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Scandium(III) Triflate-Catalyzed Friedel−Crafts Alkylation Reactions

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The $Sc(OTf)_3$-catalyzed Friedel−Crafts alkylation reaction with an alcohol, an arenecarbaldehyde or an arenecarbaldehyde acetal as the alkylating agent affords a diarylmethane or an allylbenzene derivative highly selectively. The salient feature of this reaction is that only a catalytic amount of $Sc(OTf)_3$ can effect the reaction. Furthermore, $Sc(OTf)_3$ is recoverable and reusable after the synthetic reaction. The $Sc(OTf)_3$-catalyzed benzylation using an arenecarbaldehyde and 1,3-propanediol or their acetal affords diarylmethane as a sole product in excellent yields in sharp contrast to the original Friedel−Crafts reaction. Since no reaction occurs in the absence of 1,3-propanediol, the reaction is considered to proceed through a redox process including a hydride shift. The hydride shift mechanism is strongly supported by the experimental evidence. The reaction of benzaldehyde with benzene in the presence of 1,3-propanediol-*1,1,3,3,-d*$_4$ gives rise to the deuterium incorporation into the benzylic carbon of diphenylmethane. Worthy of note is that 1,3-propanediol acts as the hydride source. Herein, diphenylmethyl 3-hydroxypropyl ether is assumed to be the most likely intermediate. In this reaction, $Sc(OTf)_3$ catalyst effectively promotes initial acetal formation, electrophilic aromatic substitution, and successive intramolecular hydride transfer.

Introduction

The alkylation of an aromatic ring through the Friedel−Crafts reaction is of great synthetic significance in view of laboratory synthesis and particularly industrial production.[1−4] For example, industrial processes for high-octane gasoline, ethylbenzene, synthetic rubber, plastics, and detergent alkylates are based on this reaction. Although such a wide variety of alkylating agents have been used such as alkyl halides, alkenes, alcohols, ethers, and aldehydes, the standard conditions for the Friedel−Crafts alkylation employ an alkyl halide and a Lewis acid catalyst such as aluminum(III) chloride. The conditions, however, coproduce a hydrogen halide which often induces side reactions and induces the production of many byproducts. In addition, disposal of the aluminum hydroxide residue excreted by usual workup causes additional environmental problems. Therefore, a reaction process which does not generate the hydrogen halide byproducts has been the target of extensive research. Furthermore, it has been desirable to use a Lewis acid catalyst resistant to aqueous media.

Because of such salient features as their hard character and their specific coordination numbers, rare earth(III) (RE) salts are expected to be strong Lewis acids. Among these, RE(III) trifluoromethanesulfonates [$RE(OTf)_3$] are assumed to be the strongest due to the least nucleophilic triflate counteranion. In contrast to most of the metal triflates that are usually prepared under strictly anhydrous conditions, $RE(OTf)_3$ are generally prepared in aqueous solution.[5] It has been recently demonstrated that $RE(OTf)_3$ are particularly useful and unique in carbon−carbon bond forming reactions in aqueous media.[6−9] Therefore, $RE(OTf)_3$ have advantages over such conventional Lewis acids as $TiCl_4$, $AlCl_3$, $SnCl_4$, and $BF_3{\cdot}OEt_2$. We disclose here in detail the $Sc(OTf)_3$-catalyzed Friedel−Crafts benzylation and allylation reactions of various aromatic compounds using the corresponding alcohols, aldehydes, and acetals as alkylating agents.[10]

Results and Discussion

$Sc(OTf)_3$-Catalyzed Friedel−Crafts Alkylation Reaction with Benzyl Alcohols. Alcohols are preferable alkylating agents rather than alkyl halides because hydrogen halides are not coproduced. However, the reaction with alcohols requires considerable amounts of $AlCl_3$, since the alcohols and/or *in situ* generated water deactivates the catalyst. Therefore, we paid attention to the characteristics and reactivities of RE(III) com-

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Table 1. REX_3-Catalyzed Friedel–Crafts Benzylation with Benzyl Alcohol[a]

run	REX_3	aromatics	product	yield (%)[b]
1	$YbCl_3$	PhH (**2a**)	**3a**	trace
2	$ScCl_3$			trace
3	$Nd(OTf)_3$			quant
4	$Sm(OTf)_3$			quant
5	$Yb(OTf)_3$			24
6	$Sc(OTf)_3$			91
7	$Y(OTf)_3$			trace
8	$Nd(OTf)_3$	PhMe (**2b**)	**3b**	5[c]
9	$Sm(OTf)_3$			94[c]
10	$Sc(OTf)_3$			quant[c]
11	$Nd(OTf)_3$	*p*-xylene (**2c**)	**3c**	trace
12	$Sm(OTf)_3$			75
13	$Sc(OTf)_3$			quant

[a] Reaction conditions: **1a** (1.0 mmol), aromatic compound **2** (5.0 mL), and RE(III) compound (0.1 mmol), 115–120 °C. [b] GLC yield. [c] Isomer ratio was *o*:*m*:*p* = 48:7:45.

pounds and studied the RE(III)-catalyzed Friedel–Crafts reaction of benzene (**2a**), toluene (**2b**), or *p*-xylene (**2c**) with benzyl alcohol (**1a**) as the alkylating agents (eq 1). The results are summarized in Table 1.

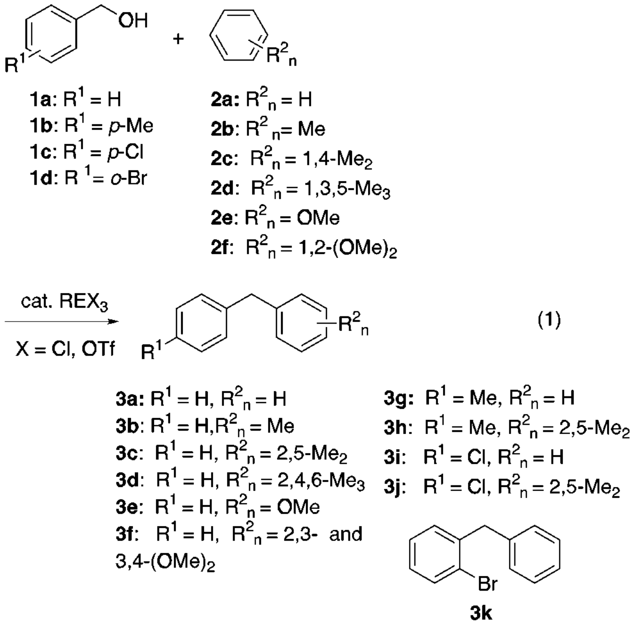

Table 2. $Sc(OTf)_3$-Catalyzed Benzylation Reaction of Aromatic Compounds with Benzyl Alcohol[a]

run	alcohol	aromatic compd	time (h)	product	yield (%)[b]	ratio of *o*:*m*:*p*
1	**1a**	**2a**	6	**3a**	91	
2		**2b**	4	**3b**	quant	48:7:45
3		**2c**	4	**3c**	quant	
4		**2d**	1	**3d**	90[c]	
5		**2d**	1.5	**3d**	quant	
6		**2e**	1	**3e**	87[c]	57:trace:43
7		**2e**	1	**3e**	quant[d]	59:1:40
8		**2f**	4	**3f**	79[c,e]	
9		**2f**	4	**3f**	91[d,e]	
10	**1b**	**2a**	3	**3g**	91	
11		**2c**	2	**3h**	73	
12		**2c**	2.5	**3h**	quant[d]	
13	**1c**	**2a**	3	**3i**	93	
14		**2c**	1	**3j**	quant	
15	**1d**	**2a**	8	**3k**	75	

[a] Reaction conditions: benzyl alcohol (1.0 mmol), an aromatic compound (5.0 mL), and $Sc(OTf)_3$ (0.1 mmol), 115–125 °C. [b] GLC yield. [c] The reaction was carried out with 5.0 molar equiv of the aromatic substrate in 1,2-dichloroethane (5.0 mL) at the reflux temperature. [d] The reaction was carried out with 5.0 molar equiv of the aromatic substrate in nitromethane (5.0 mL) at the reflux temperature. [e] Isomer ratio was approximately 1:1.

Although the recycle of the Friedel–Crafts catalysts is believed to be impractical, Fujiwara *et al.* demonstrated that $RECl_3$ could repeatedly be used for the benzylation of aromatic substrates with a benzylic halide.[11] We first studied the reaction of **2a** with **1a** using $ScCl_3$ and $YbCl_3$ and obtained only a trace amount of diphenylmethane (**3a**), probably due to the weak Lewis acidity of the catalyst (runs 1 and 2). We then used $RE(OTf)_3$ for the reaction of **2a** with **1a** and found $Nd(OTf)_3$, $Sm(OTf)_3$, and $Sc(OTf)_3$ efficiently gave **3a** (runs 3, 4 and 6), whereas the yield of **3a** was lower with $Yb(OTf)_3$ or $Y(OTf)_3$ (runs 3–7). For the reaction of toluene (**2b**) or *p*-xylene (**2c**) with **1a**, $Sc(OTf)_3$ exhibited the highest activity and afforded (methylphenyl)phenylmethane (**3b**) or (dimethylphenyl)phenylmethane (**3c**) in quantitative yields, respectively, without any contamination of byproducts (runs 10 and 13). Olah *et al.* prepared triflates of boron, aluminum, and gallium[12] and applied them to the Friedel–Crafts alkylation using alkyl halides to observe that 50 mol % of the catalyst under strictly anhydrous conditions were necessary because these triflates were extremely moisture sensitive. In contrast, $RE(OTf)_3$ is stable to moisture and easy to be handled. Thus, the $RE(OTf)_3$-catalyzed Friedel–Crafts reaction with benzyl alcohol could be carried out in an aromatic solvent simply distilled without any care. These results prompted us to survey the scope of the $Sc(OTf)_3$-catalyzed benzylation reaction using various benzylic alcohols and aromatic solvents. The results are summarized in Table 2.

The reaction of a substituted benzyl alcohol **1a**, **1b**, **1c**, or **1d** with benzene (**2a**) proceeded smoothly to afford the corresponding diarylmethane **3a**, **3g**, **3i**, or **3k** in high yield (runs 1, 10, 13, or 15).[13] In every case, the reaction was performed using arene in excess. Toluene (**2b**), *p*-xylene (**2c**), or mesitylene (**2d**) also reacted satisfac-

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(8) For selected references on some organic reactions using lanthanide(III) triflate, see: (a) Kobayashi, S.; Hachiya, I.; Takahori, T.; Araki, M.; Ishitani, H. *Tetrahedron Lett.* **1992**, *33*, 6815. (b) Inanaga, J.; Yokoyama, Y.; Hanamoto, T. *Tetrahedron Lett.* **1993**, *34*, 2791. (c) Kobayashi, S.; Hachiya, H.; Ishitani, H.; Araki, M. *Tetrahedron Lett.* **1993**, *34*, 4535. (d) Fukuzawa, S.; Tsuchimoto, T.; Kanai, T. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 2227. (e) Kobayashi, S.; Ishitani, H. *J. Am. Chem. Soc.* **1994**, *116*, 4083. (f) Meguro, M; Asao, N.; Yamamoto, Y. *J. Chem. Soc., Perkin Trans. 1* **1994**, 2597. (g) Meguro, M.; Asao, N.; Yamamoto, Y. *J. Chem. Soc., Chem. Commun.* **1995**, 1021. (h) Kobayashi, S.; Araki, M.; Ishitani, H.; Nagayama, S.; Hachiya, I. *Synlett* **1995**, 233. (i) Kobayashi, S.; Moriwaki, M.; Hachiya, I. *Synlett* **1995**, 1153. (j) Kobayashi, S.; Ishitani, H.; Nagayama, S. *Synthesis* **1995**, 1195. (k) Ishihara, K.; Kubota, M.; Kurihara, H.; Yamamoto, H. *J. Am. Chem. Soc.* **1995**, *117*, 4413. (l) Kobayashi, S.; Ishitani, H.; Nagayama, S. *Chem. Lett.* **1995**, 423. (m) Kobayashi, S.; Araki, M.; Yasuda, M. *Tetrahedron Lett.* **1995**, *36*, 5773. (n) Ishihara, K.; Karumi, Y.; Kubota, M.; Yamamoto, H. *Synlett* **1996**, 839. (o) Hanamoto, T.; Sugimoto, Y.; Yokoyama, Y.; Inanaga, J. *J. Org. Chem.* **1996**, *61*, 4491. (p) Kobayashi, S.; Ishitani, H.; Komiyama, S.; Oniciu, D. C.; Katritzky, A. R. *Tetrahedron Lett.* **1996**, *37*, 3731. (q) El Gihani, M. T.; Heaney, H.; Shuhaibar, K. F. *Synlett*, **1996**, 871.

(9) $Sc(OTf)_3$ is also applicable to the combinatorial synthesis; see: Kobayashi, S.; Moriwaki, M.; Akiyama, R.; Suzuki, S.; Hachiya, I. *Tetrahedron Lett.* **1996**, *37*, 7783.

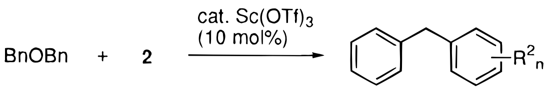
(10) Preliminary reports on the Friedel–Crafts alkylation reaction using $Sc(OTf)_3$ as the catalyst: (a) Tsuchimoto, T.; Tobita, K.; Hiyama, T.; Fukuzawa, S. *Synlett* **1996**, 557. (b) Tsuchimoto, T.; Hiyama, T.; Fukuzawa, S. *Chem. Commun.* **1996**, 2345.

(11) Mine, N.; Fujiwara, Y.; Taniguchi, H. *Chem Lett.* **1986**, 357.

(12) Olah, G. A.; Farooq, O.; Farnia, S. M. F.; Olah, J. A. *J. Am. Chem. Soc.* **1988**, *110*, 2560.

(13) The acylation reaction of benzene or toluene with acid chlorides or anhydrides using $RE(OTf)_3$ as a catalyst scarcely takes place. (a) Kawada, A.; Mitamura, S.; Kobayashi, S. *J. Chem. Soc., Chem. Commun.* **1993**, 1157; **1996**, 183; *Synlett* **1994**, 545. (b) Kobayashi, S.; Moriwaki, M.; Hachiya, I. *Bull Chem. Soc. Jpn.* **1997**, *70*, 267.

torily with **1a** (runs 2−5, 11, 12, and 14). For the reaction of high boiling point aromatics like **2d**, anisole (**2e**), and 1,2-dimethoxybenzene (**2f**), the reaction was conveniently carried out with 5 molar equiv of the substrate relative to **1a** in 1,2-dichloroethane or in nitromethane as the solvent (runs 4−9). It is noteworthy that the reaction in nitromethane proceeded quantitatively (runs 5, 7, 9, and 12). The reaction in dichloromethane or carbon disulfide at the reflux temperature gave only a trace amount of the benzylation product. An electron-donating group on aromatic substrates somewhat enhanced the benzylation reaction. The isomer distributions starting with substituted arenes were *ortho*−*para* preference in accord with the typical electrophilic aromatic substitution (runs 2, 6, and 7). These observations are consistent with those obtained with $AlCl_3$−CH_3NO_2 or $TiCl_4$ catalyst.[14] By contrast, neither of 4-nitro-, 4-methoxy-, or 4-hydroxy(phenylmethanol) underwent the reaction under the similar conditions. These functional groups might have formed complexes with $Sc(OTf)_3$ to interrupt the reaction. Formation of dibenzyl ether (**4**), dehydration products of **1**, was observed at the early stage of the reaction but was negligible at the end of the reaction.[15] Indeed, **4** was shown to react with **2a** or **2c** to furnish **3a** or **3c** in 39% or 43% yield, respectively, under the same reaction conditions (eq 2).



(2)

4

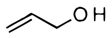
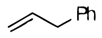
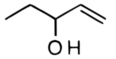
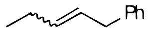
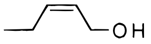
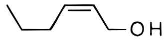
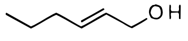
3a: 39% yield
3c: 43% yield

In some cases dibenzylated products were formed by the subsequent reaction of the benzylation products in small amount. With 1-phenylethanol as the alkylating agent, styrene was detected as a major product along with several unidentified products. The reaction of benzene with benzhydrol afforded triphenylmethane in 66% yield.

The present method is also applicable to the preparative-scale synthesis using benzyl alcohol (20 mmol), benzene (100 mL), and $Sc(OTf)_3$ (2.0 mmol) at 115 °C for 8 h. **3a** was isolated in 81% yield after distillation at 97 °C/3.0 mmHg.

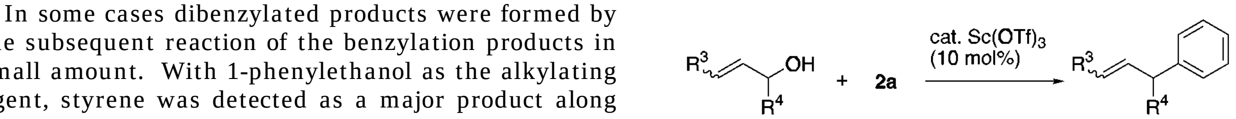
$Sc(OTf)_3$-Catalyzed Friedel−Crafts Alkylation Reaction with Allylic Alcohols. Vanillin, a vivid fragrance material isolated from vanilla fruits in the orchid family, is prepared from eugenol in an industrial process. Eugenol, in turn, is prepared by allylation of guaiacol. Thus, the Friedel−Crafts allylation reaction of aromatic compounds is straightforward tool for the synthesis of allylbenzene derivatives. It is well-known that a metal halide Lewis acid catalyst such as $AlCl_3$ exclusively induces the allylic substitution by aromatics.[2] However, HCl generated by the reaction of $AlCl_3$ and an allylic alcohol or H_2O brings about various side reactions as well as the addition to the double bond. Thus, the yields of the allylated products are generally low. The protocol is also applicable to the allylation reactions of aromatic compounds with allylic alcohols **5** as the alkylating agents.

Table 3. Friedel−Crafts Allylation Reaction of Benzene with Allyl Alcohol[a]

run	allyl alcohol (**5**)	time/h	product (**6**)	yield/%[b] (*trans* : *cis*)[c]
1	 **5a**	8	 **6a**	48
2	 **5b**	4	 **6b**	64 (94 : 6)
3	 **5c**	3	**6b**	68 (73 : 27)
4	 **5d**	2	 **6c**	91 (69 : 31)
5	 **5e**	1.5	**6c**	95[d] (98 : 2)

[a] Reaction conditions: **5** (1.0 mmol), **2a** (5.0 mL), and $Sc(OTf)_3$ (0.1 mmol), 115−120 °C. [b] GLC yield. [c] Isomer ratios were determined by GLC. [d] **6c** was isolated in 81% yield after chromatography.

As outlined in Table 3, the Friedel−Crafts allylation reaction of **2** with allylic alcohol **5** using $Sc(OTf)_3$ as a catalyst proceeded successfully to afford the corresponding allylbenzene derivatives **6** in good to excellent yields without any troublesome side reactions (eq 3), However, the reaction of benzene with 2-cyclohexen-1-ol did not produce the allylation product under the reaction conditions. As expected, the reactions occurred always at the less-substituted allylic carbon. Worthy of note is that no rearrangement of the position of the double bond took place under the reaction conditions. It should be noted that the reaction of 1-penten-3-ol (**5b**) or 2-penten-1-ol (**5c**) with benzene led to the same product **6b** with a slightly different product ratio (runs 2 and 3). These results suggest that the same alkylation products are produced irrespective of the starting regioisomeric allylic alcohols. Similarly, both *cis*- and *trans*-2-hexenol (**5d** and **5e**) with benzene preferentially gave the *trans*-2-hexenylbenzene (**6c**) in excellent yields, although the *trans*/*cis* ratio was slightly dependent on the structure of the starting allyl alcohol (runs 4 and 5). The stereochemistry of **6** derived from monosubstituted allylic alcohols and **2a** was proved to be time-independent. Thus, the reaction should proceed under kinetic control. Namely, no equilibrium between the *cis* and *trans* isomers is taking place under the reaction conditions.



(3)

5 **6**

Recovery and Reuse of $Sc(OTf)_3$. Evaporation of the aqueous layer of the reaction mixture allowed $Sc(OTf)_3$ to be recovered as a white powder, which was further dried by heating *in vacuo* at 180 °C and was employed for the same reaction. **3a** was obtained in 89% yield in the second run, 84% yield in the third run.

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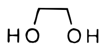
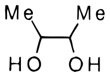
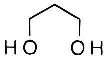
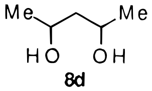
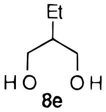
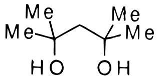
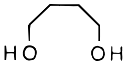
(14) The isomer distributions of **3** were determined by ^{13}C NMR spectra or GC analysis by comparing with those of the authentic samples which were prepared by the reaction of the aromatics with the corresponding benzyl halides using $TiCl_4$ or $AlCl_3$−$MeNO_3$. (a) Olah, G. A.; Kobayashi, S.; Tashiro, M. *J. Am. Chem. Soc.* **1972**, *94*, 7448. (b) Olah, G. A.; Olah, J. A. *J. Am. Chem. Soc.* **1984**, *106*, 5248.

(15) Solid superacid-catalyzed benzylation reaction induces the formation of the dehydration products as a byproduct. Yamamoto, T.; Hideshima, C.; Prakash, G. K. S.; Olah, G. A. *J. Org. Chem.* **1991**, *56*, 2089.

Table 4. $Sc(OTf)_3$-Catalyzed Friedel–Crafts Benzylation Reaction of Benzene with Benzaldehyde in the Presence of Various Alcohols[a]

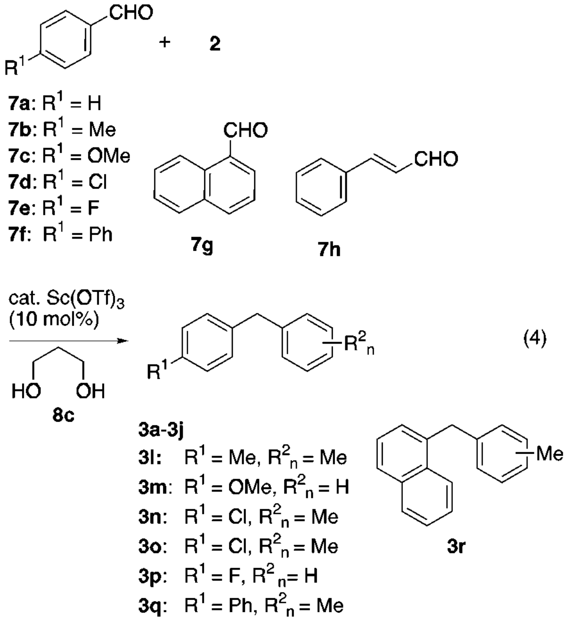
run	alcohol (**8**)	reaction conditions	yield/% of **3a**[b]
1	 **8a**	rt, 2 d	–[c]
2	**8a**	reflux, 10 h	–[c]
3	 **8b**	reflux, 10 h	–[c]
4	 **8c**	reflux, 10 h	70
5	 **8d**	reflux, 10 h	20
6	 **8e**	reflux, 10 h	68
7	 **8f**	reflux, 10 h	–[d]
8	 **8g**	reflux, 10 h	4
9	MeOH[e] **8h**	reflux, 10 h	n r
10	*i*-PrOH[e] **8i**	reflux, 10 h	23
11	*n*-BuOH[e] **8j**	reflux, 10 h	n r

[a] The reaction was carried out with benzaldehyde (1.0 mmol), diol (1.1 mmol), benzene (5.0 mL), and $Sc(OTf)_3$ (0.1 mmol). [b] GLC yield. [c] The corresponding acetals were obtained: run 1 (54% yield), run 2 (72% yield), run 3 (94% yield). [d] Complex mixture. [e] 2.2 molar equiv of alcohol to benzaldehyde were used.

Similar recovery and reuse of $RE(OTf)_3$ catalyst is reported by Kobayashi *et al.* who demonstrated that $RE(OTf)_3$ recovered from the aqueous layer after the Friedel–Crafts reaction could be reused for the same reaction.[5,6] That $Sc(OTf)_3$ is reusable is the striking feature; nevertheless scandium is uncommon and expensive. Thus, the $Sc(OTf)_3$-catalyzed organic reactions should find wide applications in industrial processes.

$Sc(OTf)_3$-Catalyzed Friedel–Crafts Alkylation Reaction with Arenecarbaldehydes in the Presence of 1,3-Propanediol. Less attention has been focused on the acid-catalyzed condensation reaction of aromatic compounds **2** with arenecarbaldehydes **7** because of the formation of many products such as triarylmethane, triarylmethanol, diarylmethane, and anthracene derivatives,[16] although the prototype has been recognized since 1886.[17] Recently, the mechanism of this reaction has been investigated independently by Shudo[18] and Olah,[19] and the product distribution proved to be dependent on the reaction conditions: triphenylmethane was exclusively produced at ambient temperature when a large excess amount of TfOH (100 equiv to benzaldehyde) was used as the acid catalyst. However, this type of the Friedel–Crafts reaction has eluded synthetic interest due to the inevitable use of a large excess amount of TfOH and formation of a complex mixture of the products. Recently, gallium dichloride was reported to promote the reductive Friedel–Crafts reaction of both aliphatic and aromatic carbonyl compounds, but here again the use of gallium dichloride in excess was essential.[20] Thus, the catalytic and practical Friedel–Crafts-type alkylation reaction using arenecarbaldehydes **7** has remained yet to be explored.[21]

During the course of our investigation of the Friedel–Crafts alkylation reaction using $Sc(OTf)_3$,[9a] we found that arenecarbaldehyde **7**, upon treatment with 1,3-propanediol (**8c**) and a catalytic quantity of $Sc(OTf)_3$, cleanly underwent an unprecedented reductive Friedel–Crafts benzylation with an aromatic compound (eq 4).[9b] Details are discussed herein of the $Sc(OTf)_3$-catalyzed reductive Friedel–Crafts reaction using an arenecarbaldehyde **7** as the electrophile. We also refer to the mechanism of the reaction.



To begin with, we examined the efficacy of an alcohol in the reaction of **2a** with benzaldehyde (**7a**) in the presence of $Sc(OTf)_3$ as a catalyst. The results are summarized in Table 4. When a solution of **7a** (1.0 mmol) and **8c** (1.1 mmol) in **2a** (5.0 mL) was heated to reflux for 10 h in the presence of a catalytic amount of $Sc(OTf)_3$, diphenylmethane (**3a**) was obtained in good yields. It is worth noting that the benzylation reaction took place by a redox process, and none of triphenylmethane, triphen-

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[16] Roberts, R. M.; EI-Khawaga, A. M.; Sweeney, K. M.; EI-Zohry, M. F. *J. Org. Chem.* **1987**, *52*, 1959 and references cited therein.

[17] Griepentrog, H. *Ber. Dtsch. Chem. Ges.* **1886**, *19*, 1876.

[18] Saito, S.; Ohwada, T.; Shudo, K. *J. Am. Chem. Soc.* **1995**, *117*, 11081.

[19] Olah, G. A.; Rasul, G.; York, C.; Prakash, G. K. S. *J. Am. Chem. Soc.* **1995**, *117*, 11211 and references cited therein.

[20] (a) Hashimoto, Y.; Hirata, K.; Kihara, N.; Hasegawa, M.; Saigo, K. *Tetrahedron Lett.* **1992**, *33*, 6351. (b) Hashimoto, Y.; Hirata, K.; Kagoshima, H.; Kihara, N.; Hasegawa, M.; Saigo, K. *Tetrahedron* **1993**, *49*, 5969.

[21] Climent, M. J.; Corma, A.; Garceía, H.; Primo, J. *J. Catal.* **1991**, *130*, 138.

Table 5. Effect of Lewis Acid Catalyst for the Friedel−Crafts Benzylation Reaction[a]

run	Lewis acid	yield (%) of **3b**[b]	run	Lewis acid	yield (%) of **3b**[b]
1	ZnCl$_2$	0	8	Sc(OTf)$_3$	98
2	AlCl$_3$	2	9	Sc(OTf)$_3$	70[c]
3	SnCl$_4$	97	10	Nd(OTf)$_3$	0
4	SnCl$_4$	2[c]	11	Y(OTf)$_3$	0
5	TiCl$_4$	0	12	Sm(OTf)$_3$	0
6	BF$_3$·OEt$_2$	0	13	Yb(OTf)$_3$	0
7	ScCl$_3$	0	14	TfOH	96

[a] The reaction was carried out with **7a** (1.0 mmol), Lewis acid (0.1 mmol), and **2b** (5.0 mL) at reflux temperature. [b] GLC yield. [c] **2a** instead of **2b** was used.

Table 6. Sc(OTf)$_3$-Catalyzed Reductive Friedel−Crafts Reaction of Arenes with Arenecarbaldehyde and 1,3-Propanediol[a]

run	aldehyde	aromatic compd	time (h)	product	yield (%)[b]	ratio of *o*:*m*:*p*
1	**7a**	**2a**	10	**3a**	70	
2		**2b**	10	**3b**	97	42:7:51
3		**2c**	10	**3c**	96	
4		**2e**	10	**3e**	36[c]	49:trace:51
5		**2e**	10	**3e**	37[d]	45:trace:55
6		**2e**	10	**3e**	nr[e]	
7	**7b**	**2a**	8.5	**3g**	64	
8		**2b**	6	**3l**	quant	34:4:62
9		**2c**	8	**3h**	73	
10	**7c**	**2a**	10	**3m**	trace	
11		**2b**	16	**3n**	30	37:3:60
12	**7d**	**2a**	17.5	**3i**	91	
13		**2b**	16	**3o**	89	41:9:50
14		**2c**	17	**3j**	quant	
15	**7e**	**2a**	20	**3p**	75	
16	**7f**	**2b**	16	**3q**	quant	34:5:61
17	**7g**	**2b**	10	**3r**	68	25:5:75
18	**7h**	**2a**	6	−[f]		

[a] The reaction was carried out with **7** (1.0 mmol), 1,3-propanediol (1.1 mmol), **2** (5.0 mL), and Sc(OTf)$_3$ (0.1 mmol) at 125 °C. [b] GLC yield. [c] The reaction was carried out with 5.0 molar equiv of anisole in nitromethane (5.0 mL) at the reflux temperature. [d] The reaction was carried out with 5.0 molar equiv of anisole in 1,2-dichloroethane (5.0 mL) at the reflux temperature. [e] The reaction was carried out with 5.0 molar equiv of anisole in chloroform (5.0 mL) at the reflux temperature. [f] Complex mixture.

ylmethanol, or anthracene was produced, in sharp contrast to the original Friedel−Crafts reactions. As summarized in Table 4, the yield of **3a** depended greatly upon the structure of the alcohol. The benzylation reaction did not take place at room temperature or at reflux conditions when a 1,2-diol such as 2,3-butanediol (**8a**) or 1,2-ethanediol (**8b**) was used; the corresponding 1,3-dioxolanes were formed in moderate to high yields (runs 1−3). The benzylation reaction of **2a** using **8c** in the presence of Sc(OTf)$_3$ at reflux temperature gave **3a** in 70% yield without any troublesome side reactions (run 4). Worthy of note is that the reaction with the same reagent system at ambient temperatures furnished 2-phenyl-1,3-dioxane in 93% yield instead of **3a**.[22] Accordingly, the reaction pathway to an acetal or a diarylmethane can be readily controlled by an appropriate choice of the reaction temperature with the same substrates. With 2-ethly-1,3-propanediol (**8e**), **3a** was again obtained in 68% yield (run 6), but with a low yield of the products formed in the reaction with 2,4-pentanediol (**8d**) or 1,4-butanediol (**8g**) (runs 5 and 8). The reaction with 2,4-dimethyl-2,4-pentanediol (**8f**) resulted in a complex mixture of products (run 7). With methanol (**8h**), 2-propanol (**8i**), or 1-butanol (**8j**), no product or only a small amount of the product formed, with **7a** being recovered (runs 9−11). After screening various alcohols, we concluded that **8c** was the coreagent of choice to accomplish the Friedel−Crafts benzylation reaction. In the absence of **8c**, no reaction took place. Thus, the use of **8c** in this reaction is essential.

The catalytic activity of several Lewis acid catalysts for the Friedel−Crafts reaction of toluene (**2b**) with **7a** in the presence of **8c** was examined. The results are summarized in Table 5. All reactions were carried out at reflux temperature of **2b**. Conventional Lewis acids like ZnCl$_2$, AlCl$_3$, TiCl$_4$, and BF$_3$·OEt$_2$ were totally inactive except for SnCl$_4$ (runs 1−3, 5, and 6). Although SnCl$_4$ effectively catalyzed benzylation of **2b** with **7a**, the reaction of **2a** with **7a** using SnCl$_4$ as the catalyst resulted in the formation of a trace amount of **3a** (run 4). The reaction was next performed using rare earth(III) compounds as the catalyst. Sc(OTf)$_3$ was found to be a quite efficient catalyst for the reaction of **2b** with **7a** to afford (methylphenyl)phenylmethane (**3b**) in a quantitative yield (run 8), whereas other rare earth(III) compounds exhibited no catalytic activity. Sc(OTf)$_3$ was also effective for the reaction of **2a** with **7a** (run 9). Brønsted acid like TfOH also catalyzed the Friedel−Crafts reaction effectively (run 14); the details of the results are already reported.[23] On the basis of these results, we concluded that Sc(OTf)$_3$ was the promising catalyst to achieve the Friedel−Crafts reaction of aromatics with arenecarbaldehydes.

These results prompted us to survey the scope of the reaction. The results are summarized in Table 6. Aromatic compounds except anisole (**2e**) were utilized not only as the substrate but also as the reaction medium. With **7a** as the benzylation reagent, the Friedel−Crafts products were produced in yields ranging from 37 to 97% (runs 1−3 and 5). The yields of the alkylation products were generally improved by use of **2b** or **2c**. However, the reaction of **2e** resulted in lower yields of the desired product due probably to side reactions, although the starting substrate was completely consumed. The side reactions were suppressed to some extent by the use of 1,2-dichloroethane or nitromethane as the solvent (runs 4 and 5). The reaction of **2e** in chloroform resulted in no reaction due to its lower boiling point (run 6). When the protocol was applied to the reaction of aldehyde **7b**, **7c**, **7d**, **7e**, or **7f**, bearing an electron-donating or -withdrawing group at *para* position, high to quantitative yields of the corresponding diarylmethane were obtained with **2a**, **2b**, or **2c**. Similarly, 1-naphthyl aldehyde (**7g**) reacted with **2b** to afford a regioisomeric mixture of 1-naphthylmethylated toluenes (**3r**) in 68% yield (run 17). However, treating pyridine-2-carbaldehyde with **2a** under the reaction condition afforded the corresponding 1,3-dioxane derivative in a high yield instead of the diarylmethane. Presumably, nitrogen within the pyridine ring might have brought about the complexation with Sc(OTf)$_3$ to prevent further activation of the acetal ring. The positional selectivity of the benzylation of substituted arenes was the *ortho-para* preference in conformity with that observed in the usual Lewis acid-catalyzed Friedel−Crafts reaction using benzyl halide or benzyl alcohol.[14] The reaction rate significantly increased with the stron-

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(22) Fukuzawa, S.; Tsuchimoto, T.; Hotaka, T.; Hiyama, T. *Synlett* **1995**, 1077.

(23) Fukuzawa, S.; Tsuchimoto, T.; Hiyama, T. *J. Org. Chem.* **1997**, *62*, 151.

Table 7. $Sc(OTf)_3$-Catalyzed Reductive Friedel−Crafts Reaction of Arenes with Arenecarbaldehyde Acetals

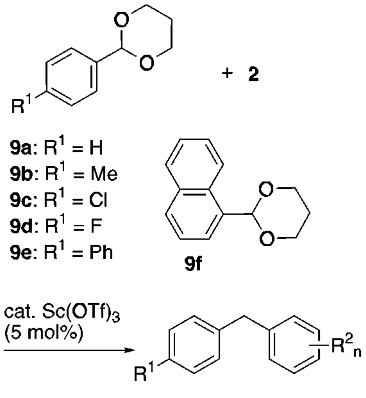
run	aldehyde	aromatic compd	time (h)	product	yield (%)[b]	ratio of *o*:*m*:*p*
1	**9a**	**2a**	22	**3a**	64	
2		**2b**	10	**3b**	quant	40:7:53
3		**2c**	10	**3c**	78	
4		**2d**	10	**3d**	68[c]	
5	**9b**	**2a**	9	**3g**	78	
6		**2b**	7	**3l**	99	33:4:63
7		**2c**	8	**3h**	95	
8	**9c**	**2a**	18	**3i**	51	
9		**2b**	17	**3o**	89	
10		**2c**	20	**3j**	82	
11	**9d**	**2a**	20	**3p**	86	
12	**9e**	**2b**	17	**3q**	quant	36:5:59
13	**9f**	**2b**	15	**3r**	78	24:7:69

[a] The reaction was carried out with **9** (1.0 mmol), **2** (5.0 mL), and $Sc(OTf)_3$ (0.05 mmol) at 125 °C. [b] GLC yield. [c] The reaction was carried out with 5.0 molar equiv of mesitylene in 1,2-dichloroethane (5.0 mL) at the reflux temperature.

ger electron-releasing ability of the substituent.[24] This observation was also consistent with the typical electrophilic aromatic substitution.

$Sc(OTf)_3$-catalyzed Friedel−Crafts Alkylation Reaction with Arenecarbaldehyde Acetals. Since acetalization reaction easily takes place in the presence of a Lewis acid catalyst, the acetals derived from arenecarbaldehydes **7** and **8c** appears to be the crucial intermediate of the present benzylation reaction. If this hypothesis is correct, the reductive Friedel−Crafts benzylation reaction should be possible starting with arenecarbaldehyde acetals **9**.

Actually, $Sc(OTf)_3$-catalyzed benzylation reaction of **2a** using 2-phenyl-1,3-dioxane (**9a**) (eq 5) cleanly proceeded to furnish **3a** in a yield comparable to that of the one-pot reaction (run 1, Table 7). Thus, the first stage of the reaction may be the $Sc(OTf)_3$-catalyzed acetalization of arenecarbaldehyde **7**. Indeed, the acetal formation was confirmed by the reaction of **7a** with **8c** at ambient temperature. Table 7 summarizes the reaction of various **9** with **2** in the presence of $Sc(OTf)_3$ as a catalyst. As readily seen, each reaction gave the corresponding **3** in good to quantitative yields. The isomer ratios and the chemical yields of **3** were virtually the same as those observed in the reaction starting with a mixture of **7** and **8c**.



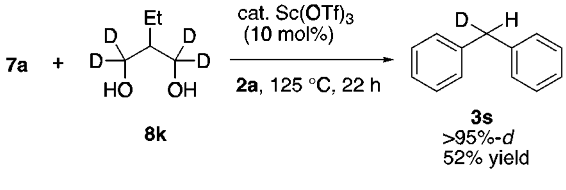
3 (5)

Reaction Mechanism

For the mechanism of this type of the Friedel−Crafts benzylation, Olah and Shudo proposed that diprotonated benzaldehyde was involved and behave as a highly reactive electrophilic intermediate.[18,19] Although Lewis acid generally activates the carbonyl function to afford an electrophilic species reactive to nucleophiles, complexation of $Sc(OTf)_3$ with arenecarbaldehyde appears to give a weak electrophile rather than the diprotonated species, and thus its reactivity toward benzene (**2a**) should remain at a low level. Since no reaction took place in the absence of 1,3-propanediol and no triarylmethane, triarylmethanol, or anthracene was isolated, the reaction appears to proceed through a process completely different from the original Friedel−Crafts reactions: a possible reaction pathway should be a redox process if one considers the formation of diarylmethanes. Without the redox process, the expected products must be triphenylmethane and/or diphenylmethyl ether. From a mechanistic viewpoint, we decided to confirm the redox reaction and to demonstrate what was the hydride source. We finally have disclosed the 1,3-propanediol (**8c**) was the hydride source and propose a reaction mechanism as summarized in Scheme 1.

The acetal formation easily takes place in the presence of a catalytic amount of $Sc(OTf)_3$ in an early stage of the reaction. $Sc(OTf)_3$ coordinates to the oxygen atom of the acetal ring and then activates the acetal carbon even in the presence of water. The activated acetal carbon undergoes electrophilic aromatic substitution by an aromatic compound followed by a ring scission of acetal and then produces diphenylmethyl ether **11** as a key intermediate. $Sc(OTf)_3$ further coordinates the ethereal oxygen of **11** and activates the benzylic carbon. The ethereal bond of **11** successively is cleaved with simultaneous 1,3- or 1,5-hydride migration to furnish **3** and 3-hydroxypropanal (**14**).[25,26]

To obtain further insight into the reaction mechanism, we heated a benzene solution of a mixture of benzaldehyde (**7a**), 1,3-propanediol-*1,1,3,3*-d_4 (**8k**), and $Sc(OTf)_3$ and were pleased to observe that deuterium was incorporated into the benzylic carbon of over 95% of the diphenylmethane (**3s**) (eq 6). That the reaction with 2,4-dimethyl-2,4-pentanediol (**8f**) instead of 1,3-propanediol (**8c**) afforded a complex mixture of products is another evidence for the hydride shift mechanism (run 7 in Table 4).



(6)

Diphenylmethyl ether **11** was separately prepared and subjected to the reaction with **2a** under the Friedel−

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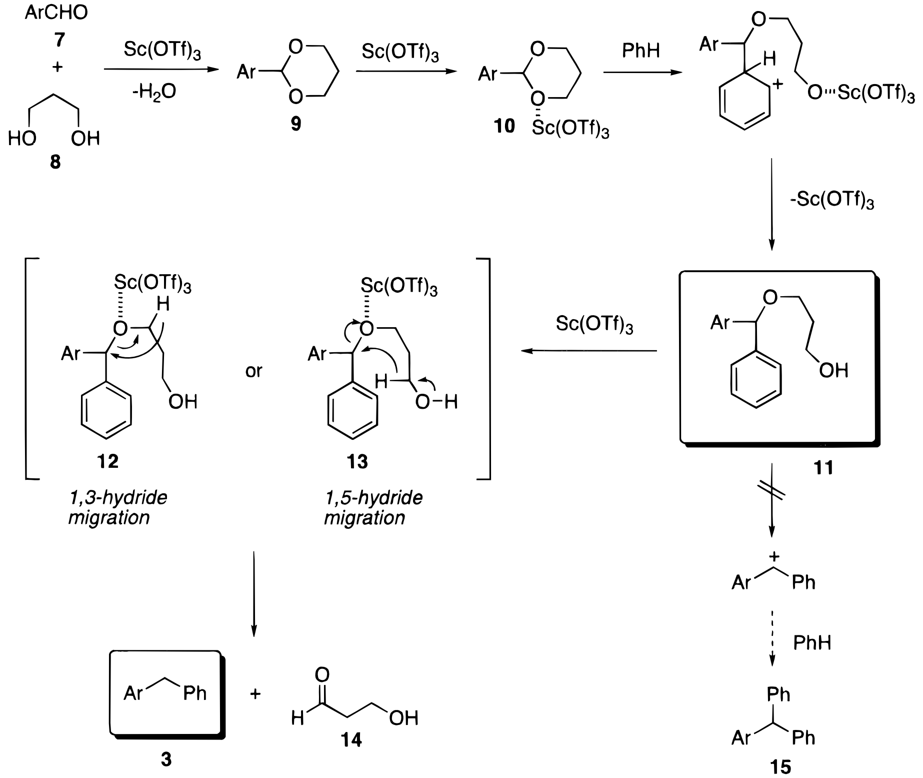
[24] (a) DeHaan, F. P.; Delker, G. L.; Covey, W. D.; Ahn, J.; Anksman, M. S.; Brehm, E. C.; Chang, J.; Chicz, R. M.; Cowan, R. L.; Ferrara, D. M.; Fong, C. H.; Harper, J. D.; Irani, C. D.; Kim, J. Y.; Meinhold, R. W.; Miller, K. D.; Roberts, M. P.; Stoler, E. M.; Suh, Y. J.; Tang, M.; Williams, E. L. *J. Am. Chem. Soc.* **1984**, *106*, 7038. (b) DeHaan, F. P.; Chan, W. H.; Chang, J.; Cheng, T. B.; Chiriboga, D. A.; Irving, M. M.; Kaufman, C. R.; Kim, G. Y.; Kumar, A.; Na, J.; Nguyen, T. T.; Nguyen, D. T.; Patel, B. R.; Sarin, N. P.; Tidwell, J. H. *J. Am. Chem. Soc.* **1990**, *112*, 356.

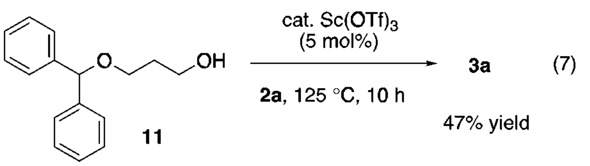
[25] The hydride ion transfer from alkoxy carbon of tetrahydrofuran, 1,3-dioxolane, and 1,3-dioxepane to a trityl cation has been reported. Din, K-u.; Plesch, P. H. *J. Chem. Soc., Perkin Trans. 2* **1987**, 937.

[26] Oxidation product of alkyl group could not be detected because it may undergo a condensation reaction to form polymeric products.

Scheme 1

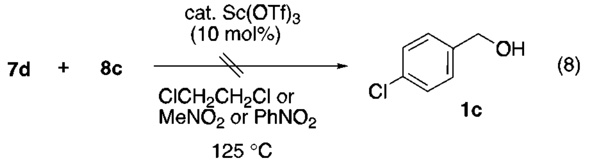


Crafts conditions (eq 7). Here again **3a** was produced in



52% yield without contamination of triphenylmethane **15**. This observation suggests that **11** is a plausible intermediate for the hydride shift process.[27] The driving force of the hydride shift should be the coordination of Sc(OTf)$_3$ to the ethereal oxygen of **11**, because **11** was recovered in the absence of Sc(OTf)$_3$. Furthermore, treatment of $Ph_2CHOCH_2CH_2CH_3$ with a catalytic amount of Sc(OTf)$_3$ similarly afforded **3a** in 48% yield under the Friedel–Crafts conditions, and the terminal hydroxyl group appears not to be essential for the hydride shift process. For the hydride shift, two routes are possible as depicted in Scheme 1. At present, the 1,3-hydride shift pathway is probable because of the experimental evidence.

The remaining possible pathway is the Friedel–Crafts reaction of benzyl alcohol **1** which may be produced *via* a bimolecular redox process between arenecarbaldehyde **7** and 1,3-propanediol (**8c**) through the Meerwein–Ponndorf–Verley reaction. The *in situ* formation of the benzyl alcohol, however, is not likely because no 4-chlorobenzyl alcohol (**1c**) was isolated in the reaction of 4-chlorobenzaldehyde (**7d**) in a 1,2-dichloroethane, nitromethane, or nitrobenzene solvent under the Friedel–Crafts conditions (eq 8).



All experiments discussed above suggest a mechanism in which the hydride source is the acetal moiety and diphenylmethyl ether **11** is the most likely intermediate. It should be noted that the reductive Friedel–Crafts reaction involves initial acetal formation, carbon–carbon bond formation, and subsequent intramolecular hydride transfer. Each step is achieved effectively by the use of a catalytic amount of Sc(OTf)$_3$.

Conclusion

We described here the Sc(OTf)$_3$-catalyzed Friedel–Crafts benzylation and allylation reaction with alcohols, arenecarbaldehyde, or arenecarbaldehyde acetals as the alkylating agent. The presently disclosed methods appear to be more practical and useful as compared with the previously reported ones in view of the following points.

(1) Friedel–Crafts reactions with alcohols as the alkylating agents are usually carried out under strictly anhydrous conditions using considerably large quantities of the Lewis acid catalyst. The presence of a small amount of water lowers the yields drastically, because the catalyst is rapidly decomposed or deactivated by the moisture. On the other hand, the reaction by use of a catalytic amount of Sc(OTf)$_3$ allows us to use an alcohol as the alkylating agent. This reaction also can be performed in an undried solvent without any special care. Although the reductive Friedel–Crafts reaction with an arenecarbaldehyde as an alkylating agent in the presence of a diol involves the formation of H_2O at an early stage of the reaction, a catalytic amount of Sc(OTf)$_3$ is enough to complete the reaction.

(2) The recovered Sc(OTf)$_3$ was shown to retain its catalytic activity of benzylation of benzene with benzyl

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[27] Effenberger, F.; Günther, G.; Bäuerle, P. *Chem. Ber.* **1992**, *125*, 941.

alcohol. $Sc(OTf)_3$ can be repeatedly employed, and diphenylmethane was obtained uniformly in high yields: 91% yield in the first run, 89% yield in the second run, 84% yield in the third run, respectively.

(3) We found that $Sc(OTf)_3$ catalyzed the reductive Friedel−Crafts reaction using an arenecarbaldehyde acetal as the alkylating agent. This reaction is concluded to proceed through a redox process involving a hydride shift from the glycoholic moiety to the benzylic carbon.

(4) In almost all cases, the reactions proceed smoothly to furnish the corresponding alkylation products in excellent to quantitative yields using a catalytic amount of $Sc(OTf)_3$.

RE(OTf)₃ is an ideal and promising catalyst to solve troublesome environmental problems caused by the Lewis acid-promoted reactions used for industrial processes.

Experimental Section

General. ^1H and ^{13}C NMR spectra were recorded in $CDCl_3$, and the chemical shifts are reported in δ units downfield from Me_4Si as an internal standard. Gas chromatography analyses were carried out using a capillary column (DB-5-30N-STD, J&W Scientific, 0.25 mm, 30 m) and helium as the carrier gas. Elemental analyses were carried out at the Elemental Analysis Center, Tokyo Institute of Technology. For thin layer chromatographic (TLC) analyses throughout this work, Merck precoated TLC plates (silica gel 60 PF_{254}, 0.25 mm) were used. Silica gel column chromatography was performed using Merck Kieselgel 60 (70−230 mesh). Flash column chromatography was performed using Merck Kiesegel 60 (230−400 mesh).

Materials. $Sc(OTf)_3$ was purchased from Aldrich Chemical Inc. and used without purification. $Y(OTf)_3$, $Nd(OTf)_3$, $Sm(OTf)_3$, and $Yb(OTf)_3$ were prepared from the corresponding RE_2O_3 (Nippon Yttrium Co., Ltd., 99.9%) and TfOH (Central Glass Co., Ltd.) in water according to the literature procedure;[5] the resulting hydrates were dried by heating under vacuum at 200 °C for 48 h. Benzene, toluene, *p*-xylene, mesitylene, and anisole were distilled under an argon atmosphere from sodium/benzophenone ketyl right before use. 1,2-Dichloroethane, chloroform, nitromethane, and dichloromethane were distilled under an argon atmosphere from calcium hydride right before use. All of the aldehydes and alcohols are commercially available and purified by distillation under reduced pressure before use. Authentic samples of substituted diarylmethanes for the GC/MS analyses were prepared by the Lewis acid-catalyzed Friedel−Crafts benzylation of the substituted benzyl chloride or benzyl bromide with arenes.[14]

$Sc(OTf)_3$-Catalyzed Benzylation Reaction of Benzyl Alcohol with Arenes in the Presence of 1,3-Propanediol. A Typical Experimental Procedure. A 50-mL two-necked round-bottomed flask, fitted with a reflux condenser, was charged with $Sc(OTf)_3$ (0.050 g, 0.1 mmol) and **2a** (5.0 mL). To this suspension of $Sc(OTf)_3$ was added **1a** (0.108 g, 1.0 mmol) at ambient temperature. The mixture was vigorously stirred at the reflux temperature for 6 h, treated with H_2O (2 mL), and extracted with diethyl ether (10 mL) three times. The combined extracts were dried over $MgSO_4$. GC/MS analysis exhibited the presence of **3a**, compared with authentic sample. The yield of **3a** was estimated to be 91% using naphthalene as an internal standard.[14] Most of the products are known compounds and were characterized by a comparison of their spectral data with those of authentic samples unless otherwise noted.[14,23,27]

Spectral and analytical data of new compounds prepared follow.

(Dimethoxyphenyl)phenylmethane (3f).[28] This compound was obtained as a ca. 1:1 regioisomeric mixture by the reaction of **2f** with **1a**: bp 135 °C/0.4 mmHg (Kugelrohr distillation); IR (neat) 700, 1030, 1080, 1140, 1154, 1237, 1262, 2834, 2936, 3027 cm^{-1}; ^1H NMR (200 MHz, $CDCl_3$) δ 3.60−4.10 (m, 8H), 6.60−7.40 (m, 8H); ^{13}C NMR ($CDCl_3$) δ 35.8, 41.4, 55.6, 55.7, 55.8, 60.3, 110−153 (additional several peaks). Anal. Calcd for $C_{15}H_{16}O_2$: C, 78.92; H, 7.06. Found: C, 79.14; H, 7.09.

$Sc(OTf)_3$-Catalyzed Allylation Reaction of Allyl Alcohol with Benzene. A Typical Experimental Procedure. A 50-mL two-necked round-bottomed flask, fitted with a reflux condenser, was charged with $Sc(OTf)_3$ (0.050 g, 0.1 mmol) and **2a** (5.0 mL). To this suspension of $Sc(OTf)_3$ was added **5a** (58.0 mg, 1.0 mmol) at ambient temperature. The mixture was vigorously stirred at the reflux temperature for 8 h, treated with H_2O, and extracted with diethyl ether (10 mL) three times. The combined extracts were then dried over $MgSO_4$. GC/MS analysis exhibited the presence of **6a**, the yield of which was estimated to be 48% using naphthalene as the internal standard. All of the products are known compounds and were characterized by a comparison of their spectral data with those of authentic samples unless otherwise noted.[29]

$Sc(OTf)_3$-Catalyzed Benzylation Reaction of Arenecarbaldehydes with Arenes in the Presence of 1,3-Propanediol. A Typical Experimental Procedure. A 50-mL two-necked round-bottomed flask, fitted with a reflux condenser, was charged with $Sc(OTf)_3$ (0.050 g, 0.1 mmol). The flask was heated at 180 °C *in vacuo* overnight. The flask was cooled down to room temperature and then was successively charged with **2b** (5.0 mL), **8c** (84 mg, 1.1 mmol), and **7d** (141 mg, 1.0 mmol) at room temperature with stirring. The whole mixture was heated at reflux temperature for 18 h under stirring, cooled to room temperature, and poured into H_2O. The organic phase was separated, and the aqueous phase was extracted with diethyl ether. The combined organic extracts were dried over $MgSO_4$. A GC/MS analysis revealed the presence of an isomeric mixture of **3o**, each amount being determined with naphthalene as the internal standard. The isomer ratio of the *ortho*-, *meta*-, and *para*-substituted diarylmethanes was estimated by GC, and the retention times were compared with those of the authentic samples.[14] All of the products are known compounds and were characterized by a comparison of their spectral data with those of authentic samples unless otherwise noted.[14,23]

Preparation of Arenecarbaldehyde Acetals. Cyclic acetals of arenecarbaldehydes were prepared by the acid-catalyzed acetalization with the corresponding diol.[31] The following procedure is typical. A two-necked, round-bottomed flask, equipped with a Dean−Stark trap, is charged with a mixture of **7b** (2.4 g, 20 mmol), **8c** (1.9 g, 25 mmol), *p*-toluenesulfonic acid (40 mg), and benzene (100 mL). The solution was heated at reflux with stirring until no further water separated. The solution was then cooled to room temperature. Triethylamine (1.0 mL) was added to the reaction mixture, which was then partitioned between diethyl ether and water. The organic phase was washed with 10% sodium hydroxide (20 mL) and then with brine and dried over K_2CO_3. Evaporation of the solvent gave practically pure **9b**, which was purified by recrystallization from pentane (3.5 g, 19.7 mmol, 98% yield). All of the arenecarbaldehyde acetals are known compounds and were characterized by a comparison of their spectral data with those of authentic samples unless otherwise noted.[23]

1,1,3,3-Tetradeuterio-2-ethyl-1,3-propanediol (8k).[23] A 50-mL two-necked round-bottomed flask, fitted with a dropping funnel and a reflux condenser connected with an argon line, was charged with lithium aluminum deuteride (949 mg, 25 mmol) and diethyl ether (20 mL). The mixture was heated to reflux for 30 min and then cooled to room temperature. A solution of diethyl ethylmalonate (3.8 g, 20 mmol) dissolved in diethyl ether (20 mL) was added slowly with stirring at such

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[28] Bandaranayake, W. M.; Riggs, N. V. *Aust. J. Chem.* **1981**, *34*, 115.

[29] The allylation products were identified by comparison to their spectral data with those of authentic samples. (a) Alexakis, A.; Cahiez, G.; Normant, J. F. *Synthesis* **1979**, 826. (b) Hayashi, T.; Konishi, M.; Yokota, K.; Kumada, M. *J. Organometal. Chem.* **1985**, *285*, 359. (c) Zadok, E.; Rubinraut, S.; Mazur, Y. *J. Org. Chem.* **1987**, *52*, 385.

[30] Roelofsen, D. P.; van Bekkum, H. *Synthesis* **1972**, 419.

[31] Napolitano, E.; Fiaschi, R.; Mastrorilli, E. *Synthesis* **1986**, 122.

a rate that the solvent continued to reflux gently. After the addition was completed, the mixture was stirred at the reflux temperature for an additional 3 h. The mixture was cooled to room temperature, and the excess deuteride was decomposed by slow addition of saturated sodium sulfate solution. The insoluble material was filtered and washed fully with chloroform. The combined filtrate was dried over $MgSO_4$ and concentrated to give a crude product, which was purified by flash chromatography, using hexane−diethyl ether (1/1) to afford the diol (984 mg, 46%) as an oil. **8k** was characterized by a comparison of the spectral data with that of an authentic sample.[23]

$Sc(OTf)_3$-Catalyzed Reaction of Arenecarbaldehyde Acetals with Arenes. A Typical Experimental Procedure. A 50-mL two-necked round-bottomed flask, fitted with a reflux condenser, was charged with $Sc(OTf)_3$ (0.050 g, 0.1 mmol). The flask was heated at 180 °C *in vacuo* overnight. The flask was then cooled to room temperature and successively charged with **2b** (5.0 mL) and **9c** (199 mg, 1.0 mmol). The mixture was stirred at reflux temperature for 17 h, cooled, and poured into H_2O. The organic phase was separated, and the aqueous phase was extracted with diethyl ether. The combined organic extracts were dried over $MgSO_4$. GC/MS analysis revealed the crude **3o** contained (4-chlorophenyl)(*p*-tolyl)methane, (4-chlorophenyl)(*o*-tolyl)methane, and (4-chlorophenyl)(*m*-tolyl)methane; each product was compared with the authentic sample,[14] and the yield and isomer ratio were determined using naphthalene as the standard.

3-Hydroxypropyl Diphenylmethyl Ether (11).[23] This ether was prepared by the reduction of 2,2-diphenyl-1,3-dioxane with $LiAlH_4-AlCl_3$. The general experimental protocols followed in this study parallel those described in the literature.[32]

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