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Fluorous reverse-phase silica gel-supported Lewis acids as recyclable catalysts in water

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Abstract—Fluorous reverse-phase silica gel (FRPSG)-supported Lewis acids which have fluorous ligands acted as effective catalysts of Baeyer–Villiger and Diels–Alder reactions in water. Direct esterification of carboxylic acid with alcohol in organic media was also catalyzed. The FRPSG-supported Lewis acids could be recycled by simple filtration after the reaction. © 2003 Elsevier Ltd. All rights reserved.

Recently, fluorous biphasic catalysis (FBC) which consists of an organic solvent and a fluorous solvent has become increasingly an important methodology from the viewpoint of green and sustainable chemistry. Since Horváth and Rábai introduced the concept of FBC in 1994,¹ much effort has been devoted to develop the chemistry of the fluorous biphasic system.² Fluorous solvents, known as less toxic chemicals, are immiscible with general organic solvents to separate into an organic phase containing organic compounds and a fluorous phase containing fluorous compounds at ambient temperature. The fluorous phase including the fluorous catalyst can be easily recovered without leaching of the catalyst, then the recovered fluorous catalyst solution can be reused as the fluorous phase in the next reaction. The advantages of the fluorous biphasic system such as easy recycling of the catalyst and rapid work-up procedure suggest the importance of application of FBC to industrial chemistry.

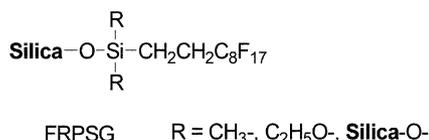
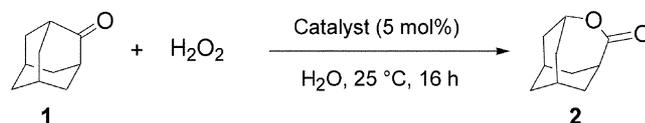


Figure 1. Fluorous reverse-phase silica gel.

Keywords: fluorous; Lewis acid; fluorous reverse-phase silica gel; recycling; water; Baeyer–Villiger reaction; Diels–Alder reaction; direct esterification.

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We have been studying fluorous Lewis acids bearing bis(perfluoroalkanesulfonyl)amide and tris(perfluoroalkanesulfonyl)methide as fluorous ligands.³ These Lewis acids are suitable for FBC due to their high solubility in fluorous solvents and strengthened Lewis acidity attributed to the electron-withdrawing effect of fluorous ligands having no hydrocarbon spacer. We reported the use of these catalysts in small-^{3d,e} and bench-scale^{3e} FBC directed to industrial processes. Also, we have great interest in organic syntheses in water,⁴ since the use of water as a solvent is safe, economical and environmentally benign, and, moreover, reaction in water often shows interesting solvent effects such as acceleration and stereoselectivity. We have already reported the immobilization of fluorous Lewis acids using β -cyclodextrin epichlorohydrin copolymer as a support and catalytic reactions with them in water.^{3a} Then, we tried to use fluorous reverse-phase silica gel (FRPSG) instead of β -cyclodextrin epichlorohydrin copolymer as a solid support immobilizing the fluorous Lewis acid and its surface as a hydrophobic reaction field. FRPSG, which is prepared by reaction of silica gel with polyfluoroalkylsilanes such as C_nF_{2n+1}CH₂CH₂Si(CH₃)₂Cl, has been generally used for solid-liquid extraction to separate fluorous compounds from organic compounds and HPLC.^{2c,5} Although Bannwarth et al. recently reported Suzuki–Miyaura and Sonogashira coupling reactions catalyzed by fluorous-tagged phosphine-palladium complexes immobilized on FRPSG in 1,2-dimethoxyethane and recycling of the supported catalyst in some cases,⁶ the use of FRPSG as the fluorous solid phase in FBC is extremely limited. Here, we report the application and the recycling of FRPSG-supported Lewis acids to Baeyer–Villiger and Diels–Alder reactions in water, and

Table 1. Baeyer–Villiger reaction of 2-adamantanone in water

Entry	Catalyst	Yield (selectivity) (%) ^a			
		Cycle 1	2	3	4
1	FRPSG-Sn[N(SO ₂ C ₈ F ₁₇) ₂] ₄	87 (89)	89 (92)	86 (90)	88 (93)
2 ^b	FRPSG-Sn[N(SO ₂ C ₈ F ₁₇) ₂] ₄	79 (100)	75 (97)	73 (96)	71 (91)
3	FRPSG-Hf[N(SO ₂ C ₈ F ₁₇) ₂] ₄	88 (91)	86 (91)	86 (91)	84 (90)
4 ^c	FRPSG-Sc[C(SO ₂ C ₄ F ₉) ₃] ₃	68 (92)	64 (82)	72 (99)	70 (96)
5	FRPSG-Yb[N(SO ₂ C ₈ F ₁₇) ₂] ₃	3 (100)			
6	Hf[N(SO ₂ C ₈ F ₁₇) ₂] ₄	79 (95)			
7	SnCl ₄	7 (30)			
8	Hf(OTf) ₄	6 (75)			
9	Sc(OTf) ₃	4 (80)			

^a Determined by GC analysis using *n*-nonane as an internal standard.

^b The reaction was carried out with H₂O₂ (1.1 equiv.) at 35°C.

^c FRPSG prepared in our laboratory was used.

direct esterification of carboxylic acid with alcohol in an organic solvent. These are the first examples of FRPSG-supported Lewis acids and reactions catalyzed by them.

In this study, a commercial FRPSG bearing CF₃(CF₂)₇CH₂CH₂Si(CH₃)₂- group (Fluorous silica, 40 μm, Fluorous Technologies, Inc.) and laboratory-made FRPSG, prepared from normal silica gel (Silica gel 100, Merck) with CF₃(CF₂)₇CH₂CH₂Si(OEt)₃ in toluene at 110°C for 24 h, were employed (Fig. 1). Fluorous Lewis acids were prepared according to our previous paper.^{3d} FRPSG-supported Lewis acid was obtained as an easy-to-handle white powdery solid.⁷

At first, Baeyer–Villiger reaction using FRPSG-supported Lewis acids with low concentration of aqueous hydrogen peroxide, which is green and not explosive, was examined.^{3d,8}

Reactivities of several FRPSG-supported Lewis acids were investigated in the oxidation of 2-adamantanone (**1**) in 4% aqueous hydrogen peroxide (10 equiv.) at 25°C for 16 h (Table 1).⁹ FRPSG-supported Sn[N(SO₂C₈F₁₇)₂]₄ and Hf[N(SO₂C₈F₁₇)₂]₄ catalyzed the reaction to give the corresponding lactone **2** in high yields and FRPSG-supported Sc[C(SO₂C₄F₉)₃]₃ showed slightly less catalytic activity than the above two catalysts (entries 1, 3, and 4), while FRPSG-supported Yb[N(SO₂C₈F₁₇)₂]₃ and commercial Sn(IV), Hf(IV), and Sc(III) salts gave **2** in poor yields (entries 5, 7–9). Hf[N(SO₂C₈F₁₇)₂]₄ without support gave **2** in good yield under the same reaction conditions. However, recycling of the catalyst by decantation was difficult, since the catalyst formed an emulsion phase after extraction of **2** (entry 6). The Baeyer–Villiger reaction of **1** proceeded to give **2** in good yield even in 0.44% aqueous hydrogen peroxide (1.1 equiv.) (entry 2).¹⁰

After the reaction, FRPSG-supported Lewis acids were recovered by simple filtration. As shown in Table 1, recycling of the catalyst was achieved by FRPSG-supported Sn(IV), Hf(IV) and Sc(III) Lewis acids without reduction of catalytic activities (entries 1–4).

The influences of the support material on reaction rate and recyclability of the catalyst were investigated. Standard (octadecylsilylated) reverse-phase silica gel (Wakogel[®] 100C18, Wako Pure Chemicals) and normal silica gel (Silica gel 100, Merck) were compared to FRPSG as support material for fluorous Lewis acids in the Baeyer–Villiger reaction of **1** using Hf[N(SO₂C₈F₁₇)₂]₄ (Table 2). The reaction in 2% aqueous hydrogen peroxide (5 equiv.) at 25°C for 3 h showed distinct differences in reaction rate resulted from the support materials. FRPSG-supported Hf[N(SO₂C₈F₁₇)₂]₄ exhibited the best result (entry 1). The reaction in water was accelerated by immobilization on FRPSG in comparison with the reaction using standard reverse-phase silica gel, normal silica gel, and no support material (entries 2–4).

Table 2. Effect of support materials on reaction rate of Baeyer–Villiger reaction of **1**

Entry	Support material	Support material-Hf[N(SO ₂ C ₈ F ₁₇) ₂] ₄ (5 mol%)	
		Yield (selectivity) (%) ^a	
1	Fluorous reverse-phase silica gel	64 (90)	
2	Standard reverse-phase silica gel	51 (94)	
3	Normal silica gel	33 (97)	
4	None	37 (84)	

^a Determined by GC analysis using *n*-nonane as an internal standard.

Table 3. Effect of support materials on recyclability of supported Sn[N(SO₂C₈F₁₇)₂]₄

Entry	Support material	Yield (selectivity) (%) ^a			
		Cycle 1	2	3	4
1	FRPSG	79 (100)	75 (97)	73 (96)	71 (91)
2	Standard reverse-phase silica gel	60 (88)	41 (84)	28 (82)	
3	Normal silica gel	49 (93)	34 (100)	24 (86)	

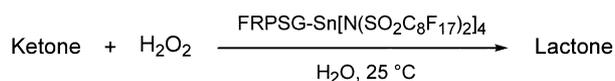
^a Determined by GC analysis using *n*-nonane as an internal standard.

Next, recyclability of the catalyst was compared by the Baeyer–Villiger reaction of **1** using supported Sn[N(SO₂C₈F₁₇)₂]₄ in 0.44% aqueous hydrogen peroxide (1.1 equiv.) (Table 3). Though FRPSG-supported Sn(IV) catalyst could be reused without reduction of catalytic activity, standard reverse-phase silica gel-supported Sn(IV) catalyst showed an obvious decrease of its activity in recycling. Normal silica gel-supported Sn(IV) catalyst was less reactive and decrease of catalytic activity was also observed. It is considered that FRPSG effectively immobilizes the fluoros Lewis acids, while standard reverse-phase silica gel and normal silica gel cannot immobilize the fluoros Lewis acids,¹¹ and consequently decrease catalytic activities.

Baeyer–Villiger reaction of other cyclic ketones using FRPSG-supported Sn[N(SO₂C₈F₁₇)₂]₄ was examined (Table 4). Cyclobutanone and bicyclo[3.3.1]nonan-9-one gave the corresponding lactones in moderate yields (entries 1 and 2). Unfortunately, the product of the

reaction of cyclohexanone was not detected by GC in spite of high (74%) conversion (entry 3).

The FRPSG-supported Lewis acids are applicable to other Lewis acid-catalyzed reactions. Here, Diels–Alder reaction catalyzed by Lewis acid in water¹² was demonstrated using FRPSG-supported Sc[C(SO₂C₄F₉)₃]₃ (Table 5). In the presence of FRPSG-supported Sc[C(SO₂C₄F₉)₃]₃ (5 mol%), 2,3-dimethyl-1,3-butadiene (**3**) with 1.2 equiv. of methyl vinyl ketone (**4**) gave the adduct **5** in high yield. After the reaction, FRPSG-supported Sc[C(SO₂C₄F₉)₃]₃ was recovered by simple filtration. Reaction using the recovered catalyst was carried out three times without reduction of catalytic activity (entry 1). The reaction catalyzed by Sc[C(SO₂C₄F₉)₃]₃ without support gave **5** in moderate yield, and the reaction in the presence of FRPSG without Lewis acid gave **5** in low yield (entries 2 and 3). The reaction with standard reverse-phase silica gel, normal silica gel, and no additive gave **5** in very poor yields (entries 4–6). These results showed that immobilization of Sc[C(SO₂C₄F₉)₃]₃ on FRPSG efficiently accelerated the reaction in water.

Table 4. Baeyer–Villiger reaction of cyclic ketones using FRPSG-supported Sn[N(SO₂C₈F₁₇)₂]₄ in water

Entry	Ketone	Conditions ^a	Yield (Selec.)/(%) ^b
1		A	64 (68) ^c
2		B	64 (74)
3		B	Not detected

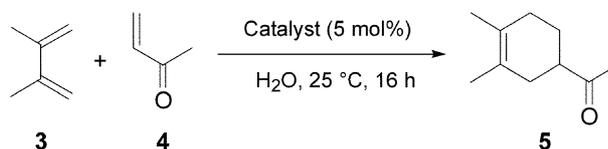
^a Conditions A: catalyst (1 mol%), 5% aq. H₂O₂ (1.05 equiv), 1.5 h; Conditions B: catalyst (5 mol%), 8.5% aq. H₂O₂ (10 equiv), 16 h.

^b Determined by GC analysis using *n*-nonane as an internal standard.

^c The catalyst was recycled. Results were 67 (71), 62 (66), and 63 (68) for cycles 2, 3, and 4, respectively.

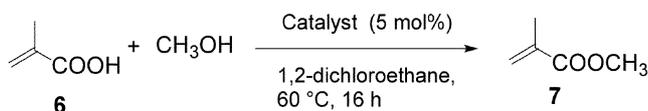
As an example of FRPSG-supported Lewis acid-catalyzed reaction in organic media, direct esterification¹³ of methacrylic acid (**6**) with methanol was carried out in 1,2-dichloroethane (Table 6).

Using Hf[N(SO₂C₈F₁₇)₂]₄ as a catalyst, **6** with 6 equiv. of methanol in 1,2-dichloroethane was stirred at 60°C for 16 h to give methyl methacrylate (**7**) in high yield (entry 1).¹⁴ In the reaction using Hf[N(SO₂C₈F₁₇)₂]₄ without support, the reaction rate was faster than that of the reaction using FRPSG-supported Hf[N(SO₂C₈F₁₇)₂]₄. After the reaction, the catalyst formed insoluble oil. The upper phase (1,2-dichloroethane solution) was removed with a pipette and the lower phase containing the catalyst could be reused; however, yield of **7** decreased with recycling of the catalyst (entry 2). Immobilization of Lewis acid on FRPSG solved this problem. The supported catalyst was recovered by simple filtration and dried under vacuum, then reused in the next cycle without reduction of catalytic activity (entry 1).

Table 5. Diels–Alder reaction using FRPSG-supported $\text{Sc}[\text{C}(\text{SO}_2\text{C}_4\text{F}_9)_3]_3$ in water

Entry	Catalyst or additive	Yield (selectivity) (%) ^a			
		Cycle 1	2	3	4
1	FRPSG- $\text{Sc}[\text{C}(\text{SO}_2\text{C}_4\text{F}_9)_3]_3$	91 (91)	91 (93)	99 (99)	95 (97)
2	$\text{Sc}[\text{C}(\text{SO}_2\text{C}_4\text{F}_9)_3]_3$	54 (54)			
3	FRPSG	23 (24)			
4	Standard reverse-phase silica gel	5 (8)			
5	Normal silica gel	5 (5)			
6	None	1 (1)			

^a Determined by GC analysis using *n*-nonane as an internal standard.

Table 6. Direct esterification of methacrylic acid with methanol in 1,2-dichloroethane

Entry	Catalyst	Yield (selectivity) (%) ^a			
		Cycle 1	2	3	4
1	FRPSG- $\text{Hf}[\text{N}(\text{SO}_2\text{C}_8\text{F}_{17})_2]_4$	86 (91)	93 (96)	94 (99)	96 (100)
2 ^b	$\text{Hf}[\text{N}(\text{SO}_2\text{C}_8\text{F}_{17})_2]_4$	87 (93)	74 (94)	67 (99)	56 (95)

^a Determined by GC analysis using naphthalene as an internal standard.

^b Reaction time was 8 h.

In summary, FRPSG-supported Lewis acids acted as a highly active catalyst of Baeyer–Villiger and Diels–Alder reactions in water and direct esterification in organic media. Recycling of the catalyst was achieved by simple filtration owing to immobilization on FRPSG. These advantages suggest that FRPSG-supported Lewis acid catalysts should be a remarkably useful tool for the development of environmentally benign green processes. In our laboratory, further studies are now in progress.

Acknowledgements

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7. Into a solution of fluoros Lewis acid (500 mg) in ethanol (20 mL), fluoros reverse-phase silica gel (5 g) was added and the resulting mixture was stirred for 1 h at room temperature. After removal of the solvent under reduced pressure, residual FRPSG-supported Lewis acid was dried under vacuum at 80°C for 6 h.
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9. A mixture of 2-adamantanone (0.25 mmol) and FRPSG-supported Lewis acid (5 mol%) in 4% aq. H₂O₂ (2.2 ml) was stirred at 25°C for 16 h. After the reaction, 1,2-dichloroethane (2 mL) was added into the mixture, and stirred for 10 min, then FRPSG-supported Lewis acid was recovered by filtration and washed with H₂O (2 mL) and 1,2-dichloroethane (6 mL). Yields of product were determined by GC using *n*-nonane as an internal standard. FRPSG-supported catalyst was dried under vacuum for reuse in the next cycle. Leaching of Sn(IV) and Hf(IV) in water and 1,2-dichloroethane was analyzed to be less than 5 ppm by ICP-AES.
10. FRPSG-supported (C₈F₁₇SO₂)₂NH (20 mol%) was compared with FRPSG-supported Sn[N(SO₂C₈F₁₇)₂]₄ (5 mol%) in the reaction of 2-adamantanone using H₂O₂ (1.1 equiv.). The former was less active (58% yield, 82% selec.) than the latter (79% yield, 100% selec.). In the reaction of cyclobutanone, FRPSG-supported (C₈F₁₇SO₂)₂NH (4 mol%) was also less active (44% yield, 48% selec.).
11. After the work-up of the reaction using standard reverse-phase silica gel- and normal silica gel-supported Sn[N(SO₂C₈F₁₇)₂]₄, the filtrate was a mixture of an aqueous solution, an organic solution, and a suspension containing Sn(IV).
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14. To a mixture of FRPSG-supported Hf[N(SO₂C₈F₁₇)₂]₄ (5 mol%) in 1,2-dichloroethane (1.5 mL), methacrylic acid (0.5 mmol) and methanol (3 mmol) was added. Reaction mixture was stirred at 60°C for 16 h. Supported catalyst was recovered by filtration and washed with 1,2-dichloroethane (5 mL). Yields of product were determined by GC using naphthalene as an internal standard.