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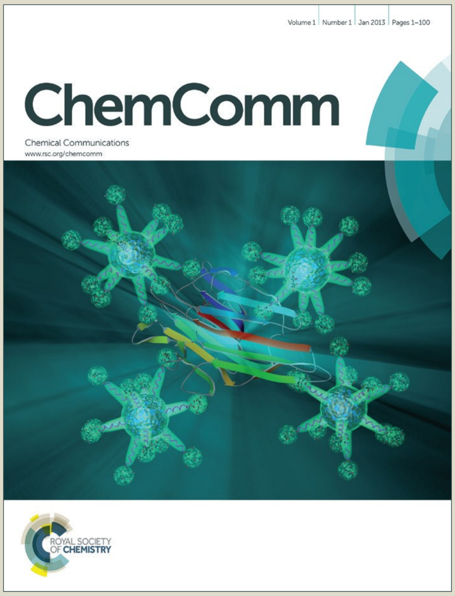

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Suzuki-type Cross Coupling between Aryl Halides and Silylboranes for the Syntheses of Aryl Silanes

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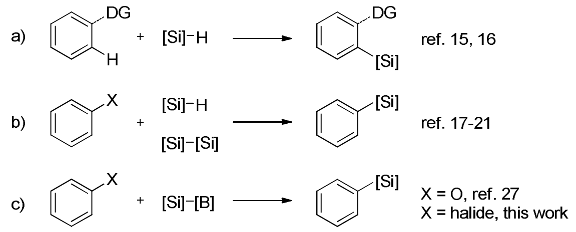
Herein we report Pd catalyzed Suzuki type cross coupling between aryl halides and silylboranes for the syntheses of aryl silanes. This reaction shows a general substrate scope, excellent compatibility with electrophilic functionalities and good yields.

Aryl silanes have drawn considerable attention in medicinal[1-4] and material chemistry.[5] On one hand, they are useful synthetic building blocks. On the other hand, the incorporation of silicon atoms could favourably alter the physiochemical properties of the parental carbon-based compounds. Over decades, many protocols have been developed for the syntheses of aryl silanes (Scheme 1). The classic method often entails reactions of silicon electrophiles with aryl Grignard or aryllithium reagents.[6, 7] This strategy has inherent limitations due to its low compatibility with other electrophilic functional groups. Transition metal catalyzed C-Si bond formation reactions thus represent a useful alternative. In this direction, the catalytic dehydrogenative coupling[8-14] between hydrosilanes Si-H and aryl C-H bonds is promised with the highest atomic efficiency (Scheme 1a). However, low regioselectivity was expected. The regioselectivity problem could be addressed by using a directing group, such that the C-H silylation occurs only at the *ortho* position (Scheme 1b).[15, 16] Employing aryl halides and their equivalents to access aryl silanes has also met with some success (Scheme 1b). To this end, hydrosilanes,[17-20] disilanes [21] could serve as the silicon source under the catalysis of Pd, [17, 18, 20, 21] Rh [19] and Ru.[19] Overall, these existing methods have encountered drawbacks including limited substrate scope and usage of large excess of silanes.



Scheme 1 Synthetic methods of the syntheses of aryl silanes.

Given our interest in organosilicon compounds,[22-24] we became curious if a Suzuki type cross coupling between aryl halide and silylboranes (e.g., Suginome's reagents) would be a viable route towards the syntheses of aryl silanes, given the stability and increasing availability of silylboranes.[25,26] Surprisingly, such a close mimic of the well-studied Suzuki coupling has not been reported to date. The only loosely related example along this line is the remarkable Ni/Cu-catalyzed silylation of inactivated C-O bonds in phenols and benzyl alcohols, reported recently by Martin and co-workers (Scheme 1c).[27] We anticipated that the oxidative insertion of a proper metal (e.g., Pd) into the aryl halide bond could subsequently undergo the signature transmetallation with Si-B, which upon reductive elimination would arrive at the aryl silane product, a pathway closely resembling the Suzuki coupling.

We commenced our study by investigating a set of established Suzuki coupling conditions. Our findings are summarized in Table 1. It is clearly seen that both Pd(II) and Pd(0) can be productive catalysts. Ligand plays a pivotal role in the reaction. For example, among various phosphine ligands, Ruphos gave the best yield in conjunction with $Pd_2(dba)_3$ (Table 1, entries 3-7). The choice of bases appeared to be important: the reaction did not proceed in absence of a base (Table 1, entry 8). Weak bases such as K_2CO_3 and Cs_2CO_3 promoted the reaction (Table 1, entries 7-10), whereas strong bases NaOEt and NaO*t*Bu were detrimental (Table 1, entries 11-12). In the latter case, no desired C-Si formation product was isolated. This observation is in line with the report of Ito and co-workers.[28] They discovered that Si-B underwent formal nucleophilic borylation with aryl halides in the presence of

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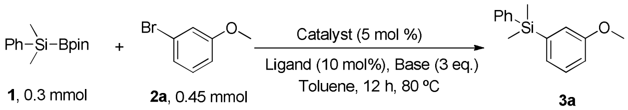
†Electronic Supplementary Information (ESI) available: Synthetic procedures, experimental details, recycling experiments and detailed characterization of products [details of any supplementary information available should be included here]. See DOI: 10.1039/x0xx00000x

KOMe. Their mechanistic study suggested that methoxy anion activates Si-B in a heterolytic fashion to give silyl anion, eventually giving rise to aryl boronates and halosilanes.[29] This pathway might explain why the required transmetallation did not occur, thus no aryl silane could be formed.

The optimal catalyst was identified to be $Pd(PPh_3)_4$, furnishing the desired aryl silane in 82% isolated yield in the presence of K_2CO_3 (Table 1, entry 13). Under this system, the model reaction can proceed well even in gram scale. The reaction was observed to be insensitive to water, as addition of water (5% v/v) to the reaction mixture did not negatively affect the reaction rate and yield. This is a notable advantage over the reactions with hydrosilanes: under Pd catalysis silanes reacted very rapid with water to give silanols, therefore stringent reaction conditions were required. Such an attractive feature of this method opens the possibility of installing silicon moiety onto macromolecules via aqueous Suzuki type coupling.

Table 1 Optimization of the reaction conditions [a]

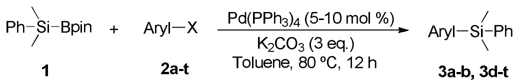


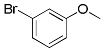
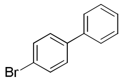
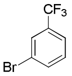
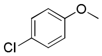
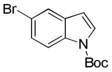
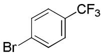
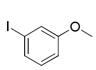
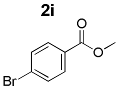
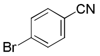
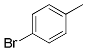
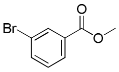
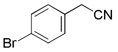
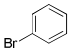
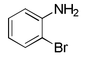
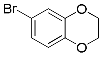
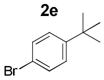
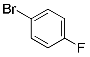
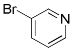
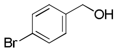
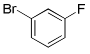
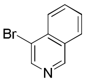
Entry	Catalyst	Ligand	Base	Yield of **3a** [%]
1	$Pd(OAc)_2$	RuPhos	K_2CO_3	trace
2	$Pd(dppf)Cl_2$	—	K_2CO_3	60
3	$Pd_2(dba)_3$	JohnPhos	K_2CO_3	0
4	$Pd_2(dba)_3$	PCy_3	K_2CO_3	0
5	$Pd_2(dba)_3$	XantPhos	K_2CO_3	44
6	$Pd_2(dba)_3$	PPh_3	K_2CO_3	59
7	$Pd_2(dba)_3$	RuPhos	K_2CO_3	80
8	$Pd_2(dba)_3$	RuPhos	—	0
9	$Pd_2(dba)_3$	RuPhos	$NaHCO_3$	70
10	$Pd_2(dba)_3$	RuPhos	Cs_2CO_3	69
11	$Pd_2(dba)_3$	RuPhos	NaO*t*Bu	0
12	$Pd_2(dba)_3$	RuPhos	NaOEt	0
13	$Pd(PPh_3)_4$	—	K_2CO_3	82

[a] Reaction condition: **2a** (0.3 mmol), base (3 eq.), catalyst (5 mol %) and **1** (0.45 mmol) were added to 1.5 mL toluene in a sealed tube in a nitrogen glove box. Then the tube was taken out and the resultant mixture was stirred for 12 h at 80 °C. All yields are after silica chromatography.

We demonstrate the substrate scope with the optimized reaction conditions (Table 2). Aryl chloride (Table 2, **2b**), bromide (**2a**) and iodide (**2c**) are all suitable substrates, although aryl chloride showed lower reactivity and yields. Both electron donating (**2a**, **2b** and **2c**) and electron withdrawing (**2j**, **2k**, **2m**, **2n**, **2o** and **2p**) substitutions on the aryl ring are well tolerated. Importantly, electrophilic groups such as cyano (**2q**, **2r**), hydroxyl (**2g**) and ester groups (**2j**, **2k**) were not affected, which showcases the advantage of this method over the classic carboanion chemistry. Nitrogen containing aryl halides such as pyridine (**2t**), aniline (**2l**) and isoquinoline (**2u**) were also converted to the corresponding aryl silanes in good yields. The substrate scope shown in Table 2 suggested that this reaction should be easily extended to more elaborated aryl halides. Unfortunately, the reaction between $Et_3SiBPin$ and aryl halides turned out to be unsuccessful, possibly due to the difficulty associated with the transmetallation, a phenomenon that has also been documented in the Suzuki coupling of secondary and tertiary alkylboronates.[30, 31]

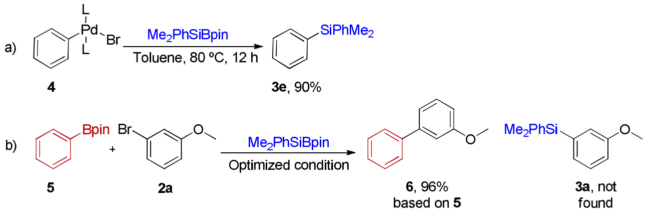
Table 2 Substrate scope study [a]



Substrate	Yield	Substrate	Yield	Substrate	Yield
 **2a**	**3a**, 82 %	 **2h**	**3h**, 56 %	 **2o**	**3o**, 78 %
 **2b**	**3b**, 68 %	 **2i**	**3i**, 87 %	 **2p**	**3p**, 50 %
 **2c**	**3a**, 50 %	 **2j**	**3j**, 56 %	 **2q**	**3q**, 90 %
 **2d**	**3d**, 73 %	 **2k**	**3k**, 76 %	 **2r**	**3r**, 77 %
 **2e**	**3e**, 88 %	 **2l**	**3l**, 77 %	 **2s**	**3s**, 49 %
 **2f**	**3f**, 74 %	 **2m**	**3m**, 86 %	 **2t**	**3t**, 80 %
 **2g**	**3g**, 93 %	 **2n**	**3n**, 73 %	 **2u**	**3u**, 57 %

[a] Reaction conditions: Aryl halides **2a-t** (0.3 mmol), K_2CO_3 (3 eq.), $Pd(PPh_3)_4$ (5-10 mol %. For **2b**, **2h**, **2o**, **2p**, 10 mol % Pd catalyst was used. For other substrates, 5 mol % Pd catalyst was used.) and **1** (0.45 mmol) were added to 1.5 mL toluene in a sealed tube in a nitrogen glove box. Then the tube was taken out and the resultant mixture was stirred for 12 h at 80 °C. All yields are after silica chromatography.

Our preliminary mechanistic study (ESI†) showed that preformed Ph-Pd-Br species (Scheme 2a, **4**) underwent smooth cross coupling with $Me_2PhSiBPin$ to give the desired aryl silane (**3e**) in a high yield. This observation suggested that the C-Si bond formation likely follows a similar pathway as in the classic Suzuki coupling. In a competition reaction in which an equal molar of PhBPin (Scheme 2b, **5**) and $Me_2PhSiBPin$ were subjected to 2 equiv. of 3-bromo-anisole (**2a**), only the Suzuki coupling product **6** was observed, hinting that the transmetallation of Si-B is significantly slower than that of the C-B species (Scheme 2b). Given the known difficulty in Suzuki coupling of tertiary alkylboronates,[30,31] the successful transmetallation of $Me_2PhSiBPin$ is indeed remarkable. Detailed kinetic study is necessary to reveal the full mechanistic profile of this reaction and to extend the reaction to trialkylsilylboranes.



Scheme 2 Preliminary mechanistic study.

In conclusion, we show that the Pd-catalyzed cross coupling between aryl halides and Si-B reagents is a viable approach to synthesize aryl silanes. This reaction shows good functional group compatibility and relatively broad substrate scope. Together with the wide availability of the reagents (e.g., aryl halides, Si-B species and Pd catalyst), we expect this method to find applications in the catalytic syntheses of aryl silanes.

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