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Palladium-Catalyzed Intramolecular Coupling of 2-[(2-Pyrrolyl)silyl]aryl Triflates through 1,2-Silicon Migration

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Transition metal catalyzed direct arylation of arenes with aryl halides or their equivalents via C−H bond activation has emerged as a very useful tool for aryl−aryl bond formations.[1] In particular, intramolecular direct arylation using heteroatom-tethering and/or heterocycle-containing substrates **1** (X = halogen or equivalent; Z and/or E = heteroatom) constitutes a straightforward approach to complex heterocycle-fused polycyclic aromatic hydrocarbons **2**, which can serve as platforms of various biologically active molecules and functional organic materials (Scheme 1, path A).[2] The intramolecular coupling involves the activation of C−X and C−H bonds (indicated by waved line *a*), which results in the direct C−C connection. In contrast, to the best of our knowledge, intramolecular cyclization that involves direct arylation accompanied by reorganization of a C−Z bond leading to a cyclized product of type **3** (path B) has remained yet to be reported. We present herein the first example of a path B type transformation with silicon-tethered indoles and pyrroles **1** (Z = SiR$_2$, E = NR′, X = OTf). Thus, palladium-catalyzed intramolecular coupling of 2-[(2-pyrrolyl)-silyl]aryl triflates **4** is found to produce silicon-rearranged products **5** exclusively or preferentially over the conventional products (**6**) in good to high yields (Table 1).

Scheme 1. Intramolecular Coupling of Tethered Bi(aryl)s

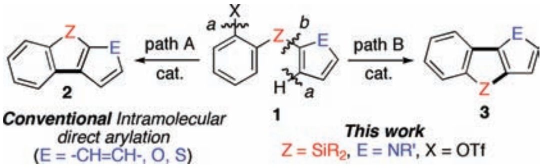
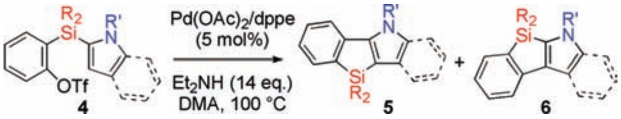
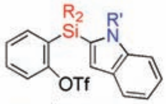
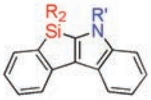
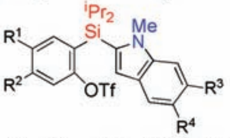
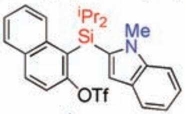
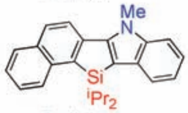
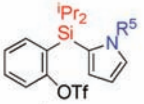
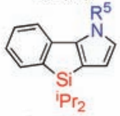
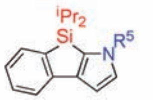


Table 1. Pd-Catalyzed Intramolecular Coupling of **4**[a]



entry	4	5 (yield)[b]	6 (yield)[b]
			
1[c]	**4a** (R = ^{i}Pr, R′ = Me)	**5a** (89)[d]	**6a** (3)
2	**4b** (R = Ph, R′ = Me)	**5b** (59)	**6b** (17)
3	**4c** (R = ^{i}Pr, R′ = *p*-MeC$_6$H$_4$)	**5c** (74)	**6c** (nd)[e]
4	**4d** (R = ^{i}Pr, R′ = *p*-MeOC$_6$H$_4$)	**5d** (73)	**6d** (nd)[e]
5	**4e** (R = ^{i}Pr, R′ = *p*-CF$_3$C$_6$H$_4$)	**5e** (80)[d]	**6e** (nd)[e]
6	**4f** (R = ^{i}Pr, R′ = Ts)	**5f** (83)[d]	**6f** (nd)
			
7	**4g** (R^1 = OMe, R^2, R^3, R^4 = H)	**5g** (77)	**6g** (nd)
8	**4h** (R^1 = CN, R^2, R^3, R^4 = H)	**5h** (75)[d]	**6h** (15)
9[c]	**4i** (R^1 = Cl, R^2, R^3, R^4 = H)	**5i** (81)	**6i** (nd)
10	**4j** (R^1, R^3, R^4 = H, R^2 = F)	**5j** (74)	**6j** (6)
11	**4k** (R^1, R^2, R^4 = H, R^3 = Cl)	**5k** (70)[d]	**6k** (10)
12	**4l** (R^1, R^2, R^4 = H, R^3 = SiMe$_3$)	**5l** (82)	**6l** (5)
13	**4m** (R^1, R^2, R^3 = H, R^4 = OMe)	**5m** (88)	**6m** (nd)
14[c]	**4n** (R^1, R^2, R^3 = H, R^4 = Cl)[d]	**5n** (63)[d]	**6n** (22)
15	**4o** (R^1, R^3 = Cl, R^2, R^4 = H)	**5o** (84)	**6o** (nd)
			
16	**4p**	**5p** (91)	**6p** (nd)
			
17	**4q** (R^5 = Me)	**5q** (78)	**6q** (nd)
18	**4r** (R^5 = Ph)	**5r** (73)	**6r** (23)
19	**4s** (R^5 = Ts)	**5s** (31)	**6s** (42)

[a] All reactions of **4** (0.3 mmol) were carried out using Pd(OAc)$_2$ (5 mol %), dppe (5 mol %), Et$_2$NH (14 equiv), DMA (1.5 mL), 100 °C, 12 h except for entries 1, 9, and 14. [b] Isolated yields. nd: not detected. [c] Reaction was conducted with 1 mmol of **4**. [d] Molecular structure was unambiguously determined by X-ray diffraction analysis of the single crystal. [e] The tiny spot of an unidentified product was observed by TLC analysis; however the byproduct could not be isolated due to the instability toward column chromatography.

We recently developed palladium-catalyzed intramolecular coupling of 2-(arylsilyl)aryl triflates (**1**, Z = SiR$_2$, X = OTf, E = −CH═CH−, S, or O),[3] a reaction that proceeded via path A. This reaction was shown to be a versatile method for silicon-bridged biaryls **2**, which have attracted growing attention in the fields of functional organic materials such as light-emitting diodes, field-effect transistors, and solar cells.[4] When the cyclization was applied to 2-(*3-indolyl*)silylphenyl triflate, 3,2′-silicon-bridged 2-phenylindole **5a** that exhibited blue fluorescence in the solid state in extremely high quantum yield was produced as the sole product.[3] To extend the substrate scope of the intramolecular coupling, we prepared 2-[diisopropyl(*2-indolyl*)silyl]phenyl triflate (**4a**), which was subjected to the original conditions (Pd(OAc)$_2$/2PCy$_3$ 5 mol %, Et$_2$NH (2 equiv), dimethylacetamide (DMA), 100 °C). To our surprise, **5a** was isolated as a major product (62% yield) along with the expected product **6a** (8%). Thus, path B type transformation was found to take place as a major reaction with **4a**. Then, we screened the conditions for the novel intramolecular coupling using **4a** and found that the use of 1,2-bis(diphenylphosphino)ethane (dppe) and Et$_2$NH in large excess in the presence of Pd(OAc)$_2$ as a catalyst was effective in suppressing the formation of **6a** so that **5a** was isolated in 89% yield with 3% yield of **6a** (Table 1, entry

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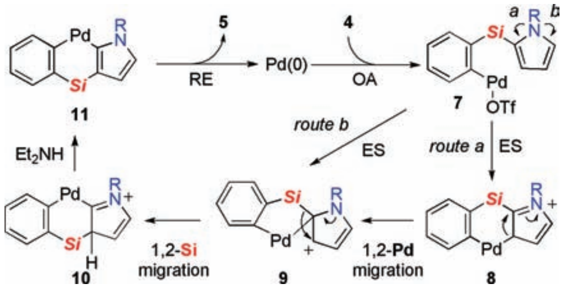
1).[5] With the optimized conditions in hand, we next examined the substrate scope as summarized in Table 1. Whereas 2-(diphenylsilyl)indole **4b** produced **5b** in a moderate yield along with **6b** in a fair amount, *N*-arylated and -tosylated indoles **4c**−**4f** gave **5c**−**5f** in good yields, respectively (entries 2−6). The presence of functional groups such as MeO, CN, Cl, F, and SiMe$_3$ on TfO-substituted and/or pyrrole-fused benzene rings generally did not affect the preference of path B type transformation over the conventional route, path A, and functionalized Si-bridged 2-phenylindoles **5g**−**5o** were isolated in good to high yields (entries 7−15). Byproduct **6** formed to some extent in the case of **4** bearing such an electron-withdrawing group (EWG) as CN, Cl, or F. It is noteworthy that chlorine tolerated the conditions to give chlorinated products in high yields; further extension of the π-conjugated system is possible by use of the chlorine functionality (*vide infra*). Naphtylsilyl derivative **4p** was also applicable to the present cyclization, giving rise to pentacyclic product **5p** in 91% yield as the sole product (entry 16). Intramolecular cyclization of 2-silylpyrroles **4q** and **4r** proceeded similarly through path B as the main course to give **5q** and **5r** in 78 and 73% yields, respectively (entries 17 and 18), whereas *N*-tosylated pyrrole **4s** afforded **6s** as a major product (entry 19). The fact that the corresponding 2-silylfuran and -(benzo)thiophenes (**1**, Z = SiR$_2$, E = O and S) did not undergo silicon migration[3] suggests that the electron-donating ability of nitrogen in the indole/pyrrole moiety should be one of the key factors for the realization of the novel intramolecular coupling.

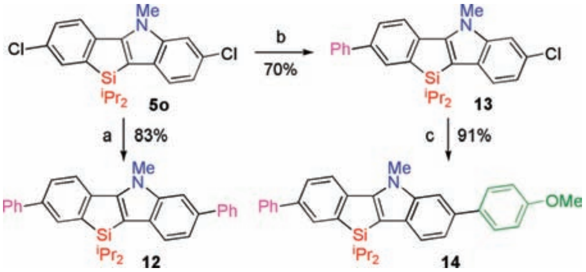
We propose a plausible catalytic cycle shown in Scheme 2. Arylpalladium **7** generated by the oxidative addition (OA) of **4** to a Pd(0) complex would undergo intramolecular electrophilic substitution (ES) at the 3-position of the pyrrole/indole to give **8** (*route a*), followed by migration of the Pd atom to the 2-position, giving rise to cationic intermediate **9**. The silicon β-cation stabilizing effect may assist the migration to overcome the steric hindrance caused by the spirocyclic structure in **9**. Alternatively, direct palladation at the 2-position in **7** leading to **9** may be operative (*route b*).[6] Subsequent 1,2-Si migration followed by deprotonation by a base and then reductive elimination (RE) furnishes the catalytic cycle to produce **5**. The *route a* mechanism looks likely according to the report of Sames and his co-workers who reported a Pd-catalyzed *intermolecular* direct C2-arylation of indole with iodobenzene and proposed a mechanism involving an electrophilic palladation of indole at the 3-position first, followed by 1,2-migration to give a C2-palladated indole.[7] Byproduct **6** may be produced from **8** via deprotonation followed by RE or RE followed by deprotonation.[5] The dependency of the product ratio **5**/**6** on substrates **4** may be explained by assuming that the presence of EWG destabilizes **9** and thus retards the Pd migration.

Finally, demonstrated in Scheme 3 are examples of synthetic transformations of dichlorinated **5o** using Pd-catalyzed cross-coupling reactions. Thus, the 2-fold cross-coupling with PhB(OH)$_2$ under the slightly modified Buchwald's conditions for aryl chlorides gave **12** in high yield.[8] Meanwhile, the same reaction with **5o** in slight excess achieved monocoupling selectively at chlorine *meta* to the silylene bridge to give **13** only, which further coupled with *p*-MeOC$_6$H$_4$B(OH)$_2$ to give **14** in an excellent yield. Thus, introduction of any two different aryl groups into **5o** is possible, allowing beneficial modification of 3,2′-Si-bridged 2-phenylindoles.

Scheme 2. Plausible Mechanism



Scheme 3. Transformation of **5o**[a]



[a] Conditions: (a) **5o** (1.0 equiv), PhB(OH)$_2$ (3.5 equiv), Pd(OAc)$_2$ (15 mol %), SPhos (30 mol %), K$_3$PO$_4$ (5.0 equiv), THF, 50 °C. (b) **5o** (1.4 equiv), PhB(OH)$_2$ (1.0 equiv), Pd(OAc)$_2$ (5 mol %), SPhos (10 mol %), K$_3$PO$_4$ (3.0 equiv), THF, 50 °C. (c) **13** (1.0 equiv), 4-MeOC$_6$H$_4$B(OH)$_2$ (3.0 equiv), Pd(OAc)$_2$ (10 mol %), SPhos (20 mol %), K$_3$PO$_4$ (3.0 equiv), THF, 50 °C.

In summary, we have demonstrated that 2-(2-pyrrolylsilyl)aryl triflates in the presence of a Pd catalyst undergo a new type of intramolecular coupling that involves direct arylation accompanied by reorganization of the C−Si bond. As observed previously with **5a**,[3] all the Si-bridged 2-phenylindoles presented here exhibit strong and highly efficient blue fluorescence in the solid state.[9]

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Supporting Information Available: Experimental procedures and spectral data for new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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(5) For details, see Supporting Information.

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(9) The photophysical properties including solid-state fluorescence will be reported in due course.

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