

Among the electrophiles employed in transition metal catalyzed cross-coupling reactions, aryl arenesulfonates are regarded as important alternatives to aryl halides and triflates.^{4,5} They can be easily generated from cheap, readily available phenols and arenesulfonyl chloride. Moreover, they are less expensive, more stable, and easier to handle than the corresponding triflates. Recently, cross-coupling reactions utilizing aryl arenesulfonates as electrophiles have been realized although they are relatively unreactive compared to the corresponding aryl halide and triflate counterparts.⁴ For instance, several cases have been realized in Suzuki–Miyaura reactions by using palladium^{4a} or nickel^{4b} catalysts. However, to the best of our knowledge, no reports have appeared for the Hiyama coupling of aryl arenesulfonates with organosilicon compounds.

To verify our hypothesis that aryl arenesulfonates can be used as electrophiles in Hiyama cross-coupling reactions, a set of experiments were carried out using 4-*tert*-butylphenyl tosylate **1a** and trimethoxy(phenyl)silane **2a** as model substrates. This preliminary survey, carried out in the presence of TBAF (1.0 M in THF) at 80 °C, allowed us to evaluate and optimize the most efficient catalytic system (Table 1). In an initial experiment, we observed the formation of desired product **3a** when the reaction was catalyzed by Pd(OAc)₂ (2 mol %) in the presence of S-Phos⁶ (Table 1, entry 1). Further investigation revealed the yield was dramatically improved when Xphos⁶ was utilized (67% yield, Table 1, entry 2). Only a trace amount of product **3a** was detected when other phosphine ligands were screened (Table 1, entries 3–8). Inferior results were displayed when *N*-heterocyclic carbene was used as a replacement (Table 1, entries 9–11). Increasing the amount of catalyst resulted in satisfactory isolated yield (88% yield, Table 1, entry 12). Further screening of Pd catalysts revealed Pd(OAc)₂ as the best choice (Table 1, entries 13–19). Decreasing the temperature retarded the reaction (Table 1, entries 20 and 21).

The scope of this reaction was then investigated under optimized conditions [Pd(OAc)₂ (4 mol %), XPhos (10 mol %), TBAF (1.0

Table 1. Conditions Screening for Pd-Catalyzed Cross-Coupling Reaction of Aryl Tosylate **1a** with Arylsilane **2a**^a



entry	[Pd] catalyst	ligand	yield (%) ^b
1	Pd(OAc) ₂ (2 mol %)	S-Phos (5 mol %)	13
2	Pd(OAc) ₂ (2 mol %)	XPhos (5 mol %)	67
3	Pd(OAc) ₂ (2 mol %)	JohnPhos (5 mol %)	trace
4	Pd(OAc) ₂ (2 mol %)	CyJohnPhos (5 mol %)	trace
5	Pd(OAc) ₂ (2 mol %)	PCy ₃ (5 mol %)	trace
6	Pd(OAc) ₂ (2 mol %)	P(<i>o</i> -tolyl) ₃	trace
7	Pd(OAc) ₂ (2 mol %)	DPPP	trace
8	Pd(OAc) ₂ (2 mol %)	DPPF	trace
9	Pd(OAc) ₂ (2 mol %)	IPr·HCl	trace
10	Pd(OAc) ₂ (2 mol %)	SIPr·HCl	trace
11	Pd(OAc) ₂ (2 mol %)	IMes·HCl	nr
12	Pd(OAc) ₂ (4 mol %)	XPhos (10 mol %)	88
13	Pd(PPh ₃) ₄ (4 mol %)	XPhos (10 mol %)	34
14	Pd ₂ (dba) ₃ (4 mol %)	XPhos (10 mol %)	trace
15	Pd(PPh ₃) ₂ Cl ₂ (4 mol %)	XPhos (10 mol %)	trace
16	Pd(PhCN) ₂ Cl ₂ (4 mol %)	XPhos (10 mol %)	81
17	[Pd(C ₃ H ₅)Cl] ₂ (4 mol %)	XPhos (10 mol %)	58
18	PdCl ₂ (4 mol %)	XPhos (10 mol %)	26
19	Pd(dppf)Cl ₂ (4 mol %)	XPhos (10 mol %)	16
20 ^c	Pd(OAc) ₂ (4 mol %)	XPhos (10 mol %)	trace
21 ^d	Pd(OAc) ₂ (4 mol %)	XPhos (10 mol %)	trace

^a Reaction conditions: ^tBuC₆H₄OTs **1a** (0.30 mmol), PhSi(OMe)₃ **2a** (2.0 equiv), TBAF (1.0 M in THF, 2.0 equiv), 80 °C, 10 h. ^b Isolated yield based on aryl tosylate **1a**. ^c The reaction performed at 30 °C. ^d The reaction performed at 50 °C.

M in THF, 2.0 equiv), 80 °C], and the results are summarized in Table 2. For most cases, aryl arenesulfonates **1** reacted with arylsilanes **2** leading to the corresponding products **3** in good to excellent yields. Additionally, the reaction of aryl arenesulfonate was found to tolerate a range of different groups with different electronic demands on the aromatic rings involving electron-donating and electron-withdrawing groups. For example, reaction of tosylate **1b** with trimethoxy(phenyl)silane **2a** gave rise to the corresponding product **3b** in 67% yield (Table 2, entry 2), while reaction of ester- or cyano-substituted tosylate **1c** or **1d** afforded biaryl compounds **3c** or **3d** in 62% or 72% yield, respectively (Table 2, entries 3–4). α -Naphthyl tosylate **1e**, as well as its benzene-sulfonate **1f**, was also found to be a suitable substrate for coupling with trimethoxy(phenyl)silane **2a** (Table 2, entries 5–6), and the

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Table 2. Pd-Catalyzed Hiyama Cross-Coupling Reactions of Arenesulfonate **1** with Arylsilane **2**

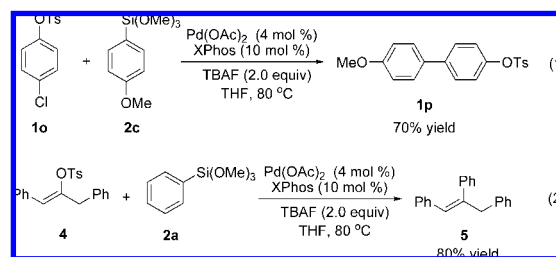
entry	R ¹ /Ar	R ² /R	yield (%) ^a
1	4- <i>t</i> -BuC ₆ H ₄ /4-MeC ₆ H ₄ 1a	C ₆ H ₅ /Me 2a	88 (3a)
2	4-PhC ₆ H ₄ /4-MeC ₆ H ₄ 1b	C ₆ H ₅ /Me 2a	67 (3b)
3	4-EtO ₂ CC ₆ H ₄ /4-MeC ₆ H ₄ 1c	C ₆ H ₅ /Me 2a	62 (3c)
4	4-NCC ₆ H ₄ /4-MeC ₆ H ₄ 1d	C ₆ H ₅ /Me 2a	72 (3d)
5	α-naphthyl/4-MeC ₆ H ₄ 1e	C ₆ H ₅ /Me 2a	88 (3e)
6	α-naphthyl/C ₆ H ₅ 1f	C ₆ H ₅ /Me 2a	94 (3e)
7	β-naphthyl/4-MeC ₆ H ₄ 1g	C ₆ H ₅ /Me 2a	95 (3f)
8	3-morpholinylphenyl/ 4-MeC ₆ H ₄ 1h	C ₆ H ₅ /Me 2a	97 (3g)
9	3-MeOC ₆ H ₄ /4-MeC ₆ H ₄ 1i	C ₆ H ₅ /Me 2a	85 (3h)
10	4- <i>tert</i> -pentylphenyl/ 4-MeC ₆ H ₄ 1j	C ₆ H ₅ /Et 2b	81 (3i)
11	4-CF ₃ C ₆ H ₄ /4-MeC ₆ H ₄ 1k	C ₆ H ₅ /Et 2b	81 (3j)
12	β-naphthyl/4-MeC ₆ H ₄ 1g	C ₆ H ₅ /Et 2b	99 (3f)
13	α-naphthyl/4-MeC ₆ H ₄ 1e	4-MeOC ₆ H ₄ /Me 2c	81 (3k)
14	3-MeC ₆ H ₄ /4-MeC ₆ H ₄ 1l	4-MeOC ₆ H ₄ /Me 2c	68 (3l)
15	3-morpholinylphenyl/ 4-MeC ₆ H ₄ 1h	4-MeC ₆ H ₄ /Me 2d	81 (3m)
16	β-naphthyl/4-MeC ₆ H ₄ 1g	4-MeC ₆ H ₄ /Me 2d	78 (3n)
17	α-naphthyl/C ₆ H ₅ 1f	4-MeC ₆ H ₄ /Me 2d	63 (3o)
18	α-naphthyl/4-MeC ₆ H ₄ 1e	4-CF ₃ C ₆ H ₄ /Me 2e	91 (3p)
19	3-MeOC ₆ H ₄ /4-MeC ₆ H ₄ 1i	4-CF ₃ C ₆ H ₄ /Me 2e	85 (3q)
20	4- <i>t</i> -BuC ₆ H ₄ /4-MeC ₆ H ₄ 1a	2-MeC ₆ H ₄ /Me 2f	53 (3r)
21	2-MeC ₆ H ₄ /4-MeC ₆ H ₄ 1m	C ₆ H ₅ /Me 2a	30 (3s)
22	3-pyridinyl/4-MeC ₆ H ₄ 1n	C ₆ H ₅ /Me 2a	31 (3t)
23	β-naphthyl/4-MeC ₆ H ₄ 1g	2-thiophenyl/Et 2g	trace

^a Isolated yield based on arenesulfonate **1**.

desired product was generated in high yield. Excellent yield was also observed when morpholinyl- or methoxy-substituted tosylate **1c** or **1d** was utilized as a substrate (Table 2, entries 8–9). Similar results were obtained when triethoxy(phenyl)silane **2b** was used as a replacement for **2a** in reactions with aryl arenesulfonates **1** (Table 2, entries 10–12). For instance, almost quantitative yield of product **3f** was generated for reaction of β-naphthyl tosylate **1g** with **2b** (Table 2, entry 12). With respect to other arylsilanes **2c–2e**, as expected both electron-rich and -poor arylsilanes are suitable partners in this process and the desired products were isolated in good yields (Table 2, entries 13–19). However, the yield was diminished when the silane or tosylate bearing *ortho*-substitution was employed under the same conditions (Table 2, entries 20–21). 3-Pyridinyl tosylate was also utilized as a substrate in the reaction of silane **2a** affording the desired product **3t** in 31% yield (Table 2, entry 22). Only a trace amount of product was detected for reaction of 2-thiophenyl(triethoxy) silane **2g** with tosylate **1g** (Table 2, entry 23).

Interestingly, when 4-chlorophenyl tosylate **1o** was employed in the reaction of arylsilane **2c** under the standard conditions shown in Table 2 (Scheme 1, eq 1), the tosyloxy group in compound **1o** was retained during the transformation and the product **1p** was afforded in 70% yield. From this reaction, it was found that an aryl chloride is more active than an aryl tosylate under the same conditions. Similar to tosylate **1b**, compound **1p** could be further elaborated to furnish the triaryl compound. This condition was also applied in the reaction of vinyl tosylate. For example, vinyl tosylate **4** reacted with trimethoxy(phenyl)silane **2a** leading to the corresponding product **5** in 80% yield (Scheme 1, eq 2).

In conclusion, we have developed the first example of achieving Hiyama couplings of aryl arenesulfonates. The desired C–C bond

Scheme 1

formation proceeds under mild conditions with good functional group tolerance.

Acknowledgment. Financial support from National Natural Science Foundation of China (20502004), and Shanghai Pujiang Program is gratefully acknowledged. We also thank Dr. Jason Wong (Roche R&D Center, China) for English review.

Supporting Information Available: Experimental procedures, characterization data, copies of ¹H and ¹³C NMR of compound **3**. This information is available free of charge via the Internet at <http://pubs.acs.org>.

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JA804672M