

Notes

Rhenium(I)-Catalyzed Formation of a Carbon–Oxygen Bond: An Efficient Transition Metal Catalytic System for Etherification of Benzyl Alcohols

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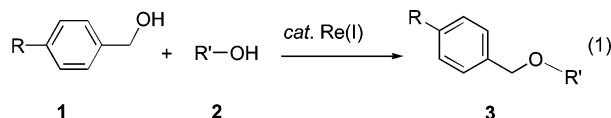
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Summary: Highly efficient rhenium(I)-catalyzed C–O bond formation from the dehydration of primary benzyl and aliphatic alcohols is reported. The reaction affords unsymmetrical benzyl ethers in good yield with high selectivity.

Transition metal complexes-mediated cleavage and formation of carbon–oxygen bonds is one of the most important and interesting subjects in organometallic and organic synthetic chemistry.¹ Ethers are an important class of organic compounds. The formation of the C–O bond in ethers can be usually realized by the dehydration of alcohols using sulfuric acid as catalyst, but this process is not suitable for the synthesis of unsymmetrical ethers due partly to low selectivity. The normal method for the preparation of unsymmetrical ethers involves the reaction of halide with alkoxide² or halide with alcohol directly using basic inorganic reagents such as KOH, NaH, etc.³ The development of a new catalytic method for the synthesis of unsymmetrical ethers from halide-free starting materials is still a challenge in organic synthetic chemistry.⁴

High-valent rhenium-oxo complexes have been found to be efficient catalysts in catalytic organic synthesis.⁵

Very recently, Toste and co-workers reported that rhenium(V)-oxo complexes catalyze C–O bond formation in propargylic etherification.^{5g} The CH₃ReO₃ complex has been used as a catalyst in the dehydration of alcohols to afford ethers, but this catalyst system shows high activity only with secondary aromatic alcohols.⁶ In this paper, we first report an efficient rhenium(I)-catalyzed dehydration of primary aromatic alcohols with primary aliphatic alcohols (C₁–C₁₆) to provide the corresponding unsymmetrical benzyl ethers in excellent yields with high selectivities (eq 1).



The reaction was carried out in an autoclave by stirring a mixture of the benzyl alcohol, an excess amount of aliphatic alcohol, and a catalytic amount of rhenium(I) complex. When a mixture of benzyl alcohol **1a** (1.0 mmol), 1-butanol **2a** (5.0 mmol), and catalyst ReBr(CO)₅ (0.03 mmol) was heated at 120 °C for 12 h, the reaction afforded benzyl butyl ether **3a** in only 10% GC yield.⁷ Neither dibenzyl ether nor dibutyl ether could be detected in the reaction mixture, confirmed by GC and GC-MS. With the increase of reaction temperature, the yield of **3a** could be increased to 78% and 90% GC yields at 140 and 160 °C, respectively. At 160 °C, dibenzyl ether and dibutyl ether were also formed in 3% and 9% GC yield. To obtain the high yield of **3a**, an excess amount (5 equiv) of **2a** was required. The reactions of **1a** with 1 or 3 equiv of **2a** gave **3a** in 30% and 73% GC yields, respectively.

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(2) Recent reports, see: (a) Ochiai, M.; Ito, T.; Takahashi, H.; Nakanishi, A.; Toyonari, M.; Sueda, T.; Goto, S.; Shiro, M. *J. Am. Chem. Soc.* **1996**, *118*, 7716. (b) Gray, W. K.; Smal, F. R.; Hitzler, M. G.; Rose, S. K.; Poliakoff, M. *J. Am. Chem. Soc.* **1999**, *121*, 10711.

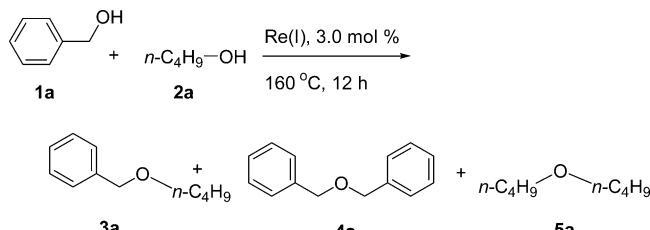
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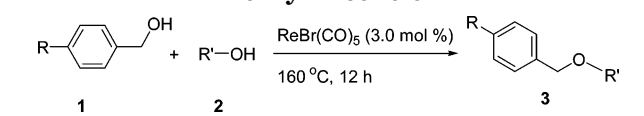
(6) Zhu, Z.; Espenson, J. H. *J. Org. Chem.* **1996**, *61*, 324.

(7) All ethers obtained in this paper are known compounds. Their structures were confirmed by ¹H and ¹³C NMR and GC-MS spectroscopies by comparison with the authentic samples.

Table 1. Catalytic Activity of Rhenium Complexes in the Reaction of Benzyl Alcohol **1a with *n*-Butanol **2a**^a**


entry	catalyst	3a yield (%) ^b	4a yield (%) ^b	5a yield (%) ^c
1	ReBr(CO) ₅	90	3	9
2	Re(CO) ₅ Cl	83	6	7
3	CpRe(CO) ₃	14	6	3
4	Re ₂ (CO) ₁₀	65	14	5

^a The reactions were carried out at 160 °C for 12 h by using 1.0 mmol of **1a**, 5.0 mmol of **2a**, and 0.03 mmol of catalyst. ^b GC yield based on the amount of **1a**. ^c GC yield based on the amount of **2a**.

Table 2. ReBr(CO)₅-Catalyzed Etherification of Benzyl Alcohols^a


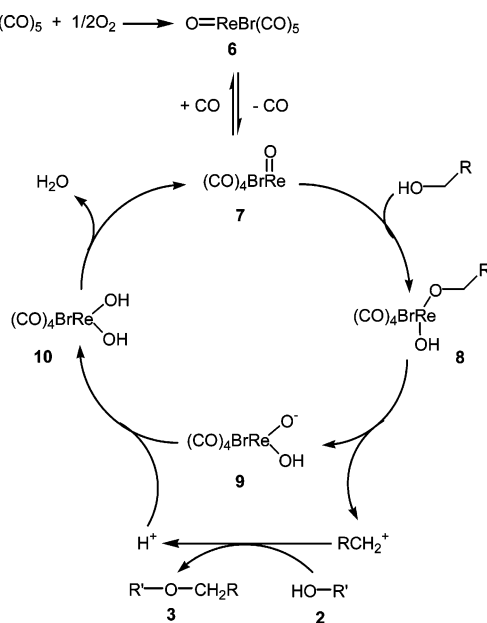
entry	R	R'	3 yield (%) ^b
1	H	1a <i>n</i> -C ₄ H ₉	2a 3a 90
2	H	1a CH ₃	2b 3b 99
3	H	1a <i>n</i> -C ₆ H ₁₃	2c 3c 74
4	H	1a <i>c</i> -C ₆ H ₁₁	2d 3d 73
5	H	1a <i>n</i> -C ₈ H ₁₇	2e 3e 72
6	H	1a <i>n</i> -C ₁₂ H ₂₅	2f 3f 73
7	H	1a <i>n</i> -C ₁₆ H ₃₃	2g 3g 60
8	CH ₃	1b <i>n</i> -C ₄ H ₉	2a 3h 87
9	Cl	1c <i>n</i> -C ₄ H ₉	2a 3i 77
10	H	1a PhCH ₂	1a 3j 78

^a The reactions were carried out at 160 °C for 12 h by using 1.0 mmol of **1**, 5.0 mmol of **2**, and 0.03 mmol of ReBr(CO)₅. ^b GC yield based on the amount of **1**.

Table 1 summarizes the results of the etherification of **1a** with **2a** in the presence of other rhenium(I) or rhenium(0) complexes. ReCl(CO)₅ also showed high catalytic activity to give **3a** in 83% GC yield (entry 2). The use of CpRe(CO)₃ gave **3a** in only 14% GC yield (entry 3). Re₂(CO)₁₀, a zerovalent rhenium complex, also showed catalytic activity to afford **3a** in 65% GC yield (entry 4). In this case, the yield of dibenzyl ether was increased to 14% (GC yield), indicating that Re₂(CO)₁₀ shows low selectivity for dehydration of alcohols compared to rhenium(I) complexes.

The new catalytic procedure can be readily applied to the dehydration of benzyl alcohols **1** with a wide range of aliphatic alcohols **2** as summarized in Table 2. The ReBr(CO)₅-catalyzed reaction of **1a** with methanol **2b** gave benzyl methyl ether **3b** in 99% GC yield (Table 2, entry 2). The dehydration of **1a** with aliphatic alcohols such as 1-hexanol **2c**, cyclohexanol **2d**, 1-octanol **2e**, 1-dodecanol **2f**, and 1-hexadecanol **2g** afforded the corresponding ethers in good yields⁸ (Table 2, entries 3–7).

(8) Under the same reaction conditions, the reaction of benzyl alcohol with *tert*-butyl alcohol afforded the corresponding benzyl *tert*-butyl ether in only 31% GC yield. In this case, isobutylene formed from the dehydration of *tert*-butyl alcohol, and the conversion of *tert*-butyl alcohol reached 82%.

Scheme 1. Proposed Catalytic Cycle for the ReBr(CO)₅-Catalyzed Etherification

Under the same reaction conditions, the etherification of benzyl alcohols **1b** and **1c** with **2a** gave the corresponding ethers **3h** and **3i** in 87% and 77% GC yields, respectively (Table 2, entries 8, 9).

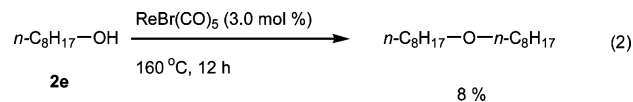
Although the mechanism of the present catalytic dehydration of alcohols remains to be elucidated, we proposed the catalytic cycle shown in Scheme 1. The following observations support the proposed scheme. When the reactions of **1a** with **2a–c** were performed under an inert atmosphere, the corresponding ethers were formed in very low yields (<5%), indicating that oxygen was essential for achieving satisfactory yields of the ethers. In addition, although dibenzyl ether could be obtained in 78% GC yield by the dehydration of **1a** catalyzed by ReBr(CO)₅ (Table 2, entry 10), under the same conditions the dehydration of **2e** produced the di-*n*-octyl ether in only 8% GC yield (eq 2). In this case, neither the rearrangement product nor elimination product could be determined in the reaction mixture by GC and GC-MS. These results implied that the formation of the benzyl cation would be the crucial step in the formation of the ether. On the basis of these results, we propose a mechanism involving⁹ (1) the oxidation of ReBr(CO)₅ to give the rhenium(III) oxide **6**;¹⁰ (2) decarbonylation of **6** to afford the 16-electron intermediate ReOBr(CO)₄ **7**;¹¹ (3) the formation of the benzyl cation and subsequent formation of unsymmetrical ether **3** and

(9) Our proposed mechanism includes the step of the formation of a carbocation (cation of benzyl); thus this mechanism can also be considered as transition metal-based Lewis acid catalysis. For ReBr(CO)₅ as Lewis acid catalyst, see: Nishiyama, Y.; Kakushou, F.; Sonoda, N. *Bull. Chem. Soc. Jpn.* **2000**, *73*, 2779, and references therein.

(10) For the similar oxidation of Re(III) and Re(V) by oxygen, see: (a) Smith, K. J.; Ondracek, A. L.; Gruhn, N. E.; Lichtenberger, D. L.; Fanwick, P. E.; Walton, R. A. *Inorg. Chim. Acta* **2000**, *300/302*, 23. (b) Edwards, P. G.; Wilkinson, G.; Hursthouse, M. B.; Michael, B.; Malik, K. M. A. *J. Chem. Soc., Dalton Trans.* **1980**, 2467.

(11) The decarbonylation of the Re(I) complex has been reported: (a) Jolly, P. W.; Stone, F. G. A. *J. Chem. Soc.* **1965**, 5259. (b) Zingales, F.; Sartorelli, U.; Canziani, F.; Raveglia, M. *Inorg. Chem.* **1967**, *6*, 154.

(dihydroxo)rhenium(III) **10**; and (4) the dehydration of **10** to regenerate **7**.¹²



In conclusion, we have developed the rhenium(I)-catalyzed etherification of primary benzyl alcohols with various primary aliphatic alcohols under air to afford unsymmetrical ethers in good yields with high selectivities. This is the first example of low-valent rhenium complexes being used as catalysts in the formation of C–O bonds. Further investigations on the application

(12) The dehydration of (dihydroxo)rhenium(VII) has been reported: Gutierrez, A.; Wilkinson, G.; Hussain-Bates, B.; Hursthouse, M. S. *Polyhedron* **1990**, *9*, 2081.

of rhenium(I) complexes in the other catalytically synthetic reactions are in progress.

Experimental Section

Typical Procedure for ReBr(CO)₅-Catalyzed Etherification of Benzyl Alcohol **1a with Butanol **2a** (Table 1, entry 1).** In a 20 mL autoclave was placed a mixture of 1.0 mmol of **1a**, 5.0 mmol of **2a**, and 0.03 mmol of ReBr(CO)₅ under an air atmosphere. The mixture was heated with stirring at 160 °C for 12 h. After cooling, the reaction mixture was diluted with toluene to 5.0 mL and an appropriate amount of C₁₆H₃₄ was added as the internal standard for GC and GC-MS analyses. **3a** was obtained by removal of volatiles in vacuum and purification by column chromatography (silica gel, eluted with hexane).

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