A Novel $B(C_6F_5)_3$-Catalyzed Reduction of Alcohols and Cleavage of Aryl and Alkyl Ethers with Hydrosilanes†

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The primary alcohols **1a**−**e** and ethers **4a**−**d** were effectively reduced to the corresponding hydrocarbons **2** by $HSiEt_3$ in the presence of *catalytic amounts* of $B(C_6F_5)_3$. To the best of our knowledge, this is the first example of catalytic use of Lewis acid in the reduction of alcohols and ethers with hydrosilanes. The secondary alkyl ethers **4j**,**k** enabled cleavage and/or reduction under similar reaction conditions to produce either the silyl ethers **3m**−**n** or the corresponding alcohol **5a** upon subsequent deprotection with TBAF. It was found that the secondary alcohols **1g**−**i** and tertiary alcohol **1j**, as well as the tertiary alkyl ether **4l**, did not react with $HSiEt_3/(B(C_6F_5)_3$ reducing reagent at all. The following relative reactivity order of substrates was found: primary ≫ secondary > tertiary. A plausible mechanism for this nontraditional *Lewis acid catalyzed* reaction is proposed.

Reactions of hydrosilanes in the presence of Lewis acids are very important tools in modern synthetic organic chemistry. Thus, the Lewis acid-catalyzed hydrosilylation of carbon−carbon unsaturated systems is a powerful approach for the synthesis of various types of organylsilanes,[1] whereas the Lewis acid-catalyzed reduction of carbonyl function equivalents with hydrosilanes serves as a useful synthetic tool for the preparation of alcohols.[2] Another area of application of Lewis acid−hydrosilane combination is the reduction of alcohols and ethers. The known reducing methods of this type require *at least stoichiometric amounts of Lewis acid*.[3] Furthermore, the previous methods are most effective for the reduction of C−O bond at tertiary carbon,[3] much less effective for the reduction of secondary substrates,[4] and absolutely noneffective for that of primary alcohols[5] and ethers (Scheme 1).[3] Such reactivity order of tertiary, secondary, and primary substrates is well understood in terms of the classical S_N1 mechanistic pathway (Scheme 1).[3]

We have recently communicated[6] the following: (1) even catalytic amount of $B(C_6F_5)_3$ is enough to effectively reduce certain alcohols and ethers with $HSiEt_3$; (2) the reactivity order for the reduction of tertiary, secondary, and primary substrates with $HSiEt_3$/cat.-$B(C_6F_5)_3$ is completely reverse from that of the traditional $HSiR_3$/Lewis acid reducing systems (Scheme 2).[3] In this paper, we report a full account on this $B(C_6F_5)_3$-catalyzed reaction, involving reduction of alcohols and reductive cleavage of alkyl and aryl ethers, as well as mechanistic studies of these novel transformations.

Results and Discussion

$B(C_6F_5)_3$-Catalyzed Reduction of Alcohols with Hydrosilanes. During our studies on the $B(C_6F_5)_3$-catalyzed hydrostannation of carbon−carbon multiple bonds,[7] we noticed remarkably strong affinity of $B(C_6F_5)_3$ toward the hydride of hydrostannanes.[8] This fact, together with the exceptionally high stability of $B(C_6F_5)_3$,[8] encouraged us to investigate the possibility of reduction of C−O bonds with hydrosilanes in the presence of *catalytic* amounts of this unique Lewis acid (eq 1). In a test experiment, we found that 1-hexadecanol (**1a**) underwent complete dehydrocondensation with 1.1 equiv of $HSiEt_3$ in the presence of 5 mol % of $B(C_6F_5)_3$ to give the corresponding silyl ether **3a** (Table 1, entry 1).[9] Surpris-

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(4) For a report on the reduction of secondary benzyl alcohols in the presence of primary alkyl alcohols with $HSiEt_3/BF_3$ system, see ref 3c.

(5) Recently an effecient one-pot radical-initiated reduction of primary and secondary alcohols with Et_3SiH was reported, see: Ferreri, C.; Costantino, C.; Chatgilialoglu, C.; Boukherroub, R.; Manuel, G. *J. Organomet. Chem.* **1998**, *554*, 135.

(6) Gevorgyan V.; Liu J.-X.; Rubin M.; Benson S.; Yamamoto Y. *Tetrahedron Lett.* **1999**, *40*, 8919.

(7) (a) Gevorgyan, V.; Liu, J.-F.; Yamamoto, Y. *J. Org. Chem.* **1997**, *62*, 2963. (b) Gevorgyan, V.; Liu, J.-F.; Yamamoto, Y. *J. Chem. Soc., Chem. Commun.* **1997**, 37.

(8) Strong affinity of $B(C_6F_5)_3$ toward hydride of hydrosilanes is well-known; for a review, see: Piers, W. E.; Chivers, T. *Chem. Soc. Rev.* **1997**, *26*, 345. See also ref 2d.

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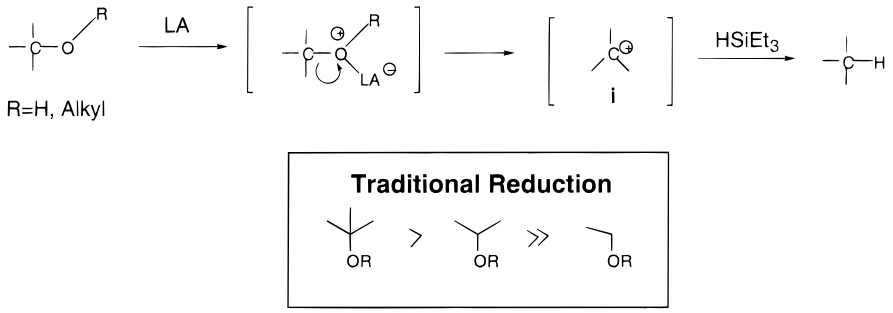
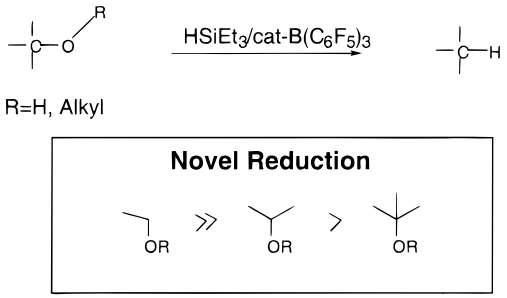
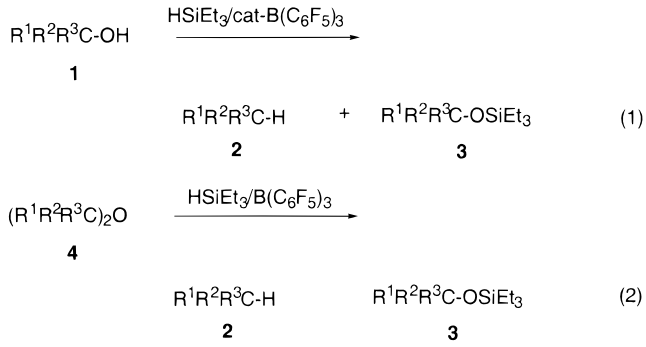
Scheme 1. Traditional Reduction of Alcohols and Ethers with Stoichiometric LA−$HSiEt_3$ System



Scheme 2. Novel Reduction of Alcohols and Ethers with Catalytic $B(C_6F_5)_3$−$HSiEt_3$ System





ingly, we found that in the presence of 3 equiv of $HSiEt_3$ the primary alcohol **1a** was quantitatively reduced into *n*-hexadecane (**2a**, entry 2).[10] All other primary alcohols tested (**1b**−**e**) under the same reaction conditions (see the Experimental Section for details) were also smoothly reduced into the corresponding hydrocarbons **2b**−**e** in high to quantitative yields (entries 3−6). Other hydrosilanes tested, such as $HSiPh_3$, $HSiMePh_2$, and $HSiMeEt_2$, were similarly effective. As expected, phenol (**1f**) did not undergo reduction even in the presence of 6 equiv of hydrosilane, the phenyl triethylsilyl ether **3b** was obtained quantitatively, instead (entry 7). Surprisingly again, the secondary alcohols **1g**−**i**, in contrast to primary ones, produced the silyl ethers **3c**−**e** in essentially quantitative yields (entries 8−10), thus exhibiting a complete resistance toward the reduction.[11] The tertiary alkyl alcohol (**1j**) did not undergo the reduction at all but gave 96% of the dehydrocondensation product, silyl ether, **3f** (entry 11). In contrast to the alkyl analogues, the secondary alcohol **1k**, possessing two phenyl groups and tertiary trityl alcohol (**1l**), smoothly underwent the reduction even upon treatment with 1.1 equivalents of hydrosilane to give diphenylmethane **2f** and triphenylmethane (**2g**) almost quantitatively (entries 12 and 13, Table 1).

$B(C_6F_5)_3$-Catalyzed Cleavage and/or Reduction of Alkyl Ethers with Hydrosilanes. Inspired by the successful reduction of alcohols with $HSiEt_3$/cat-$B(C_6F_5)_3$ (eq 1, Table 1), we attempted to apply this new reducing system for the reduction of ethers **4** (eq 2, Table 2). It was found that stoichiometric amounts of $HSiEt_3$, in the presence of 5 mol % $B(C_6F_5)_3$, enabled the cleavage of linear primary alkyl ethers **4a**,**b** into the corresponding hydrocarbons **2a**,**e** and silyl ethers **3a,h**, respectively (Table 2, entries 1 and 3), whereas in the presence of excess amounts of $HSiEt_3$, **4a**,**b** underwent smooth exhaustive reduction into the hydrocarbons **2a**,**e** in quantitative to high yields, respectively (entries 2 and 4). Very similarly, reduction of a cyclic primary ether **4c** in the presence of 1.1 equiv of $HSiEt_3$/10 mol % $B(C_6F_5)_3$ gave the corresponding ring-cleaved silyl ether **3i** in 96% yield (entry 5). Here again, the use of 3.0 equiv of $HSiEt_3$/10 mol % $B(C_6F_5)_3$ afforded the corresponding hydrocarbon **2h** (entry 6). Phthalan (**4d**) was easily reduced into the *o*-xylene in 78% yield (**2i**, entry 7). As expected, the aryl C−O bonds in 2,3-dihydrobenzofuran (**4e**) and methylenedioxybenzene (**4i**) were tolerant toward the reduction, and consequently, the cleavage products triethylsilyl ether of *o*-ethylphenol (**3j**) and catechol (**5a**) were produced in quantitative and 79% yields, respectively (entries 8, 12). Similarly, anisole derivatives **4f**,**g**,**h** were readily cleaved to form the corresponding phenyl silyl ethers **3b**,**k**,**l** in virtually quantitative isolated yields (entries 9−11). This method could serve as a useful tool for the deprotection of alkyl aryl ethers, because it allows one to perform a quantitative demethylation of anisoles under very mild conditions,[12] unlike the known methods.[13] Obviously, TES-ethers of phenols can be easily desilylated in situ by a variety of known procedures.[13] It was interesting to find that the secondary alkyl ether **4j** in the presence of 3 equiv of $HSiEt_3$ was quantitatively cleaved to give the silyl ether **3m** (entry 13). Thus, the secondary alkyl silyl ether **3m** (as well as the secondary

(9) While our project was underway, a paper describing silylation of alcohols in the presence of $HSiEt_3/B(C_6F_5)_3$ system was published; see: Blackwell, J. M.; Foster, K. L.; Beck, V. H.; Piers, W. E. *J. Org. Chem*. **1999**, *64*, 4887.

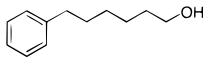
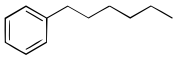
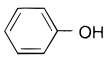
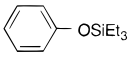
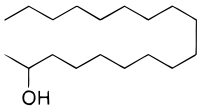
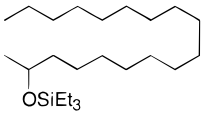
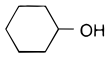
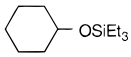
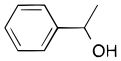
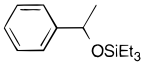
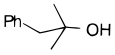
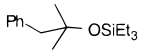
(10) It is well-known that primary alcohols and ethers do not undergo reduction with traditional hydrosilane/Lewis acid reducing system; see refs 3 and 4.

(11) The observed reduction of primary alcohols and resistance of secondary alcohols toward reduction by $HSiEt_3/B(C_6F_5)_3$ system is absolutely opposite to the reactivity order which was observed in the reduction of alcohols by the classical methods; see refs 3 and 4 (eq 1).

(12) Although reproducible results were obtained with 5 mol % of commercially available boron catalyst, it was found that the freshly prepared catalyst was notably more efficient. Thus, only 1 mol % of $B(C_6F_5)_3$ was enough for the complete cleavage of anisoles **4g**,**h**. For the routine synthesis of $B(C6F_5)_3$, see: Massey, A. G.; Park, A. J. *J. Organomet. Chem*. **1964**, *2*, 245.

(13) Greene, T. W.; Wuts, P. G. *Protective Groups in Organic Synthesis*, 3rd ed.; Wiley: New York, 1999.

Table 1. Reduction of Alcohols 1 with $HSiR_3$/Cat.-$B(C_6F_5)_3$ System

Entry	Alcohol **1**	$HSiEt_3$ (eq)	Products (Isolated Yield, %)
1	*n*-$C_{16}H_{33}OH$ (**a**)	1.1	*n*-$C_{16}H_{33}OSiEt_3$ (**3a**) (>99)
2	//	3.0	*n*-$C_{16}H_{34}$ (**2a**) (95)
3	 (**b**)	6.0	 (**2b**) (>99)
4	$Ph(CH_2)_3OH$ (**c**)	3.0	$Ph(CH_2)_3H$ (**2c**) (>95)[a]
5	$Ph(CH_2)_2OH$ (**d**)	//	$Ph(CH_2)_2H$ (**2d**) (>95)[a]
6	$PhCH_2OH$ (**e**)	6.0	$PhCH_3$ (**2e**) (78)[a]
7	 (**f**)	//	 (**3b**) (>99)[b]
8	 (**g**)	3.0	 (**3c**) (>99)
9	 (**h**)	6.0	 (**3d**) (>95)[a]
10	 (**i**)	//	 (**3e**) (>95)[a]
11	 (**j**)	//	 (**3f**) (96)
12	Ph_2CHOH (**k**)	1.1	Ph_2CH_2 (**2f**) (98)
13	Ph_3COH (**l**)	1.1	Ph_3CH (**2g**) (98)

[a] NMR yield. [b] GC yield.

alkyl alcohols, see also Table 1, entries 8−10) exhibited striking resistance toward reduction. Cyclic secondary ether **4k** behaved similarly, producing the cleavage product **3n** in very high yield (entry 14). Ether **4l**, possessing both tertiary and primary alkyl units, did not undergo reduction at all (entry 13).[14]

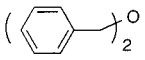
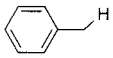
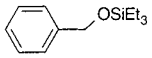
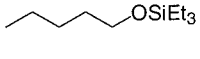
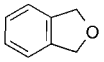
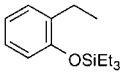
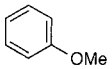
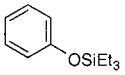
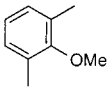
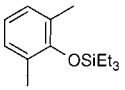
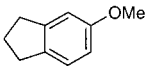
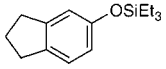
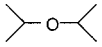
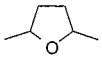
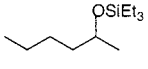
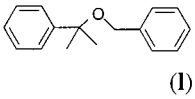
Mechanistic Studies and Discussion. The observed unusual high reactivity of primary alcohols **1a**−**e** (eq 1, Table 1) and ethers **4a**−**h** (eq 2, Table 2) toward reduction with the $HSiEt_3$/cat.-$B(C_6F_5)_3$ system seemed to be easily understood in terms of the S_N2 mechanistic pathway rather than S_N1 protocol.[15] This proposal can be examined by investigating the stereochemistry of the reduction of the chiral alcohol (e.g., (*S*)-(−)-**1i**) with deuterated silane (Scheme 3). Indeed, if the reduction proceeds through the carbenium intermediate **6** (S_N1 pathway, Scheme 3), the formation of racemic hydrocarbon **7** is unavoidable.[3] However, if the concerted mechanism is involved (transition state **8**), the formation of product **9** with complete or notable inversion of configuration at the secondary carbon center[16] should be observed (S_N2 pathway, Scheme 3). Since the above-mentioned study cannot be applied to primary alcohols, we searched for a suitable secondary substrate. It was found that triethylsilyl ether of (*S*)-(−)1-phenylethanol (*S*)-(−)-**1i** could serve for this purpose. Although the secondary silyl ether **3e** did not undergo reduction with triethylsilane (Table 1, entry 10), the test experiments indicated that it could be reduced into **2d** by treatment with less bulky dimethylethylsilane. Therefore, to study the stereochemistry of the reduction, (*S*)-(−)-**3e** was prepared. The experiment on the reduction of (*S*)-(−)-**3e**

(14) Similarly, rather bulky silyl ethers of benzyl alcohol, such as TIPSOBn (**1m**), TBDPSOBn (**1n**), and TBDMSOBn (**1o**), were resistant toward reduction with $HSiEt_3/B(C_6F_5)_3$ system.

(15) Generally, the nucleophilic substitution at primary sp^3 carbon should proceed via S_N2 rather than through an S_N1 pathway. For a review, see, for example: Hartshorn, S. R. *Aliphatic Nucleophilic Substitution*; Cambridge University Press: Cambridge, 1973.

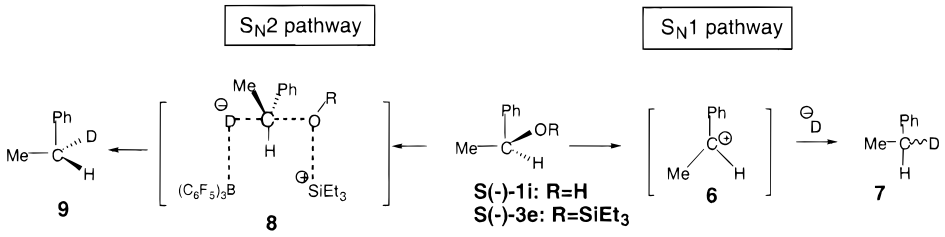
(16) For trapping of carbenium cation with chiral hydrosilane, see: Fry, J. *J. Am. Chem. Soc.* **1971**, *93*, 3558.

Table 2. Cleavage and/or Reduction of Ethers 4 with $HSiEt_3$/Cat.-$B(C_6F_5)_3$ System[a]

Entry	Ether **4**	$HSiEt_3$ (eq)	Products (Isolated Yield, %)	
1	$(n\text{-}C_{16}H_{33})_2O$ (**a**)	1.1	$n\text{-}C_{16}H_{34}$ (**2a**) (98)	$n\text{-}C_{16}H_{33}OSiEt_3$ (**3a**) (98)
2	//	3.0		2 × **2a** (>95)
3	 (**b**)	1.1	 (**2e**) (77)[c]	 (**3h**) (93)[b]
4	//	3.0		2 × **2e** (86)[b]
5	 (**c**)	1.1		(**3i**) (96)
6	//	3.0		(**2h**) (97)[b]
7	 (**d**)	//		(**2i**) (78)[b]
8	 (**e**)	1.1		(**3j**) (>99)
9	 (**f**)	1.1		(**3b**) (>99)
10	 (**g**)	1.1		(**3k**) (>99)
11	 (**h**)	1.1		(**3l**) (96)
12	 (**i**)	3.0		(**5a**) (79)[b,c]
13	 (**j**)	//		(**3m**) (>95)[b]
14	 (**k**)	//		(**3n**) (97)
15	 (**l**)	//	no reaction, recovery of **4l** 97%	

[a] All reactions were carried in CH_2Cl_2. For more detailed reaction conditions, see the Experimental Section. [b] NMR yield. [c] Yields of alcohols **5** after TBAF deprotection of the corresponding alkoxysilanes **3**.

Scheme 3. Classical S_N1 and S_N2 Pathways for the Reduction of Alcohols with LA−$HSiEt_3$ System

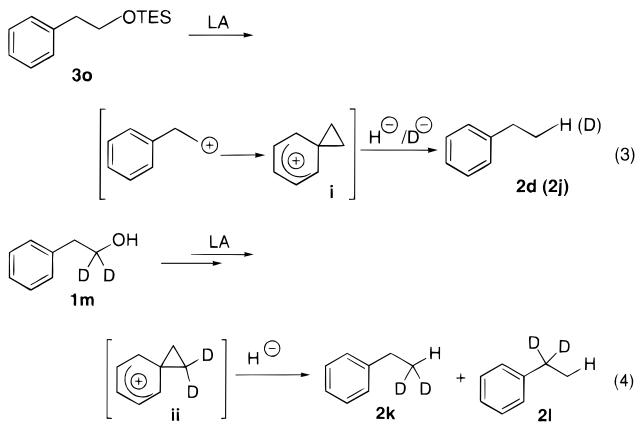


with $DSiEtMe_2/B(C_6F_5)_3$[17] in pentane revealed substantial inversion of its configuration (41% ee of (*R*)-(−)-phenylethane-1-*d* (**9**) was obtained,[18] Scheme 3). However, in slightly more polar solvent, dichloromethane, the reduction of (*S*)-(−)-**3e** produced nearly racemic **7** (2% ee, inversion). The last result is in agreement with known data, where 2% ee (retention) was observed in the reduction of the same secondary alcohol (*S*)-(−)-**1i** under the traditional method: $HSiEt_3$−stoichiometric amounts

(17) The isotopically homogeneous $DSiEtMe_2$ was prepared under the phase-transfer conditions, see: (a) Gevorgyan, V.; Ignatovich, L.; Lukevics, E. *J. Organomet. Chem.* **1985**, *284*, C31. (b) Liepins, E.; Gevorgyan, V.; Lukevics, E. *J. Magn. Reson.* **1989**, *85*, 170.

(18) On absolute configuration of enantiomerically pure deuterated phenylethanes, see: Elsenbaumer, R. L.; Mosher, H. S. *J. Org. Chem.* **1979**, *44*, 600.

of BF_3(gaseous).[19] Intrigued by the contradictory results of stereochemistry on the reduction of secondary substrate (*S*)-(−)-**3e**, we were eager to learn about the mechanism for the reduction of primary substrates. The study of kinetic hydrogen/deuterium isotope effect in the reduction of primary alcohols could give an important missing information on this matter.[20] Provided that the concerted mechanism with certain degrees of symmetry (traditional S_N2 pathway, Scheme 2) is responsible for the reduction of primary substrates, then the substantial primary isotope effect should be observed.[20] This effect will occur because the transition of deuteride from the reagent system to the electrophilic carbon center will take place at the rate-determining step.[20] Otherwise, if the reduction of primary substrates proceeds via the carbenium intermediate **6**, the deuteride transfer would not be a rate determining step,[21] consequently no notable isotope effect should be detected (Scheme 3). For the measurement of the primary kinetic isotope effect, we chose the reduction of triethylsilyl ether of phenylethanol **3o**[22] with 1:1 mixture of $HSiEt_3$ and $DSiEt_3$ in the presence of 10 mol % of $B(C_6F_5)_3$. These studies revealed negligible primary hydrogen/deuterium isotope effect (1.11 ± 0.03, and 0.97 ± 0.03 for two series of experiments), thus confirming the classical S_N1 type reaction pathway for the reduction of primary alcohols and ethers (Scheme 3). It is reasonable to propose that the reduction of **3o** proceeds via the well-known[23] phenonium cation **i** which leads to a 1:1 mixture of **2d** and **2j** (eq 3). This pathway can be easily justified by reduction of 1,1-dideuteriophenethyl alcohol **1m** (eq 4). Indeed, if the



phenonium ion **ii** is the true intermediate in the reduction of **1m**, then the formation of nearly equimolar mixture of **2k** and **2l**[24] is unavoidable[25] (eq 4). Accordingly, the deuterated alcohol **1m** was prepared[26] and subjected to the reduction with $HSiEt_3$ under the typical reaction conditions. In contrast to expectations, minor deuterium scrambling was observed. A 90:10 mixture of **2k** and **2l** was obtained, thus ruling out an involvment of the **ii** as a major intermediate in the mentioned transformation. Puzzled by the confrontational results obtained from the stereochemical and isotope effect studies, we conducted kinetic investigations on the reduction of phenylethanol **1d** with 3 equivalents of $HSiEt_3$ in the presence of 10 mol % of $B(C_6F_5)_3$ catalyst. The plot of the reaction coordinates vs time is presented in Figure 1. It became clear that the reduction of the alcohol **1d** proceeded in two steps. At the first step, **1d** underwent fast dehydrocondensation[27] with hydrosilane to produce the silyl ether **3o**. Thus, after only 1 min, the reaction mixture consisted of 78% of **3o** and 22% of **1d**, whereas in two minutes the transformation **1d** → **3o** was almost quantitative (Figure 1). The second step, reduction of the silyl ether **3o**, appeared to be dramatically slower than the first step and it took more than 8 h to complete the formation of the hydrocarbon **2d** (Figure 1).

Based on the above-mentioned stereochemical, kinetic, and isotope effect studies, we propose the following mechanistic rationale for the observed unusual reduction of alcohols and ethers in the presence of $HSiEt_3$/cat.-$B(C_6F_5)_3$ system (Schemes 4 and 5). The plausible mechanisms for the silylation of alcohols and for the reduction of particular alcohols are depicted in the Scheme 4. The reduction of diphenylmethanol (**1k**) and triphenylmethanol (**1l**), the alcohols possessing strong cation-stabilizing groups, could be explained in terms of the classical (path A) or the modified (path B) S_N1 pathways (Scheme 4). Reversible interaction of **10** with **1k** or **1l** would form an oxonium complex **11**, which would be transformed into the carbenium intermediate **12**. The latter would react with hydrosilane **13** to produce diphenylmethane (**2f**) or triphenylmethane (**2g**) and regenerate the catalyst **10** (path A, Scheme 4). According to an alternative mechanism (path B, Scheme 4), the reversible interaction of **10** with **13** would produce an ate complex **15**. The silicenium cation of **15**[28] could serve as a new Lewis acid that would coordinate to **1** to form the oxonium complex **16**,[29,30] which via the carbenium intermediate **17** would produce hydrocarbons **2f** or **2g** and would regenerate **10**. It is hard to distinguish between these two possible S_N1 pathways (paths A and B), since both of them reasonably explain the formation of the same reaction products, the hydrocarbons **2f** or **2g** and the byproduct silanol **14**[31] (Scheme 4). In the case of other alcohols, which do not possess any strong cation-stabilizing groups, the oxonium complex **16** does not transform into the carbenium intermediate **17**, instead it collapses via the dehydrocondensation process into the silyl ether **3**,[9] boron catalyst **10**, and dihydrogen[27] (path C, Scheme 4). Accordingly, in the

(19) Smonou, I.; Orfanopoulos, M. *Tetrahedron Lett.* **1988**, *29*, 5793.

(20) For a discussion on interpretation of kinetic and product isotope effects at the rate-determining step in the ene reaction, see, for example: (a) Douglas, Z. S.; Beak, P. *J. Org. Chem.* **1987**, *52*, 3938. (b) For investigation of kinetic hydrogen/deuterium primary isotope effect in the reduction of alcohols with hydro- and deuteriosilanes in the presence of stoichiometric amount of BF_3, see ref 19.

(21) For kinetic studies on hydride transfer from hydrosilanes to carbenium ions, see: Mayr, H.; Basso, N.; Hagen, G. *J. Am. Chem. Soc.* **1992**, *114*, 3060.

(22) We used silyl ether **3k** for investigation of isotope effect since the reduction of silyl ethers seems to be the slowest step in the overall transformation: alcohol → hydrocarbon (see Figure).

(23) For earlier reports on phenonium ions, see: (a) Cram D. J. *J. Am. Chem. Soc.* **1949**, *71*, 3863. (b) Cram D. J.; Davis R. *J. Am. Chem. Soc.* **1949**, *71*, 3875. (c) Cram D. J. *J. Am. Chem. Soc.* **1964**, *86*, 3764.

(24) We assume that $k_\Delta \gg k_S$ and that the secondary isotopic effect is negligible.

(25) Saunders W. H.; Asperger S.; Edison D. H. *J. Am. Chem. Soc.* **1958**, *80*, 2421.

(26) Wong, C. W.; Hamilton J. T. G.; O'Hagan, D.; Robins, R. J *Chem. Commun.* **1998**, 1045.

(27) Vigorous hydrogen emission was observed.

(28) We do not postulate an involvement of *free* silicenium cation in the proposed mechanism.

(29) Involvement of such ate-complexes in the dehydrocondensation of alcohols,[9] as well as in the reduction of carbonyl group equivalents,[30] have been recently unambiguously demonstrated.

(30) Parks, D. J.; Blackwell J. M.; Piers W. E. *J. Org. Chem.* **2000**, *65*, 3090.

(31) Formation of **14** was confirmed by GC−MS analyses of the crude reaction mixtures.

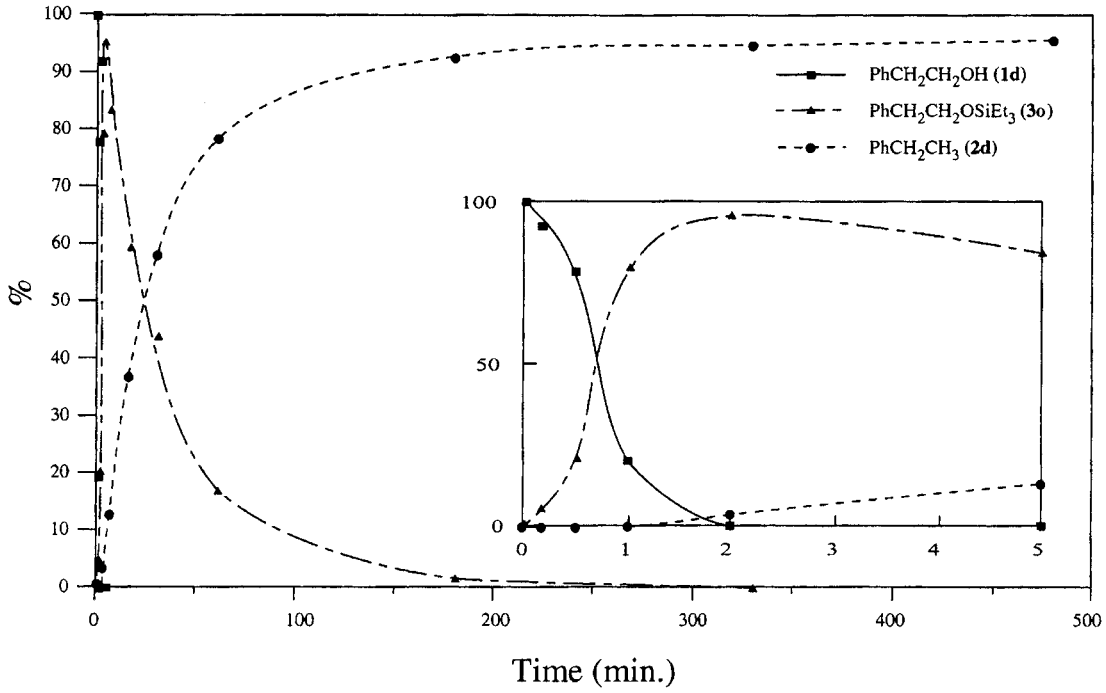
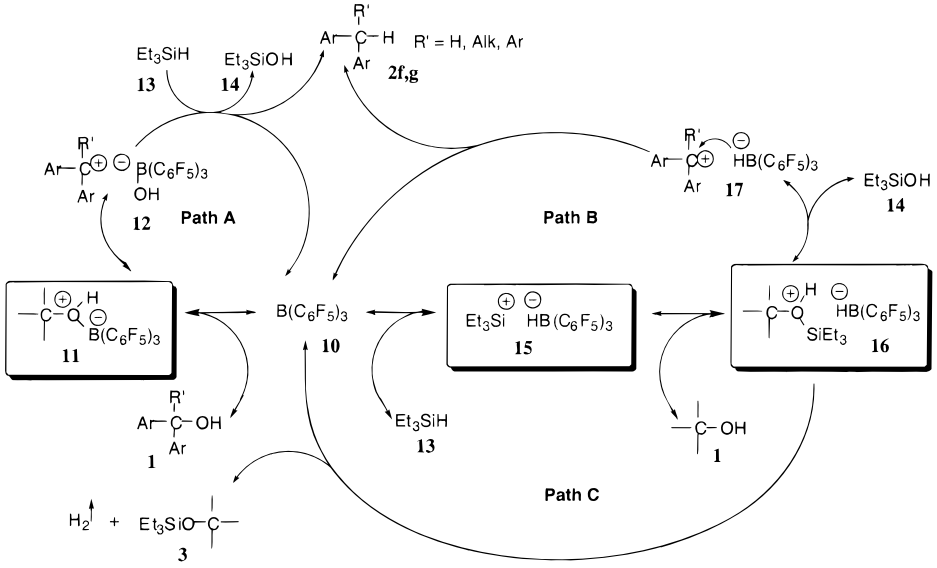


Figure 1. Reaction coordinates on reduction of **1d** with $HSiEt_3$/cat.-$B(C_6F_5)_3$ system.

Scheme 4. Proposed Mechanism for the Reduction of 1k,l and Silylation of 1a−j with 1 Equiv of Et_3SiH



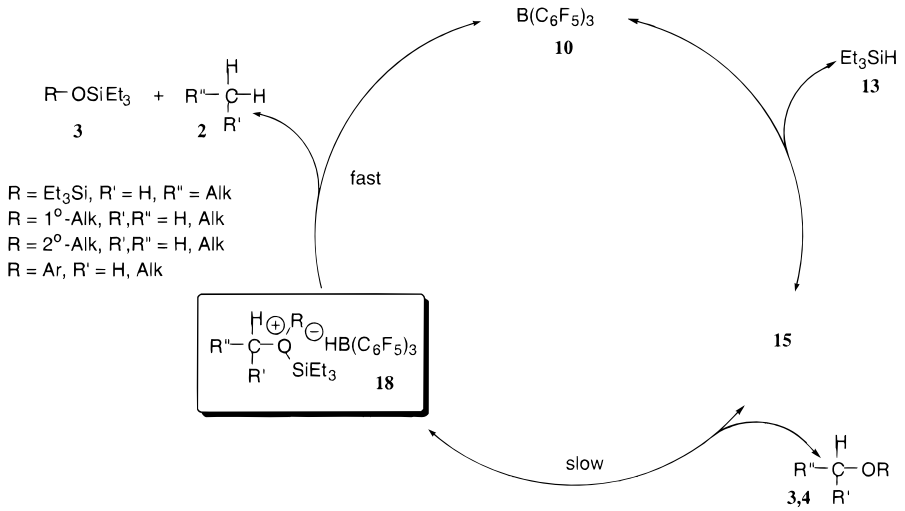
reduction of the "regular" alcohols, the first equivalent of hydrosilane is completely consumed for the formation of silyl ethers (entry 1, Table 1; Figure 1; path C, Scheme 4).

We propose that the ate-complex **15** is responsible for the reduction of silyl and alkyl ethers (Scheme 5). The silicenium cation of the ate-complex **15** would reversibly coordinate to the oxygen of silyl ether **3** (or alkyl ether **4)** to form an oxonium complex **18**, which would produce the reaction product, hydrocarbon **2**, siloxane (or silyl ether **3**) and would regenerate **10** (Scheme 5). The hydride transfer step **18** → **2** should be a fast step, as it was supported by the negligible kinetic hydrogen/deuterium isotope effect in the reduction of **3o** (see the text above). In contrast, the reversible coordination of **15** to **3** to form **18** seems to be the slowest step among the overall reduction process and completely sterically controlled. This is the key step for understanding the unusual reactivity order of primary, secondary and tertiary alcohols and ethers toward reduction. Thus, only less hindered triethylsilyl ethers **3** derived from the primary alcohols **1a**−**e** (Table 1, entries 2−6; Figure 1)[32] and primary ethers **4a**−**e** (Table 2, entries 2−8) enabled to undergo the reduction. In contrast, the triethylsilyl ethers, obtained from more bulky secondary[33] or tertiary alcohols and ethers,[33] exhibited no detectable reduction under similar reduction conditions (Table 1, entries 8−11; Table 2, entries 13−14). Reasons for the observed notable inversion of configuration of the secondary silyl ether (*S*)-(−)-**3e** (Scheme 3 and text above) are not clearly understood. It is hypothesized that (*S*)-(−)-**3e** being a border-

(32) Test experiments revealed that primary triethylsilyl ethers underwent reduction into the corresponding hydrocarbons **2**.

(33) Control experiments showed that secondary and tertiary triethylsilyl ethers in contrast to primary ones[32] did not undergo reduction with excess amounts of $HSiEt_3$.

Scheme 5. Proposed Mechanism for the Reductive Cleavage of Silyl−Alkyl, Aryl−Alkyl, and Alkyl−Alkyl Ethers



line substrate between simple alkyl alcohols and **1k**,**l** undergoes reduction via both intermediate **18** (Scheme 5) and some free carbenium intermediate, similar to **12** or **17** (Scheme 4).

In conclusion, we have developed a novel, effective, nontraditional method for reduction of primary alcohols and ethers and for deprotection of aryl alkyl ethers with hydrosilanes in the presence of catalytic amounts of $B(C_6F_5)_3$. The reactivity order for the reduction of primary, secondary and tertiary susbstrates (Scheme 2) is reverse to that observed in the classical reduction protocols (Scheme 1).[3,4] We believe that the present novel methodology will serve as a useful tool in synthetic organic chemistry, complementary to existing methods.

Experimental Section

General Information. All manipulations were conducted under an argon atmosphere using standard Schlenk techniques. Anhydrous solvents were purchased from Aldrich. Tertiary alcohol **1k**,[34] primary ether **4a**,[35] and tertiary ether **4l**[36] were prepared according to the standard procedures. All other compounds used were commercially available and purchased from Aldrich. Products **3b**,[37] **3d**,[38] **3e**,[39] **3h**,[40] **3i**,[41] and **3m**[42] as well as **4l** are known compounds and their analytical data were in agreement with literature data. The spectral data of new compounds **3a**,**c**,**j**−**l**,**n** are provided below. All other reaction products are commercially available compounds and their analytical data were in perfect agreement with the authentic samples.

$B(C_6F_5)_3$-Catalyzed Reduction of Alcohols and Ethers with $HSiEt_3$ (General Procedure). $HSiEt_3$ was added under an argon atmosphere to a mixture of $B(C_6F_5)_3$ (5 mol %) and alcohol **1** or ether **4** (1 mmol) in hexane or CH_2Cl_2 (1 mL). After being stirred for 20 h at room temperature, the reaction mixture was quenched by addition of triethylamine (0.05 mL), filtered through Celite, and concentrated. After the addition of appropriate internal standard (CH_2Br_2 or CH_3CCl_3 for NMR or *n*-pentadecane for GC), the mixture was analyzed by capillary GC or NMR. In the case of low bp products, the reaction mixture was analyzed by ^1H NMR without concentration. Isolated yields were determined after preparative column chromatography on silica gel.

Kinetic Isotope Effect Studies (Reduction of 3o). A mixture of $HSiEt_3$ and $DSiEt_3$ was added at once to a stirred solution of $B(C_6F_5)_3$ (10 mol %) and **3o** (1 mmol) in anhydrous hexane (1 mL) under an argon atmosphere. After stirring for 20 h at room temperature, the reaction mixture was quenched with triethylamine (0.05 mL), filtered through Celite, and concentrated. The ratios **2d**/**2j** were determined by ^1H NMR analyses. The isotope effects were found as 1.11 ± 0.03 and 0.97 ± 0.03 for two series of experiments with the following ratios **3o**/$HSiEt_3$/$DSiEt_3$ = 1.0:1.5:1.5 and 1.0:0.5:0.5, respectively.[43]

Stereochemical Studies on the Reduction of (*S*)-(−)-3e. $EtMe_2SiD$ (15 mmol) was added dropwise to the stirred mixture of (*S*)-(−)-**3e** (10 mmol), $B(C_6F_5)_3$ (5 mol %), and anhydrous solvent (0.5 M). The reaction mixture was stirred for 20 h at room temperature, quenched with isopropylamine (0.5 mL), and filtered through a short column of Silica gel (eluent: dichloromethane). Eluate was concentrated under ambient pressure, and the residue was purified by column chromatography on silica gel (eluent: pentane). Combined fractions containing 1-deuterioethylbenzene (**7** or **9**) were concentrated under an ambient pressure. The resulting concentrate of **7** or **9** was used for $[\alpha]^{20}_D$ determination. Exact concentration of ethylbenzene-*d* (*c* = 30−50) was determined by ^1H NMR using CH_2Br_2 as an internal standard. The following stereochemical results were obtained, for the reduction in pentane: $[\alpha]^{20}_D = -0.356°$ (*c* = 50, pentane), ee = 44% and for dichloromethane: $[\alpha]^{20}_D = -0.016°$ (*c* = 30, pentane), ee = 2%.

3a: ^1H NMR ($CDCl_3$, 200.13 MHz) δ 3.59 (t, J = 6.6 Hz, 2H), 1.52 (m, 2H), 1.26 (m, 26H), 0.96 (t, J = 8.0 Hz, 9H), 0.88 (t, J = 6.8 Hz, 3H), 0.59 (q, J = 8.0 Hz, 6H); ^{13}C NMR (50.32 MHz, $CDCl_3$) δ 62.9, 32.8, 31.8, 29.6, 29.4, 29.3, 25.7, 22.6, 14.0, 6.6, 4.3; GC/MS *m*/*z* 355 ($M^+ - 1$, <1), 327 (100).

3c: ^1H NMR ($CDCl_3$, 400.13 MHz) δ 3.76 (m 1H), 1.26 (m, 26H), 1.12 (d, J = 6.3 Hz, 3H), 0.96 (t, J = 7.9 Hz, 9H), 0.88

(34) For a review on preparation of alcohols via alkylation of ketones, see for example: Ashby, E. C.; Laemmle, J.; Neumann, H. M. *Acc. Chem. Res.* **1974**, *7*, 272.

(35) Lenne, H.-U.; Mez, H. C.; Schlenk, W., Jr. *Justus Liebigs Ann. Chem.* **1970**, *732*, 70.

(36) Reuchardt, C.; Grundmeier, M. *Chem. Ber.* **1975**, *108*, 2448. For preparation of benzyl ethers, see, for example: Fukuzawa, A.; Sato, H.; Masamune, T. *Tetrahedron Lett.* **1987**, *28*, 4303.

(37) Hudrlik, P. F.; Minus, D. K. *J. Organomet. Chem.* **1996**, *521*, 157.

(38) Onaka, M.; Higuchi, K.; Nanami, H.; Izumi, Y. *Bull. Chem. Soc. Jpn.* **1993**, *66*, 2638.

(39) Wright, A.; West, R. *J. Am. Chem. Soc.* **1974**, *96*, 3214.

(40) (a) Liepins E.; Zicmane I.; Luckevics E. *J. Organomet. Chem.* **1986**, *306*, 167. (b) Fujita M.; Hiyama, T. *J. Org. Chem.* **1988**, *53*, 5405.

(41) (a) Bourhis, R.; Frainnet, E. *J. Org. Chem.* **1975**, *40*, 205. (b) Diekman et al. *J. Org. Chem.* **1967**, *32*, 3904.

(42) Lorenz C.; Schubert U. *Chem. Ber.* **1995**, *128*, 1267. See also ref 40a.

(43) For the measurement and calculation of k_H/k_D, see, for example: Beak, P.; Berger, K. R. *J. Am. Chem. Soc.* **1980**, *102*, 3848. See also ref 19.

(t, J = 6.7 Hz, 3H), 0.59 (q, J = 7.9 Hz, 6H); ^{13}C NMR (100.61 MHz, $CDCl_3$) δ 68.4, 39.8, 31.9, 30.0, 29.3, 25.8, 23.7, 22.6, 14.0, 6.8, 4.9; GC/MS m/z 355 ($M^+ - 1$, <1), 327 (100).

3f: ^{1}H NMR ($CDCl_3$, 500.13 MHz) δ 7.29 (m 2H), 7.24 (m 3H), 2.76 (s 2H), 1.24 (s 6H), 0.95 (t, J = 7.9 Hz, 9H), 0.59 (q, J = 7.9 Hz, 6H); ^{13}C NMR (125.75 MHz, $CDCl_3$) δ 139.3, 131.2, 127.9, 126.3, 74.0, 51.7, 30.1, 7.5, 7.2; GC/MS m/z 249 ($M^+ -$ 15, 3), 173 (100).

3j: ^{1}H NMR ($CDCl_3$, 400.13 MHz) δ 7.19 (dd, J = 7.3, 1.6 Hz, 1H), 7.10 (td, J = 7.7, 1.6 Hz, 1H), 6.93 (td, J = 7.3, 0.9 Hz, 1H), 6.82 (dd, J = 7.7, 0.9 Hz, 1H), 2.86 (q, J = 7.5 Hz, 2H), 1.24 (t, J = 7.5 Hz, 3H), 1.06 (t, J = 7.9 Hz, 9H), 0.82 (q, J = 7.8 Hz, 6H); ^{13}C NMR (100.61 MHz, $CDCl_3$) δ 153.4, 134.4, 129.0, 126.4, 120.8, 118.0, 23.5, 14.0, 6.5, 5.2; GC/MS 236 (M^+, 48), 207 (100).

3k: ^{1}H NMR ($CDCl_3$, 400.13 MHz) δ 7.00 (d, J = 7.4 Hz, 2H), 6.82 (t, J = 7.5 Hz, 1H), 2.27 (s, 6H), 1.03 (t, J = 7.8 Hz, 9H), 0.81 (q, J = 7.9 Hz, 6H); ^{13}C NMR (100.61 MHz, $CDCl_3$) δ 152.8, 128.4, 128.2, 121.1, 17.5, 6.8, 5.8; GC/MS 236 (M^+, 45), 207 (100).

3l: ^{1}H NMR ($CDCl_3$, 500.13 MHz) δ 7.08 (d, J = 8.0 Hz, 1H), 6.77 (d, J = 2.2 Hz, 1H), 6.67 (dd, J = 8.0, 2.2 Hz, 1H), 2.91 (t, J = 7.4 Hz, 2H), 2.87 (t, J = 7.4 Hz, 2H), 2.10 (ps-quintet, J = 7.4 Hz, 2H), 1.05 (t, J = 7.9 Hz, 9H), 0.78 (t, J = 7.9 Hz, 6H); ^{13}C NMR (125.77 MHz, $CDCl_3$) δ 154.5, 146.0, 137.1, 125.0, 118.0, 116.3, 33.5, 32.5, 26.2, 7.1, 5.4; GC/MS m/z 248 (M^+, 56), 219 (100).

3n: ^{1}H NMR ($CDCl_3$, 400.13 MHz) δ 3.77 (m, 1H), 1.29 (m, 6H), 1.12 (d, J = 6.2 Hz, 3H), 0.96 (t, J = 7.9 Hz, 9H), 0.89 (t, J = 6.9 Hz, 3H), 0.59 (q, J = 7.9 Hz, 6H); ^{13}C NMR (100.61 MHz, $CDCl_3$) δ 68.3, 39.4, 27.9, 23.7, 22.7, 14.0, 6.8, 4.8; GC/MS m/z 215 ($M^+ - 1$, <1), 103 (100).

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