Aromatic C–H silylation of arenes with 1-hydrosilatrane catalyzed by an iridium(I)∕2,9-dimethylphenanthroline (dmphen) complex

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Aromatic C–H silylation of neat arenes with 1-hydrosilatrane was found to be efficiently catalyzed by iridium catalysts composed of 1∕2[Ir(OMe)(cod)] 2 and 2,9-dimethyl-1,10-phenanthroline at 120 °C to afford the corresponding silylated products in high yields. The silylated products can be used to Hiyama cross-coupling reaction.

Silyl-substituted arenes are an important class of compounds that have been shown to be useful in synthetic organic chemistry, material science, and pharmaceutical sectors. Traditional methods for their synthesis are based on alkylation of silicon electrophiles with aryl-lithium or -magnesium compounds. Transition metal-catalyzed cross-coupling of aromatic halides with disilanes or hydrosilanes is a milder variant in which the preparation of magnesium or lithium reagents is avoided.

Alternatively, metal-catalyzed C–H silylation of arenes is highly attractive as a convenient, economical, and environmentally benign process. Thus, there have been several attempts at C–H functionalization of arenes with disilanes or hydrosilanes.

Since tetraorganosilicon compounds reported in these precedents are inert to C–Si bond activation with F bases for metal-catalyzed bond-forming reactions, we reported the first access to arylidifluorosilanes via direct C–H silylation of arenes with [SiF 2(t-Bu) 2] in the presence of iridium(I) catalysts. Although the reaction achieved high yields for representative arenes, this protocol is limited due to the many tedious steps required for obtaining fluorodisilanes and the fact that only half of the silyl groups of the disilanes participate in the reaction. Such drawbacks prompted us to use easily available alkoxysilanes as silylation reagents. We disclose here a useful C–H silylation of arenes 1 with 1-hydro-2,8,9-trioxas-aza-1-silabicyclo[3.3.3]undecane 11 (1-hydrosilatrane) 2 catalyzed by a 1∕2[Ir(OMe)(cod)] 2∕2,9-dimethyl-1,10-phenanthroline (dmphen) complex at 120 °C to give the corresponding 1-arylsilatrane 3 in high yields (Scheme 1). The silylated products 3 can be used to Hiyama cross-coupling procedure in high yield. Air- and moisture-stable 1-hydrosilatrane, obtained in one step by treatment of triethoxysilane with boratrane, is advantageous over fluorodisilanes for large-scale preparation from commercial materials. 11

Ligands for catalysts of aromatic C–H silylation such as modified 2,2′-bipyridines and unsubstituted 1,10-phenanthroline were not efficient for 1-hydrosilatrane 2. Thus, the effects of steric and electronic properties of phenanthroline ligands (phen) were re-evaluated by using 1∕2[Ir(OMe)(cod)] 2 as a catalyst precursor (Table 1). A phen possessing two methyl groups at the 2- and 9-positions (dmphen) displayed good reactivity (Entry 2), whereas its 2,9-di-tert-butyl, 2,9-di-isopropyl and 2,9-di-i-butyl derivatives showed almost no activity (Entries 3–5). These results indicate the importance of an appropriately hindered coordination sphere around the iridium metal center. Electron-rich 2,9-dimethylphenanthroline ligands work better than electron-poor 2,9-dimethylphenanthroline ligands. Thus, the highest yield was obtained with 4,7-bis(dimethylamino) (Entry 6), whereas 4,7-dimethoxy, 4,7-dichloro and 4,7-bis(trifluoromethyl) derivatives displayed moderate or low activity (Entries 7–9). Metal-catalyzed C–H silylation with hydrosilanes is often retarded by hydrogen generated during coupling. Thus, reactions were carried out in a flask fitted with a condenser and a nitrogen bubbler to remove hydrogen in place of a sealed Schlenk tube. As expected, 50% yield in a sealed Schlenk tube was improved to 74% in a flask fitted with a nitrogen bubbler (Entry 2). Use of hydrogen scavengers such as 3,3-dimethyl-1-buten and 2-norbornene in a sealed Schlenk tube was not effective. Of the representative alkoxysilanes screened, small and thermally stable 2 provided the best yields, but ethoxymethylsilane, diethoxymethylsilane, and triethoxysilane did not give any coupling products at all.

We evaluated the scope and limitations of the reaction using dmphen because of the commercial availability of this ligand. Reactions of 2 (1 mmol) in neat arenes (60 mmol) at 120 °C for 32 h in a flask fitted with a nitrogen bubbler are summarized in Table 2. In contrast to the control of regioselectivity of electrophilic and nucleophilic substitution of arenes by the electronic properties of substituents, the regiochemistry of the present C–H silylation is primarily controlled by the steric effect of substituents. Thus, reactions located meta or para to a
in preference of those located in the ortho position. 1,2- and 1,3-Dichlorobenzenes gave a single coupling product at the meta-carbon (3b: 87%, 3a: 77%). Bicyclic arenes such as indane, tetralin and 1,4-benzodioxane selectively yielded β-silylarenes (3c: 76%, 3d: 81%, 3e: 73%). Arenes in which the rings were electron-poor or electron-rich participated in the silylation reactions (3b: 87%, 3f: 75%, 3g: 73%), though m-xylene exceptionally resulted a low yield for an unknown reason (3i: 24%). The reaction of 1,3-disubstituted arenes selectively occurred only at the common meta position; therefore, isomerically pure silylarenes were obtained even with two distinct substitutes on the aromatic ring (3j: 71%, 3k: 70%). It is notable that aromatic C–H bonds (112 kcal/mol) are selectively silylated in the presence of weaker benzylic C–H bonds (85 kcal/mol) or C–Cl bonds (95 kcal/mol).

**Table 2.** C–H silylation of various arenes with 2

<table>
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<tr>
<th>Entry</th>
<th>R&lt;sub&gt;1&lt;/sub&gt;</th>
<th>R&lt;sub&gt;2&lt;/sub&gt;</th>
<th>Yield of 3a (%)&lt;sup&gt;a&lt;/sup&gt;</th>
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<td>9</td>
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<td>CF&lt;sub&gt;3&lt;/sub&gt;</td>
<td>28</td>
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</table>

<sup>a</sup> The reactions were carried out by using 1,3-dichlorobenzene (60 mmol), 2 (1.0 mmol), [Ir(OMe)(cod)]<sub>2</sub> (0.015 mmol), and ligand (0.03 mmol) at 120 °C for 16 h in a flask fitted with a condenser and a nitrogen bubbler. H NMR yields based on 2 by using mesitylene as an internal standard.

The reaction may proceed through a catalytic cycle analogous to that of aromatic C–H borylation:<sup>12</sup> (a) generation of a (silyl)iridium intermediate (4) from 1-hydrosilatrane 2 and the Ir(1)-OMe complex, (b) oxidative addition of an aromatic C–H bond to 4 followed by reductive elimination of an arylsilane 3 to give an iridium hydride complex (5), and (c) oxidative addition of 2 to 5 followed by reductive elimination of hydrogen to regenerate 4 (Scheme 2). A proposed catalytic cycle for C–H borylation involves oxidative addition of an aromatic C–H bond to a tris(boryl)iridium(III) intermediate. Although there is no supporting information on whether the silyl intermediate is iridium(I) or iridium(III) complex (4, n=1 or 3), both complexes may allow C–H oxidative addition of arenes and reductive elimination of silylarenes.<sup>12b</sup>

![Scheme 2. Plausible mechanism.](image)

1-Arylsilatranes 3 thus obtained are useful reagents for carbon-carbon bond-forming reactions (Scheme 3). For example, silylarene 3 underwent Hiyama cross-coupling with aryl halides, thus suggesting that arylsilatranes are activated for transmetalation to transition metals in the presence of F bases.<sup>24</sup>

![Scheme 3. Synthetic utility of 3.](image)

In summary, we provided the first access to arylsilatranes via C–H silylation of arenes. Since organo(trialkoxy)silanes are versatile intermediates for metal-catalyzed bond-forming reactions, this procedure should be applicable for other silylated products as a useful method to obtain these potentially bioactive compounds. Further investigations to survey the scope and limitations as well as to elucidate the reaction mechanisms are in progress.

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Notes and references


Aromatic C–H silylation of neat arenes with 1-hydrosilatrane was found to be efficiently catalyzed by iridium catalysts composed of 1/2[Ir(OMe)(cod)]₂ and 2,9-dimethyl-1,10-phenanthroline at 120°C to afford the corresponding silylated products in high yields.
Supporting Information

Aromatic C–H silylation of arenes with 1-hydrosilatrane catalyzed by iridium(I)/2,9-dimethylphenanthroline (dmphen) complex

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General. All the experiments were carried out under a nitrogen atmosphere. ¹H and ¹³C NMR spectra were recorded in CDCl₃ solutions using a JEOL JNM-A400II spectrometer (400 or 100 MHz) and Me₄Si or residual protiated solvent as an internal standard. Low- and high-resolution mass spectra were obtained on a JEOL JMS-DX303. GC analyses were conducted on a Hitachi G-3500 instrument equipped with a glass column (OV-101 on Uniport B, 2 m). [Ir(OMe)(cod)]⁺, 2,9-diisopropyl-1,10-phenanthroline,¹ 2,9-di-tert-butyl-1,10-phenanthroline,² 1-hydro-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane,¹ and 2,9-dimethyl-4,7-dichloro-1,10-phenanthroline¹ were synthesized by the reported procedure. 2,9-Dimethyl-4,7-bis(dimethylamino)-1,10-phenanthroline and 2,9-dimethyl-4,7-dimethoxy-1,10-phenanthroline were prepared by the methods similar to those for 4,7-bis(dimethylamino)-1,10-phenanthroline³ and 4,7-dimethoxy-1,10-phenanthroline,¹ respectively. 2,9-Dimethyl-4,7-bis(trifluoromethyl)-1,10-phenanthroline was obtained by chlorine-iodine exchange⁶ of 2,9-dimethyl-4,7-dichloro-1,10-phenanthroline and coupling⁷ of the iodide with in situ generated (trifluoromethyl)copper. Aromes were purified by distillation from appropriate drying agents. All of other compounds were used as received.

2,9-Dimethyl-4,7-bis(dimethylamino)-1,10-phenanthroline. ¹H NMR (400 MHz, CDCl₃) δ 2.84 (s, 6H), 3.03 (s, 12H), 6.88 (s, 2H), 7.89 (s, 2H); ¹³C NMR (100 MHz) δ 26.32, 44.11, 109.93, 119.85, 120.64, 147.34, 157.72, 158.92; LRMS (EI) m/z 294 (M⁺, 100), 279 (9.5), 263 (6.3), 250 (4.9), 236 (3.6), 147 (5.9), 139 (4.5); HRMS (EI) calcd for C₁₅H₁₃N₂O₂ 294.1684, found 294.1683.

2,9-Dimethyl-4,7-dimethoxy-1,10-phenanthroline. ¹H NMR (400 MHz, CDCl₃) δ 2.89 (s, 6H), 4.07 (s, 6H), 6.86 (s, 2H), 8.08 (s, 2H); ¹³C NMR (100 MHz, CDCl₃) δ 26.63, 55.66, 102.74, 117.95, 119.42, 145.97, 160.26, 162.28; LRMS (EI) m/z 268 (M⁺, 100), 253 (14.1), 225 (22.8), 210 (4), 182 (7.5), 134 (4.9); HRMS (EI) calcd for C₁₅H₁₁NO₂ 268.1212, found 268.1207.

2,9-Dimethyl-4,7-bis(trifluoromethyl)-1,10-phenanthroline. ¹H NMR (400 MHz, CDCl₃) δ 3.05 (s, 6H), 7.86 (s, 2H), 8.19 (s, 2H); ¹³C NMR (100 MHz, CDCl₃) δ 26.13, 120.81 (q, J = 5.2 Hz), 121.90 (q, J = 1.7 Hz), 122.78 (q, J = 1.7 Hz), 123.30 (q, J = 274.2 Hz), 134.74 (q, J = 319.4), 146.09, 159.94; LRMS (EI) m/z 344 (M⁺, 100), 325 (4.7), 274 (6.7), 172 (5.5), 40 (9.3); HRMS (EI) calcd for C₁₅H₁₃F₂N 344.0748, found 344.0750.

General procedure for the C–H silylation (Table 2). An oven-dried flask fitted with a condenser and a nitrogen bubbler was charged with 1-hydrosilatrane (1.0 mmol), [[Ir(OMe)(cod)]_]₂ (0.015 mmol) and dmphen (0.03 mmol), and then flushed with nitrogen. Under a positive flow of nitrogen, an arene (60 mmol) was added. The reaction mixture was stirred at 120°C for 32 h. The product was isolated by Kugelrohr distillation to give an analytically pure sample.

1-(3,4-Dichlorophenyl)-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane (3b).

¹H NMR (400 MHz, CDCl₃) δ 2.92 (s, J = 5.9 Hz, 6 H), 3.89 (s, J = 5.9 Hz, 6 H), 7.32 (d, J = 7.8 Hz, 1 H), 7.53 (dd, J = 1.5, 7.8 Hz, 1H), 7.79 (d, J = 1.5 Hz, 1H); ¹³C NMR (100 MHz, CDCl₃) δ 50.95, 57.48, 129.22, 131.23, 131.28, 133.57, 136.19, 143.66; LRMS (EI) m/z 319 (M⁺, 8), 174 (100); HRMS (EI) calcd for C₁₄H₁₁F₂NO₃SiCl 319.0198, found 319.0198.

1-(5-Indanyl)-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane (3c).
1H NMR (400 MHz, CDCl₃) δ 1.94-2.01 (m, 2 H), 2.81-2.90 (m, 7 H), 3.88 (t, J = 5.9 Hz, 6 H), 7.13 (d, J = 7.3 Hz, 1 H), 7.50 (d, J = 7.3 Hz, 1 H), 7.59 (s, 1 H); 13C NMR (100 MHz, CDCl₃) δ 25.31, 32.76, 32.81, 51.08, 57.80, 123.33, 129.81, 131.82, 138.77, 142.82, 143.61; LRMS (EI) m/z 291 (M⁺, 19.7), 174 (100); HRMS (EI) calcd for C₁₃H₁₄NO₂Si 291.1291, found 291.1293.

1-(6-Tetralinyl)-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane (3d).

1H NMR (400 MHz, CDCl₃) δ 1.72-1.75 (m, 4 H), 2.69 (br s, 2 H), 2.75 (br s, 2 H), 2.89 (t, J = 5.9 Hz, 6 H), 3.88 (t, J = 5.9 Hz, 6 H), 6.96 (d, J = 7.3 Hz, 1 H), 7.41 (s, 1 H), 7.42 (d, J = 7.8 Hz, 1 H); 13C NMR (100 MHz, CDCl₃) δ 23.45, 23.56, 29.40, 29.49, 51.18, 57.86, 128.10, 131.14, 134.74, 135.65, 136.63, 137.98; LRMS (EI) m/z 305 (100), 174 (100); HRMS (EI) calcd for C₁₃H₁₂NO₂Si 305.1447, found 305.1449.

1-(2,3-dihydrobenz[a]1,4[dioxin-6-yl]-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane (3e).

1H NMR (400 MHz, CDCl₃) δ 2.90 (t, J = 5.9 Hz, 6 H), 3.88 (t, J = 5.9 Hz, 6 H), 4.20 (s, 3 H), 6.78 (d, J = 8.0 Hz, 1 H), 7.20 (dd, J = 1.5 and 8.0 Hz, 1 H), 7.25 (d, J = 1.5 Hz, 1 H); 13C NMR (100 MHz, CDCl₃) δ 51.06, 57.72, 64.26, 64.53, 116.28, 123.06, 127.38, 134.79, 142.78, 143.42; LRMS(EI) m/z 311 (M⁺, 59.2), 174 (100); HRMS (EI) calcd for C₁₄H₂₀NO₂Si 309.1032, found 309.1031.

1-(3,4-Dimethylphenyl)-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane (3f).

1H NMR (400 MHz, CDCl₃) δ 2.19 (s, 3 H), 2.29 (s, 3 H), 2.87 (t, J = 6.0 Hz, 6 H), 3.87 (t, J = 5.9 Hz, 6 H), 7.03 (d, J = 7.3 Hz, 1 H), 7.44 (d, J = 7.6 Hz, 1 H), 7.47 (s, 1 H); 13C NMR (100 MHz, CDCl₃) δ 19.68, 19.79, 51.11, 57.83, 128.66, 131.67, 134.96, 135.28, 135.85, 138.67; LRMS (EI) m/z 279 (M⁺, 23), 236 (3.2), 206 (3.1), 174 (100), 119 (3); HRMS (EI) calcd for C₁₃H₁₂NO₂Si 279.1291, found 279.1301.

1-(3,4-Dimethoxyphenyl)-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane (3g).

1H NMR (400 MHz, CDCl₃) δ 2.92 (t, J = 6.1 Hz, 6 H), 3.84 (s, 3 H), 3.90 (t, J = 5.9 Hz, 6 H), 3.91 (s, 3 H), 6.83 (d, J = 7.8, 1 H), 7.28 (d, J = 1.5 Hz, 1 H), 7.30 (dd, J = 1.4 and 7.8 Hz, 1 H); 13C NMR (100 MHz, CDCl₃) δ 51.09, 55.59, 55.68, 57.81, 110.78, 116.65, 127.11, 133.67, 147.98, 148.88; LRMS(EI) m/z 311 (M⁺, 59.2), 174 (100); HRMS (EI) calcd for C₁₃H₂₀NO₂Si 311.1189, found 311.1194.

1-[3,5-Bis(trifluoromethyl)phenyl]-2,8,9-trioxa-5-aza-1-silabicyclo[3.3.3]undecane (3h).
1H NMR (400 MHz, CDCl₃) δ 2.95 (t, J = 6.1 Hz, 6 H), 3.92 (t, J = 6.1 Hz, 6 H), 7.71 (s, 1 H), 8.18 (s, 2H); 13C NMR (100 MHz, CDCl₃) δ 50.97, 57.44, 121.09-121.25 (m), 124.18 (q, J = 272.3 Hz), 129.45 (q, J = 31.9 Hz), 134.25-134.50 (m), 146.26; LRMS (EI) m/z 387 (M⁺, 3.2), 174 (100); HRMS (EI) calcd for C₁₃H₁₂NO₅Si 387.0725, found 387.0722.

1-(3,5-Dichlorophenyl)-2,8,9-trioxo-5-aza-1-silabicyclo[3.3.3]undecane (3a).

1H NMR (400 MHz, CDCl₃) δ 2.94 (t, J = 6.1 Hz, 6 H), 3.91 (t, J = 6.1 Hz, 6 H), 7.21 (t, J = 2.0 Hz, 1 H), 7.58 (d, J = 2.0 Hz, 2 H); 13C NMR (100 MHz, CDCl₃) δ 51.01, 57.49, 127.42, 132.31, 133.93, 147.25; LEMS (EI) m/z 319 (M⁺, 5.4), 174 (100), 130 (3); HRMS (EI) calcd for C₁₂H₁₃NO₂SiCl 319.0198, found 319.0204.

1-(3,5-Dimethylphenyl)-2,8,9-trioxo-5-aza-1-silabicyclo[3.3.3]undecane (3i).

1H NMR (400 MHz, CDCl₃) δ 2.27 (s, 6 H), 2.90 (t, J = 5.9 Hz, 6 H), 3.90 (t, J = 5.9 Hz, 6 H), 6.88 (s, 1 H), 7.35 (s, 2 H); 13C NMR (100 MHz, CDCl₃) δ 21.45, 51.09, 57.82, 129.58, 131.68, 136.26, 141.12; LRMS (EI) m/z 279 (M⁺, 19), 174 (100), 148 (3.1), 119 (3.1), 105 (3.2); HRMS (EI) calcd for C₁₅H₁₆O₅SiCl 279.1291, found 279.1298.

1-(3-Chloro-5-trifluoromethylphenyl)-2,8,9-trioxo-5-aza-1-silabicyclo[3.3.3]undecane (3j).

1H NMR (400 MHz, CDCl₃) δ 2.93 (t, J = 6.1 Hz, 6 H), 3.91 (t, J = 5.9 Hz, 6 H), 7.44 (s, 1 H), 7.87 (s, 2 H); 13C NMR (100 MHz, CDCl₃) δ 50.94, 57.44, 124.01 (q, J = 272.3 Hz), 124.26 (q, J = 4.1 Hz), 128.97 (q, J = 3.9 Hz), 130.53 (q, J = 31.9 Hz), 133.59, 137.68, 147.12; LRMS (EI) m/z 353 (M⁺, 4), 174 (100); HRMS (EI) calcd for C₁₃H₁₁NO₃F₂SiCl 353.0462, found 353.0461.

1-(3-Chloro-5-methylphenyl)-2,8,9-trioxo-5-aza-1-silabicyclo[3.3.3]undecane (3k).

1H NMR (400 MHz, CDCl₃) δ 2.28 (s, 3 H), 2.92 (t, J = 5.9 Hz, 6 H), 3.90 (t, J = 5.9 Hz, 6 H), 7.02 (s, 1 H), 7.40 (s, 1 H), 7.51 (s, 1 H); 13C NMR (100 MHz, CDCl₃) δ 21.20, 50.98, 57.60, 128.28, 131.04, 132.83, 133.20, 138.38, 144.61; LRMS (EI) m/z 299 (M⁺, 10.3), 174 (100); HRMS (EI) calcd for C₁₀H₁₀ClN₁O₃Si 299.0744, found 299.0737.

Cross-coupling of 1-(3,4-dimethylphenyl)-2,8,9-trioxo-5-aza-1-silabicyclo[3.3.3]undecane with 4-iodoacetophenone (Scheme 3). A mixture of Pd(OAc)₂ (0.1 mmol), PPh₃ (0.2 mmol), 1-(3,4-dimethylphenyl)-2,8,9-trioxo-5-aza-1-silabicyclo[3.3.3]undecane (2.0 mmol), 4-
iodoacetophenone (1.0 mmol), and DMF (10 ml) was stirred at r.t. for 10 min. 1.0 M TBAF in THF (2.0 mmol) was added and the resulting mixture was stirred at 90 °C for 2 h. Isolation by column chromatography over silica gel gave an analytically pure sample.

4-(3,4-Dimethylphenyl)acetophenone 4.

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\begin{align*}
\text{H NMR} & (400 \text{ MHz, CDCl}_3) \delta 2.32 (s, 3 H), 2.35 (s, 3 H), 2.63 (s, 3 H), 7.24 (t, J = 6.6 \text{ Hz}, 1 H), 7.38 (dd, J = 2.0 \text{ and } 7.8 \text{ Hz}, 1 H), 7.42 (d, J = 1.5 \text{ Hz}, 1 H), 7.67 (dt, J = 2.0 \text{ and } 8.3 \text{ Hz}, 2 H), 8.02 (dt, J = 2.0 \text{ and } 8.8 \text{ Hz}, 2 H); \\
\text{\text{\text{\text{\text{C NMR}}} (100 \text{ MHz, CDCl}_3) \delta 19.48, 19.90, 26.61, 124.59, 126.92, 128.43, 128.84, 130.22, 135.50, 136.89, 137.16, 137.38, 145.84, 197.74; HRMS (EI) calcd for C_{16}H_{16}O 224.1201, found 224.1199.}
\end{align*}
\]

References