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Direct Observation of the Oxidative Addition of the Aryl Carbon−Oxygen Bond to a Ruthenium Complex and Consideration of the Relative Reactivity between Aryl Carbon−Oxygen and Aryl Carbon−Hydrogen Bonds

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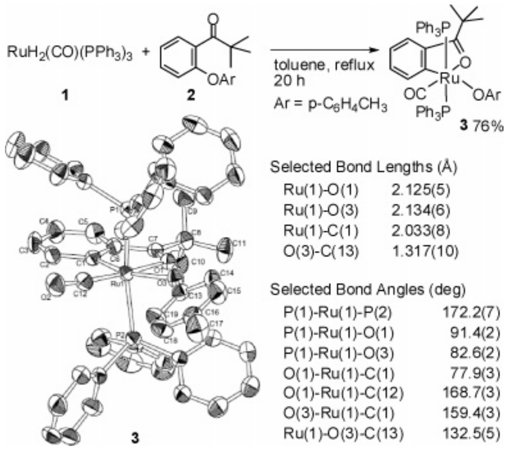
The transition-metal-catalyzed functionalization of unreactive aryl carbon−oxygen bonds in aryl ethers as well as that of unreactive carbon−hydrogen bonds is a potentially useful synthetic tool. Two types of catalytic reactions have been reported to date; one is the nickel-catalyzed coupling reaction of anisoles with Grignard reagents,[2] and the other is the ruthenium-catalyzed coupling of *ortho*-alkoxy aromatic ketones with organoboronates.[3] In the above studies, the catalytic reactions were proposed to take place through an oxidative addition of these bonds to the low-valent transition metals, but no direct observation regarding the oxidative addition step has been reported and mechanistic information concerning this step is limited.[4]

In 1997, Milstein et al. reported the stoichiometric reaction of pincer-type aromatic ethers with a rhodium complex.[4] They proposed that aryl C−O bond cleavage by the rhodium complex took place to give an Ar−Rh−OCH_3 intermediate, and the β-hydride elimination from this intermediate subsequently resulted in the reduction of the C−O bond to a C−H bond. In their studies, they did not directly observe an oxidative addition of the C−O bond to the rhodium complex. Herein, we describe the first example of the direct observation of the oxidative addition of an aryl C−O bond to a transition metal complex and the relative reactivity between aryl C−O and C−H bonds toward a low-valent ruthenium complex.

When $RuH_2(CO)(PPh_3)_3$ (**1**) was reacted with 2,2-dimethyl-1-(2-*p*-tolylphenyl)propan-1-one (**2**) in refluxing toluene for 20 h, the ruthenium−aryloxy complex **3** was obtained in 76% yield as a deep-red solid (Scheme 1). Recrystallization of **3** from toluene/hexane afforded a microcrystal suitable for X-ray analysis. To the best of our knowledge, this is the first example of the direct observation of the oxidative addition of an unreactive aryl C−O bond in an aromatic ether to a transition metal complex.[5] The analysis revealed that the aryloxy ligand was located trans to the aryl carbon (C1) of the pivalophenone moiety, the CO ligand was coordinated at the position cis to the aryl carbon, and the ketone carbonyl group was coordinated to the ruthenium center to produce a five-membered ruthenacycle (Scheme 1). The origin of this regioselectivity was the weaker trans influence of the aryloxy ligand compared to the CO ligand.[6] The bond length of Ru(1)−O(3) (2.134(6) Å) and the bond angle of Ru(1)−O(3)−C(13) (132.5(5)°) are consistent with ruthenium−aryloxy complexes that were previously synthesized by a ligand exchange reaction.[7] In the ^{31}P NMR spectrum, one phosphine signal was observed at 31.16 ppm, and the two aromatic hydrogens of the pivalophenone moiety were shifted to higher field at 6.30 and 6.48 ppm as triplets ($J_{HH} = 7.0$ Hz) in the ^1H NMR spectrum. C−O stretching bands of the CO and the ketone carbonyl in the IR spectrum were observed at 1903 and 1498 cm^{-1}, respectively. This low wave number shift of the ketone carbonyl vibrational peak suggests the coordination of the carbonyl oxygen to the ruthenium.[8] These spectral data are consistent with the X-ray analysis.

Scheme 1. Preparation of Aryloxy−Ruthenium Complex and Its ORTEP Illustration

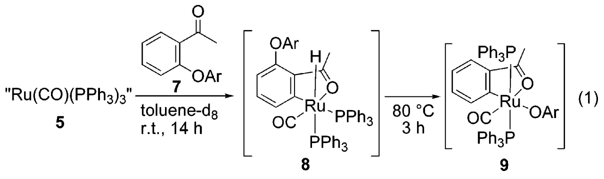


Selected Bond Lengths (Å)	
Ru(1)-O(1)	2.125(5)
Ru(1)-O(3)	2.134(6)
Ru(1)-C(1)	2.033(8)
O(3)-C(13)	1.317(10)

Selected Bond Angles (deg)	
P(1)-Ru(1)-P(2)	172.2(7)
P(1)-Ru(1)-O(1)	91.4(2)
P(1)-Ru(1)-O(3)	82.6(2)
O(1)-Ru(1)-C(1)	77.9(3)
O(1)-Ru(1)-C(12)	168.7(3)
O(3)-Ru(1)-C(1)	159.4(3)
Ru(1)-O(3)-C(13)	132.5(5)

To confirm the catalytic activity of **3** in the coupling of aryl ethers with an organoboronate, the reaction of **2** with phenylboronate **4**, Ph−$B(OCH_2C(CH_3)_2CH_2O)$, was carried out in refluxing toluene in the presence of 4 mol % of **3**. The corresponding ortho phenylation product was obtained in 74% yield. This catalytic activity is similar to that of **1**, and **3** seems to be an intermediate of this reaction.[3]

Clarification of the relative reactivity of C−H and C−O bonds toward the ruthenium complex appears to be important in terms of designing new catalytic reactions involving the cleavage of such bonds. The reaction of $Ru(CO)(PPh_3)_3$ (**5**), generated by reacting **1** with trimethylvinylsilane **6** (1.2 equiv) at 90 °C for 1.5 h,[9] with 1-(2-*p*-tolyloxyphenyl)ethanone (**7**) (eq 1) was examined at room temperature.[12]



The ^1H and ^{31}P NMR spectra indicated that C−H bond cleavage took place to give the hydride complex **8** as the major product. One hydride signal was observed at −5.97 ppm as a doublet of doublets with a spin−spin coupling from the triphenylphosphine ligands ($J_{PH} = 91.5$ and 23.8 Hz), and in the ^{31}P NMR spectrum, two phosphine signals were observed at 35.49 and 39.85 ppm.[13] It

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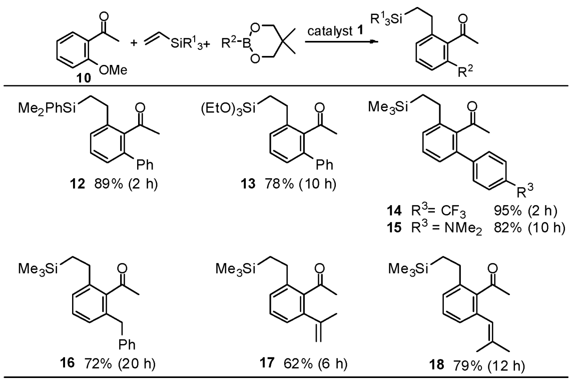
Table 1. Reaction of *o*-Methoxyacetophenone (**10**) with Vinylsilanes and Organoboronates[a]

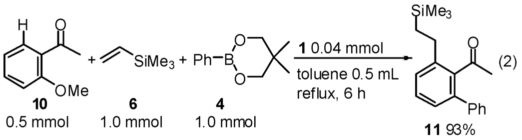


[a] Reaction conditions: **10** (0.5 mmol), vinylsilane (1 mmol), organoboronate (1 mmol), **1** (0.04 mmol), toluene (0.5 mL), reflux.

is noteworthy that, although the bond dissociation energy of a C−H bond in benzene (BDE (C_6H_5-H) = 113 kcal/mol) is larger than that of the aryl C−O bond in anisole (BDE ($C_6H_5-OCH_3$) = 101 kcal/mol,[14] C−H bond cleavage took place preferentially.

Interestingly, complex **8** remained unchanged, even after reaction at room temperature for 2 days. When the reaction mixture was heated at 80 °C for 3 h, **8** completely disappeared and a new deep-red species **9** appeared at 33.16 ppm in the ^{31}P NMR spectrum which was almost the same as that of **3**. These results indicate that the hydride complex **8** is the kinetic product and the aryloxy complex **9** is the thermodynamic one.

On the basis of this difference in reactivity between C−H and C−O bonds, we attempted to develop highly chemoselective selective sequential C−C bond formations using vinylsilanes and organoboronates. Thus, alkylation should take place preferentially at the C−H bond, and coupling with the organoboronate should proceed at the C−O bond. When the reaction of 2′-methoxyacetophenone (**10**) with **6** and phenylboronate **4** was carried out in refluxing toluene, alkylation at the C−H bond and a phenylation at the C−O bond proceeded selectively to give **11** in 93% yield (eq 2). Neither dialkylated nor diphenylated acetophenones were produced. These observations indicate the following important features of this coupling reaction: (1) the C−H/olefin coupling reaction proceeds faster than the C−H/R−B(OR′)$_2$ coupling because phenylation of the C−H bond can also take place under these reaction conditions;[15] (2) once the carbon−oxygen bond is cleaved, transmetalation between the Ru−OMe intermediate and the phenylboronate occurred rapidly as evidenced by the fact that no product formed via β-hydride elimination from the Ru−OCH_3 intermediate was observed.[10]



The scope and limitations of this sequential coupling reaction were also examined in further experiments, and some selected results are shown in Table 1.

Dimethylphenyl- and triethoxylvinylsilanes can be utilized in this reaction. The corresponding coupling products **12** and **13** were obtained in 89 and 78% yields, respectively. Several organoboronates involving aryl-, alkyl-, and alkenylboronates can also be used. In the cases of 4-trifluoromethyl- and 4-*N*,*N*-dimethylaminophenylboronates, **14** and **15** were formed in 95 and 82% yields, respectively. A sequential double alkylation using **6** and benzylboronate afforded **16** in 72% yield. The use of alkenylboronates provided alkyl−alkenyl coupling products, such as **17** and **18**, in high yields. For the present coupling reaction, vinylsilanes were highly reactive, but allyl(trimethyl)silane and phenyltrimethylsilyl acetylene were less reactive under these reaction conditions.

We described herein the first direct observation of the oxidative addition of an aryl carbon−oxygen bond in an aromatic ether to a transition metal complex. The structure of **3** was determined from ^1H and ^{31}P NMR and X-ray data. C−H bond cleavage with the ruthenium complex is the kinetically favored process, but aryl C−O bond cleavage is the thermodynamically favorable one. Chemoselective C−C bond formation using vinylsilanes and organoboronates can be achieved on the basis of the difference in the reactivity of C−H and C−O bonds toward the ruthenium complex. Further studies of the reactivity of these carbon bonds and the scope of the reaction will be the subject of future work.

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Supporting Information Available: X-ray crystallographic files in CIF format for **3** and text providing experimental procedures and spectroscopic data for all new compounds. This material is available free of charge via the Internet at http://pubs.acs.org.

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