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$Ru_3(CO)_{12}$-Catalyzed Silylation of Benzylic C−H Bonds in Arylpyridines and Arylpyrazoles with Hydrosilanes via C−H Bond Cleavage

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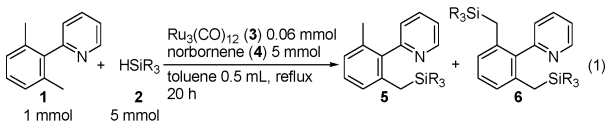
The catalytic functionalization of C−H bonds is a highly valuable methodology in organic synthesis because no functional groups are sacrificed using this protocol.[1] To date, several catalytic reactions, such as C−H/olefin,[2,3] C−H/acetylene,[4] C−H/CO/olefin,[5] C−H/$ArB(OR)_2$,[6] C−H/Ar_4Sn,[7] C−H/$HSiR_3$,[8−12] and C−H/$HB(OR)_2$[13] couplings, have been developed. In almost all cases, sp^2 C−H bonds, i.e., aromatic and olefinic C−H bonds, are involved. Recently, several notable results with respect to catalytic, selective functionalization of sp^3 C−H bonds, e.g., the alkylation[2b,14] and carbonylation[5c] of an sp^3 C−H bond adjacent to a heteroatom, the borylation of an sp^3 C−H bond in alkanes with hydroboranes,[13a] the dehydrogenation of alkanes to give alkenes,[15] the intramolecular arylation of an sp^3 C−H bond,[16] and the introduction of a heteroatom at an sp^3 C−H bond,[17] have been reported. In this paper, we describe a new type of catalytic functionalization of sp^3 C−H bonds at a benzylic position with hydrosilanes, to give benzylsilane derivatives by means of a chelation-assisted C−H bond cleavage.

To date, there are precedent studies with respect to the catalytic silylation of sp^3 C−H bonds: (1) the rhodium-catalyzed silylation of alkanes and alkylbenzenes under photoirradiation condtions;[12] (2) the ruthenium-catalyzed silylation of alkylbenzenes with hydrosilanes;[10] and (3) the nickel- or platinum-catalyzed silylation of alkylbenzenes with strained disilanes.[18] However, their efficiency and selectivity are low, and the scope of these reactions is narrow.

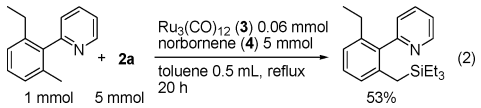
We found that chelation-assisted C−H bond cleavage is effective for a selective functionalization involving the silylation of aromatic C−H bonds.[1,2,11] We applied this protocol to the silylation of benzylic C−H bonds. When the reaction of 2-(2,6-dimethylphenyl)-pyridine (**1**) with triethylsilane (**2a**) was carried out using $Ru_3(CO)_{12}$ (**3**) catalyst in the presence of norbornene (**4**) as a hydrogen acceptor, mono- (**5a**) and disilylation (**6a**) products were obtained in 30% and 55% yields, respectively (run 1 in eq 1).[19] In these products, C−Si bond formation occurred predominantly at the benzylic positions, i.e., the methyl group.



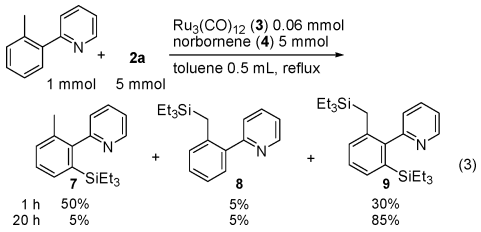
run 1	R_3 = Et_3 (**2a**)	**5a** 30%	**6a** 55%
run 2	R_3 = Me_2Ph (**2b**)	**5b** 55%	**6b** 23%
run 3	R_3 = $Me_2{}^tBu$ (**2c**)	**5c** 44%	**6c** trace
run 4	R_3 = Ph_3 (**2d**)	**5d** 59%	**6d** not detected

Some other hydrosilanes also showed evidence of reactivity, e.g., $HSiMe_2Ph$ (**2b**) (run 2), $HSiMe_2{}^tBu$ (**2c**) (run 3), and $HSiPh_3$ (**2d**) (run 4). The coupling reaction using sterically hindered hydrosilanes (**2c** and **2d**) selectively gave the 1:1 coupling product **5** (**5c** and **5d**, respectively). However, HSi^iPr_3 and $HSi(OEt)_3$ were not active for this reaction. The most reactive $HSiEt_3$ (**2a**) was chosen for the reactions described here. Styrene, *tert*-butylethylene, and cyclooctene were used as hydrogen acceptors, but a small amount (less than 6% yield) of coupling product was obtained. Norbornene was also employed as a hydrogen acceptor of this reaction. The catalytic activity of several ruthenium, rhodium, and iridium complexes were examined. Among the complexes screened, such as $Ru_3(CO)_{12}$ (**3**), $RuH_2(CO)(PPh_3)_3$, Ru(cod)(cot), $[RuCl_2(p\text{-cymene})]_2$, $RuCl_3{\cdot}3H_2O$, $(\eta^5\text{-}C_5Me_5)RhH_2(SiEt_3)_2$, $[Rh(OH)(cod)]_2$, $Rh_4(CO)_{12}$, and $[Ir(OMe)(cod)]_2$, **3** showed the highest activity.

In the case of 2-(2-ethyl-6-methylphenyl)pyridine, two different benzylic C−H bonds are present (CH_3 and CH_2) (eq 2). The silylation proceeded exclusively at the methyl group. This result suggests that steric congestion at the benzylic position severely affects the reactivity of benzylic C−H bonds.



In the case of 2-(2-tolyl)pyridine, an aryl C−H bond and a benzylic C−H bond are available as a reaction site. After heating for 1 h, arylsilane **7**, benzylsilane **8**, and the disilylation product **9** were obtained in 50%, 5%, and 30% yields, respectively. The yield of **9** was increased to 85% after 20 h. These results suggest that the silylation of the aryl C−H bond is more facile than that of the benzylic C−H bond, even though the bond dissociation energy of benzylic C−H bonds (ca. 90 kcal/mol) is lower than that of phenyl C−H bonds (ca. 110 kcal/mol).[20]



A variety of directing groups were screened. Among these, it is found that pyridyl and pyrazolyl groups, and the imino group in hydrazones, function as directing groups. The results of silylation reactions using several aromatic compounds are listed in Table 1. The reaction of 2-(2,6-dimethylphenyl)-4-methoxypyridine afforded the corresponding 1:1 and 1:2 coupling products in 5% and 85% yields, respectively (run 1). The electron-donating group on the pyridine ring improved the reactivity of the arylpyridines. Thus, the electron density on the nitrogen atom of the pyridine ring affects the reactivity. Steric factors are also important in this coupling reaction. In the case of the reaction of 2-(2,6-dimethylphenyl)-6-methylpyridine, the yield was seriously decreased to 4% (run 2).

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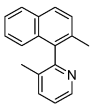
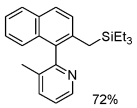
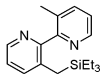
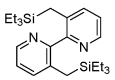
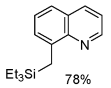
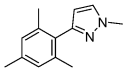
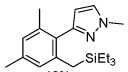
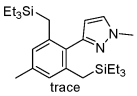
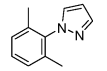
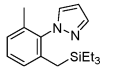
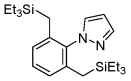
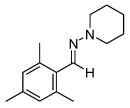
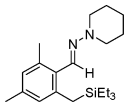
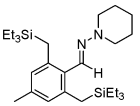
Table 1. Ruthenium-Catalyzed Silylation of Benzylic C−H Bonds with **2a**[a]

run	aromatic compound	products and yields[b]	
1	R = 4-OMe	5%	85%
2	R = 6-Me	4%	0%
3	R = 3-Me	44%	42%
4		 72%	
5		 trace	 58%
6		 78%	
7		 40%	 trace
8		 41%	 41%
9		 40%	 15%

[a] Reaction conditions: aromatic compounds (1 mmol), triethylsilane **2a** (5 mmol), $Ru_3(CO)_{12}$ (**3**) (0.06 mmol), norbornene **4** (5 mmol), toluene (0.5 mL), reflux, 20 h. [b] Isolated yield.

The origin of this decrease was severe steric congestion around the pyridine nitrogen that decreased the coordinating ability of the nitrogen. In the cases of 2-(2,6-dimethylphenyl)-3-methylpyridine (run 3) and 3-methyl-2-(2-methylnaphthalen-1-yl)pyridine (run 4), the aryl groups cannot achieve a coplanar geometry due to steric repulsion around a biaryl axis. In these cases, silylation also took place smoothly to give the corresponding products in high yields. These results indicate that the coordination of the nitrogen is important for attaining high efficiency, but a coplanar geometry in the C−H bond cleavage step is not required for this silylation reaction to proceed. In the case of 3,3′-dimethyl-[2,2′]bipyridyl, silylation occurred at both methyl groups (run 5). When 8-methylquinoline was used, silylation proceeded exclusively at the methyl group (run 6). An sp^2 nitrogen in a pyrazole ring can also be used as a directing group. The corresponding monosilylation product was selectively obtained in 40% yield (run 7). The silylation took place only at the ortho CH_3 group, and not at the para CH_3 group. This result indicates that the coordination of the nitrogen is key to this silylation reaction. In the case of the reaction of 1-(2,6-dimethylphenyl)-1*H*-pyrazole, a mixture of mono- (41% yield) and disilylation (41% yield) products was obtained (run 8). The silylation of arylhydrazones gave benzylsilanes in moderate yields (run 9). Some other aromatic compounds having a nitrogen directing group, such as aromatic imines, benzylamines, oxime ethers, *N*,*N*-dimethylanilines, and arylpyridyl ethers, were used for this reaction. Unfortunately, however, these substrates did not show activity under these reaction conditions.

In conclusion, we demonstrated a new type of catalytic functionalization of benzylic C−H bonds. This method provides a convenient route for preparing benzylsilane derivatives using hydrosilanes via the cleavage of a benzylic C−H bond. Explorations of new catalytic reactions involving C−H bond cleavage, especially that of an sp^3 C−H bond, open an exiting new research area in organic chemistry. We are currently broadening the scope of this silylation reaction and attempting to elucidate the reaction mechanism.

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Supporting Information Available: Experimental procedures and spectral analyses of all reaction products. This material is available free of charge via the Internet at http://pubs.acs.org.

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