Palladium(0)-Catalyzed Silylation of Aryl Halides with Triorganosilanes: Synthesis of Aryl(2-furyl)silanes

Miki Murata,* Hiroya Ohara, Ryo Oiwa, Shinji Watanabe, Yuzuru Masuda

Department of Materials Science, Kitami Institute of Technology, Kitami 090-8507, Japan Fax +81(157)264973; E-mail: muratamk@mail.kitami-it.ac.jp Received 25 November 2005; revised 13 January 2006

Abstract: Triorganosilanes, which possess two aryl groups on the silicon atom, undergo palladium-catalyzed silylation of aryl iodides. Aryl(2-furyl)silanes thus obtained are potentially useful starting materials for carbon–carbon bond-forming reactions in the presence of transition-metal catalysts and tetrabutylammonium fluoride.

Key words: silicon, palladium, catalysis, cross-coupling, halides

Recently, much attention has focused on the coupling reaction of metalloid hydride with organic electrophiles as an atom-economical method for the synthesis of organometalloids. The metalations of aryl halides using various metalloid hydrides, including boron,¹ silicon,² germanium,³ and tin compounds,⁴ have been extensively studied; however, the scope of metalloid hydrides used as metalating reagents is still limited. In fact, examples of silvlation using hydrosilanes other than triethoxysilane are rare.⁵ Therefore, we were interested in expanding the scope of palladium-catalyzed silvlation to another hydrosilane as the silicon source. We report herein that triorganosilanes 1 couple with aryl halides 2 in the presence of a palladium catalyst to give carbon-substituted arylsilanes 3; the selective silvlation requires two aryl groups on the silicon atom of triorganosilanes 1 (Equation 1). During the completion of this work, Yamanoi reported a similar palladium-catalyzed method for the combination of triorganosilanes with aryl iodides.6



Equation 1 Palladium-catalyzed silylation of aryl halides using triorganosilanes

An initial screening was performed using several triorganosilanes **1** for the silylation of 4-iodoanisole (**2a**; Table 1). Treatment of **2a** with **1** and *i*-Pr₂NEt in the presence of Pd₂(dba)₃·CHCl₃ and P(*o*-tol)₃ in NMP at room temperature was found to lead to the corresponding aryl-

SYNTHESIS 2006, No. 11, pp 1771–1774 Advanced online publication: 05.05.2006 DOI: 10.1055/s-2006-942368; Art ID: F20205SS © Georg Thieme Verlag Stuttgart · New York silanes **3aa–ha**. The formation of anisole **4a** by reduction of the starting aryl halide **2a** was the major side reaction. Under our conditions, the ratio of **3/4a** was strongly influenced by substituents on the silicon atom of **1**. Among the hydrosilanes **1a–h** examined, diarylmethylhydrosilanes **1d–f** (Equation 1, n = 2) exhibited the highest product selectivity to produce the corresponding arylsilanes **3da–fa** in 75–82% yields (Table 1, entries 4–6). The use of diarylhydrosilanes was suitable for the silylation, as the differences in the yields and selectivity among diarylmethylhydrosilanes **1d–f** were not particularly great. Unfortunately, the use of triarylhydrosilanes **1a–c** (n = 3) produced lower **3/4a** ratios (Table 1, entries 1–3). For dimethylphenylsilane (**1g**) and triethylsilane (**1h**), no selectivity was observed (Table 1, entries 7 and 8).

The results obtained with representative aryl halides 2, giving arylsilanes 3 are listed in Table 2. On the whole,

Entry	1	3	Yield (%) ^b	
			3	4a
1	$Ph_3SiH(1a)$	3aa	64	(33)
2	(□ SiH	3ba	71	(29)
3	1b	3ca	68	(31)
4	$1c$ $Ph_2MeSiH (1d)$	3da	79	(18)
5	(3ea	82	(12)
6	$1e$ $\left(\underbrace{\bigcup}_{S} \right)_{2} MeSiH$	3fa	75	(14)
7	1f PhMe ₂ SiH (1g)	3ga	34	(57)
8	$Et_3SiH(1h)$	3ha	(44)	(46)

^a Reaction conditions: **2a** (1.0 mmol), **1** (1.5 mmol), *i*-Pr₂NEt (3 mmol), $Pd_2(dba)_3$ ·CHCl₃ (15 mmol), $P(o-tol)_3$ (60 mmol), in NMP (4 mL) at r.t. for 2 h.

^b Isolated yields are based on **2a**. Yields in parentheses are GC yields.

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the desired products **3** were contaminated with small amounts of reduced by-products **4**, but their isolation was very easy. The present process was extremely tolerant of a variety of common functional groups. Thus, **2** containing a free amine NH₂ (Table 2, entry 4), a phenolic OH moiety (Table 2, entry 5), an amide (Table 2, entry 12), an acetoxy group (Table 2, entry 6), and a halogen atom (Table 2, entry 7) were all efficiently converted to the corresponding products **3**. In contrast, the traditional methods via Grignard reagents or organolithiums require the protection of functional groups frequently.⁷ Although aryl io-

dides were significantly reactive, replacing the leaving group of aryl halides with the corresponding bromide or triflate gave a lower yield under our normal conditions. Gratifyingly, by treating the reaction mixture with an additional excess amount of iodide anion, the silylation of aryl bromide, triflate, and nonaflate afforded moderate to good product yields (Table 2, entries 9–12).⁸ In such cases, KOAc was a more favorable base for selective silylation. Unfortunately, all attempts at silylation of *ortho*-substituted or electron-deficient aryl halides were unsuccessful.^{2,6}

Entry	Hydrosilane 1	Aryl halide 2	Product 3	Yield (%) ^b
1	1e			67°
2	1e	2b	3eb	80
2		I—	MeSi-Me	00
2	10	2c	3ec	00
3	11	2c		90
4	1.		3fc	71
4	Ie			/1
~		2d	3ed	
5	le	ІОН		55
(1.	2e	3ee	70
0	le	IOAc		19
7	1.	2f	3ef	77
/	le	I-CI		11
0	1.	2g	3eg	00
8	le			88
od		2h	3eh	60
9 ^u	ld	Br-OMe	3da	69
10 ^d	1d	TfO-OMe	3da	84
11 ^d	1d	NfO-OMe	3da	83
12 ^d	1d		Ph ₂ MeSi	72

Table 2 Reaction of Representative Aryl Halides^a

^a Reaction conditions: 2 (1.0 mmol), 1 (1.5 mmol), *i*-Pr₂NEt (3 mmol), Pd₂(dba)₃·CHCl₃ (15 mmol), P(*o*-tol)₃ (60 mmol), in NMP (4 mL) at r.t. for 2 h.

^b Isolated yields are based on **2**.

^c GC yield.

^d KI (3 mmol) was used as an additive, and KOAc (3 mmol) was used instead of *i*-Pr₂NEt.

We then turned our attention toward a synthetic application of aryl(2-furyl)silanes 3 thus obtained via the transition-metal-catalyzed coupling reaction. Recently, several groups have demonstrated the palladium-catalyzed crosscoupling reactions of all-carbon-substituted organosilanes, such as 2-pyridyl-9 and 2-thienyl(alkenyl)silanes.^{10,11} In these reactions, the heteroaryl group acts as a good dummy group upon treatment with a fluoride ion to form possible organosilanols. We found that a 2-furyl group on a silicon atom worked in a manner similar to those heteroaryl groups (Scheme 1).¹² For example, after treatment of di(2-furyl)(methyl)phenylsilane 3eb with TBAF in dioxane-H₂O (8:1) at 90 °C, the palladium-catalyzed cross-coupling reaction with 4-bromobenzotrifluoride took place to produce the corresponding unsymmetrical biaryl in 76% yield. Also, **3eb** participated in rhodium-catalyzed 1,4-addition to an α , β -unsaturated ester to give the desired adduct in good yield.¹³



Scheme 1 Synthetic utility of aryl(2-furyl)silanes

In conclusion, triorganosilanes, which possess two aryl groups on the silicon atom, were found to undergo palladium-catalyzed silylation of aryl iodides; however, the mechanism for this silylation is unclear at the present stage.¹⁴ In addition, we have demonstrated that aryl(2-furyl)silanes can be coupled with electrophiles, such as aryl halides and α , β -unsaturated carbonyl compounds.

All experiments were carried out under an argon atmosphere. NMR spectra were recorded on a JNM-A500 spectrometer. Mass spectra were obtained at an ionization potential of 70 eV with a JEOL JMS-SX102 spectrometer. Heteroarylsilanes (**1b**, **1c**, **1e**, and **1f**) were prepared from the corresponding lithium reagents and chlorosilanes.¹⁵

Silylation of Aryl Iodides; General Procedure

 $Pd_2(dba)_3$ ·CHCl₃ (0.015 mmol) and $P(o-tol)_3$ (0.06 mmol) were placed in a test tube capped with a rubber septum. The test tube was flushed with nitrogen and then charged with NMP (4 mL). Aryl iodide **2** (1.0 mmol), *i*-Pr₂NEt (3 mmol), and hydrosilane **1** (1.5 mmol) were added successively. The reaction mixture was then stirred at r.t. for 2 h. When the reaction was complete, Et₂O (10 mL) was added; the organic phase was washed with H₂O (3 × 15 mL) to remove NMP and dried over Na₂SO₄. The solvent was removed under reduced pressure and the residue was purified by flash column chromatography (hexane–Et₂O, 20:1) to give the desired arylsilane **3**.

3ea

¹H NMR (CDCl₃): $\delta = 0.78$ (s, 3 H), 3.81 (s, 3 H), 6.42 (dd, J = 3.0, 1.8 Hz, 2 H), 6.76 (d, J = 3.0 Hz, 2 H), 6.93 (d, J = 8.5 Hz, 2 H), 7.54 (d, J = 8.5 Hz, 2 H), 7.72 (d, J = 1.8 Hz, 2 H).

 ^{13}C NMR (CDCl₃): δ = -4.24, 55.05, 109.61, 113.79, 122.79, 124.52, 136.24, 147.72, 155.38, 161.14.

HRMS (EI): m/z calcd for $C_{16}H_{16}O_3Si$ [M⁺]: 284.0868; found: 284.0840.

3fa

¹H NMR (CDCl₃): δ = 0.88 (s, 3 H), 3.81 (s, 3 H), 6.92 (d, *J* = 7.9 Hz, 2 H), 7.21 (dd, *J* = 4.3, 3.6 Hz, 2 H), 7.34 (d, *J* = 3.6 Hz, 2 H), 7.52 (d, *J* = 7.9 Hz, 2 H), 7.68 (d, *J* = 4.3 Hz, 2 H).

¹³C NMR (CDCl₃): $\delta = -0.87$, 55.03, 113.69, 128.26, 131.98, 135.77, 126.43, 136.26, 136.80, 161.05.

HRMS (EI): m/z calcd for $C_{16}H_{16}OS_2Si$ [M⁺]: 316.0412; found: 316.0443.

3eb

¹H NMR (CDCl₃): δ = 0.81 (s, 3 H), 6.43 (dd, *J* = 3.0, 1.2 Hz, 2 H), 6.78 (d, *J* = 3.0 Hz, 2 H), 7.3–7.5 (m, 3 H), 7.62 (d, *J* = 8.0 Hz, 2 H), 7.73 (d, *J* = 1.2 Hz, 2 H).

 ^{13}C NMR (CDCl₃): δ = -4.47, 109.65, 122.98, 127.97, 129.96, 133.84, 134.65, 147.82, 154.95.

HRMS (EI): m/z calcd for $C_{15}H_{14}O_2Si$ [M⁺]: 254.0763; found: 254.0721.

3ec

¹H NMR (CDCl₃): δ = 0.78 (s, 3 H), 2.36 (s, 3 H), 6.42 (dd, *J* = 3.0, 1.8 Hz, 2 H), 6.77 (d, *J* = 3.0 Hz, 2 H), 7.20 (d, *J* = 7.5 Hz, 2 H), 7.51 (d, *J* = 7.5 Hz, 2 H), 7.72 (d, *J* = 1.8 Hz, 2 H).

¹³C NMR (CDCl₃): $\delta = -4.38$, 21.57, 109.61, 122.84, 128.84, 130.11, 134.70, 140.01, 147.74, 155.22.

HRMS (EI): m/z calcd for $C_{16}H_{16}O_2Si$ [M⁺]: 268.0919; found: 268.0912.

3fc

¹H NMR (CDCl₃): δ = 0.89 (s, 3 H), 2.36 (s, 3 H), 7.2–7.3 (m, 4 H), 7.35 (d, *J* = 3.1 Hz, 2 H), 7.50 (d, *J* = 7.3 Hz, 2 H), 7.69 (d, *J* = 4.3 Hz, 2 H).

 ^{13}C NMR (CDCl₃): δ = -0.99, 21.55, 128.26, 128.77, 132.00, 133.02, 134.74, 135.55, 136.85, 139.92.

HRMS (EI): m/z calcd for $C_{16}H_{16}S_2Si$ [M⁺]: 300.0463; found: 300.0442.

3ed

¹H NMR (CDCl₃): δ = 0.75 (s, 3 H), 3.78 (br s, 2 H), 6.41 (dd, J = 3.0, 1.2 Hz, 2 H), 6.69 (d, J = 8.0 Hz, 2 H), 6.75 (d, J = 3.0 Hz, 2 H), 7.40 (d, J = 8.0 Hz, 2 H), 7.71 (d, J = 1.3 Hz, 2 H).

 ^{13}C NMR (CDCl₃): δ = -4.23, 109.54, 114.63, 122.58, 129.27, 136.08, 147.58, 148.13, 155.78.

HRMS (EI): m/z calcd for $C_{15}H_{15}NO_2Si$ [M⁺]: 269.0872; found: 269.0834.

3ee

¹H NMR (CDCl₃): δ = 0.78 (s, 3 H), 4.85 (s, 1 H), 6.42 (dd, *J* = 3.0, 1.8 Hz, 2 H), 6.76 (d, *J* = 3.0 Hz, 2 H), 6.85 (d, *J* = 8.5 Hz, 2 H), 7.50 (d, *J* = 8.5 Hz, 2 H), 7.72 (d, *J* = 1.8 Hz, 2 H).

¹³C NMR (CDCl₃): $\delta = -4.27$, 109.61, 115.47, 122.81, 126.12, 136.49, 147.73, 155.28, 157.15.

HRMS (EI): m/z calcd for $C_{15}H_{14}O_3Si$ [M⁺]: 270.0712; found: 270.0733.

3ef

¹H NMR (CDCl₃): $\delta = 0.77$ (s, 3 H), 2.30 (s, 3 H), 6.43 (dd, J = 1.8, 3.0 Hz, 2 H), 6.79 (d, J = 3.0 Hz, 2 H), 7.10 (d, J = 8.0 Hz, 2 H), 7.62 (d, J = 8.0 Hz, 2 H), 7.73 (d, J = 1.8 Hz, 2 H).

¹³C NMR (CDCl₃): δ = -4.41, 21.17, 109.68, 120.75, 122.78, 128.94, 131.44, 136.02, 147.88, 152.18, 169.30.

HRMS (EI): m/z calcd for $C_{17}H_{16}O_4Si$ [M⁺]: 312.0818; found: 312.0845.

3eg

¹H NMR (CDCl₃): $\delta = 0.79$ (s, 3 H), 6.44 (dd, J = 3.6, 1.2 Hz, 2 H), 6.78 (d, J = 3.6 Hz, 2 H), 7.36 (d, J = 8.3 Hz, 2 H), 7.53 (d, J = 8.3 Hz, 2 H), 7.73 (d, J = 1.2 Hz, 2 H).

¹³C NMR (CDCl₃): $\delta = -4.49$, 109.71, 123.19, 128.25, 132.25, 136.02, 136.41, 147.98, 154.38.

HRMS (EI): m/z calcd for $C_{15}H_{13}O_2^{35}ClSi$ [M⁺]: 288.0373; found: 288.0418.

3eh

¹H NMR (CDCl₃): δ = 0.85 (s, 3 H), 6.43 (dd, J = 1.2, 3.7 Hz, 2 H), 6.83 (d, J = 3.7 Hz, 2 H), 7.23 (dd, J = 4.9, 3.1 Hz, 1 H), 7.43 (d, J = 3.1 Hz, 1 H), 7.69 (d, J = 4.9 Hz, 1 H), 7.73 (d, J = 1.2 Hz, 2 H). ¹³C NMR (CDCl₃): δ = -3.24, 109.47, 109.73, 123.07, 128.34, 132.32, 137.00, 147.90, 154.45.

HRMS (EI): m/z calcd for $C_{13}H_{12}O_2SiS$ [M⁺]: 260.0327; found: 260.0368.

Palladium-Catalyzed Cross-Coupling of Aryl(2-furyl)silanes

A mixture of di(2-furyl)(methyl)phenylsilane (2 mmol) and TBAF·3H₂O (2 mmol) in dioxane–H₂O (8:1, 3.6 mL) was stirred at 90 °C for 2 h. To this solution were added PdCl₂(dppf) (0.05 mmol) and 4-bromobenzotrifluoride (1.0 mmol). After stirring at 90 °C for 16 h, GC analysis of the resulting mixture indicated the formation of 4-phenylbenzotrifluoride in 76% yield.

Rhodium-Catalyzed 1,4-Addition of Aryl(2-furyl)silanes to α , β -Unsaturated Esters

A mixture of di(2-furyl)(methyl)phenylsilane (2 mmol) and TBAF·3H₂O (2 mmol) in dioxane–H₂O (8:1, 3.6 mL) was stirred at 90 °C for 2 h. To this solution were added [Rh(OH)(cod)]₂ (0.025 mmol) and *tert*-butyl acrylate (1.0 mmol). After stirring at 90 °C for 16 h, GC analysis of the resulting mixture indicated the formation of *tert*-butyl 3-phenylpropionate in 80% yield.

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References

- (a) Murata, M.; Watanabe, S.; Masuda, Y. J. Org. Chem. 1997, 62, 6458. (b) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. J. Org. Chem. 2000, 65, 164. (c) Baudoin, O.; Guénard, D.; Guéritte, F. J. Org. Chem. 2000, 65, 9268. (d) Broutin, P.-E.; Čerña, I.; Campaniello, M.; Leroux, F.; Colobert, F. Org. Lett. 2004, 6, 4419.
- (2) (a) Murata, M.; Suzuki, K.; Watanabe, S.; Masuda, Y. J. Org. Chem. 1997, 62, 8569. (b) Manoso, A. S.; DeShong, P. J. Org. Chem. 2001, 66, 7455. (c) Murata, M.; Ishikura, M.; Nagata, M.; Watanabe, S.; Masuda, Y. Org. Lett. 2002, 4, 1843. (d) Komuro, K.; Ishizaki, K.; Suzuki, H. Touagouseikenkyu-nenpo 2003, 6, 24.
- (3) Nakamura, T.; Kinoshita, H.; Shinokubo, H.; Oshima, K. *Org. Lett.* **2002**, *4*, 3165.
- (4) Murata, M.; Watanabe, S.; Masuda, Y. Synlett 2000, 1043.
- (5) (a) Murata, M.; Watanabe, S.; Masuda, Y. *Tetrahedron Lett.* **1999**, 40, 9255. (b) Denmark, S. E.; Kallemeyn, J. M. Org. Lett. **2003**, 5, 3483.
- (6) The silylation using trialkylsilanes was reported, however, no example of diarylmethylsilanes was provided, see: Yamanoi, Y. J. Org. Chem. 2005, 70, 9607.
- (7) The Chemistry of Organic Silicon Compounds; Patai, S.; Rappoport, Z., Eds.; Wiley & Sons: New York, 2000.
- (8) For examples of coupling reactions of aryl nonaflates, see:
 (a) Rottlander, M.; Knochel, P. J. Org. Chem. 1998, 63, 203.
 (b) Anderson, K. W.; Mendez-Perez, M.; Priego, J.; Buchwald, S. L. J. Org. Chem. 2003, 68, 9563.
- (9) (a) Itami, K.; Nokami, T.; Yoshida, J. J. Am. Chem. Soc.
 2001, 123, 5600. (b) Itami, K.; Nokami, T.; Ishimura, Y.; Mitsudo, K.; Kamei, T.; Yoshida, J. J. Am. Chem. Soc. 2001, 123, 11577.
- (10) Hosoi, K.; Nozaki, K.; Hiyama, T. Chem. Lett. 2002, 138.
- (11) For examples of the cross-coupling reaction of other all-carbon-substituted organosilanes, see: (a) Denmark, S. E.; Choi, J. Y. J. Am. Chem. Soc. 1999, 121, 5821. (b) Nakao, Y.; Oda, T.; Sahoo, A. K.; Hiyama, T. J. Organomet. Chem. 2003, 687, 570. (c) Trost, B. M.; Machacek, M. R.; Ball, Z. T. Org. Lett. 2003, 5, 1895.
- (12) Cross-coupling of aryltri(2-furyl)germanes with aryl halides has been reported, see ref. 3.
- (13) (a) Huang, T. S.; Li, C. J. *Chem. Commun.* 2001, 2348.
 (b) Mori, A.; Danda, Y.; Fujii, T.; Hirabayashi, K.; Osakada, K. *J. Am. Chem. Soc.* 2001, *123*, 10774. (c) Fujii, T.; Koike, T.; Mori, A.; Osakada, K. *Synlett* 2002, 298. (d) Koike, T.; Du, X.; Mori, A.; Osakada, K. *Synlett* 2002, 301. (e) Oi, S.; Honma, Y.; Inoue, Y. *Org. Lett.* 2002, *4*, 667. (f) Murata, M.; Shimazaki, R.; Ishikura, M.; Watanabe, S.; Masuda, Y. *Synthesis* 2002, 717.
- (14) To some extent a plausible mechanism can be derived from that proposed by us for triethoxysilane (see ref. 2a); however, the role of KI (Table 2, entries 9–12) is not easily interpreted.
- (15) Cunico, R. F.; Bedell, L. J. Org. Chem. 1980, 45, 4797.