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Phenyl trifluorovinyl sulfide: a radical acceptor for preparation of *gem*-difluoromethylene compounds

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Abstract—Phenyl trifluorovinyl sulfide was prepared from the reaction of trifluorovinyllithium and *S*-phenyl benzenethiosulfonate. The fluorinated olefin showed reactivity with alkyl radicals generated from halogen-abstraction from alkyl halides. Reactions with alkyl halides required tris(trimethylsilyl)silane as a chain transfer reagent to improve selectivity of the products. Initiation of radical reaction was effected by thermal decomposition of AIBN. Oxidation of the thioether products gave the corresponding sulfoxides, which were successively converted into α,α-difluoroalkanecarboxylic acid thiol esters by Pummerer reaction.
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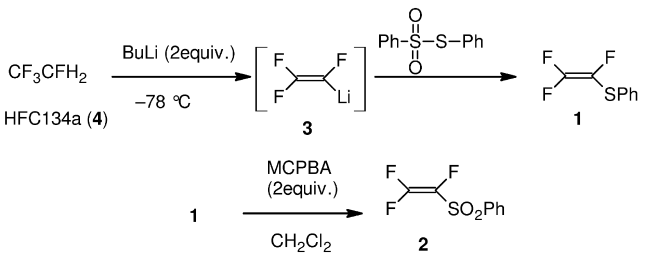
1. Introduction

Difluoromethylene compounds[1–3] have attracted increasing interest in recent years due to the wide variety of their biological activities.[4–6] α,α-Difluoroalkanecarboxlic acid derivatives are potentially versatile starting materials and synthetic building blocks for such biologically active difluoromethylene compounds. The regioselective addition of alkyl radicals[7,8] to the electron-deficient 1,1-dichloro-2,2-difluoroethene provided us with a promising route to α,α-difluoroalkanecarboxlic acids.[1,9–14] However, in order to avoid the use of the ozone-depleting chlorofluorocarbons for the environmental reason, currently another good radical acceptor is required to obtain difluoromethylene products regioselectively, which can be readily converted into synthetically useful functional groups with a difluoromethylene group. In this paper, we report new radical acceptors, phenyl trifluorovinyl sulfide (**1**) and phenyl trifluorovinyl sulfone (**2**), and the functional group conversion of the radical adducts to synthetically useful difluoroalkanecarboxylic acid thiol esters.

2. Results and discussion

2.1. Preparation of trifluorovinyl phenyl sulfide 1 and sulfone 2

Phenyl trifluorovinyl sulfide (**1**) and the corresponding sulfone (**2**) were previously prepared from phenylsulfenyl chloride and also a chlorofluorocarbon CF_2=CFCl in low yields.[15–17] Recently, new preparation methods of trifluorovinyllithium (**3**) from non-ozone-depleting 1,1,1,2-tetrafluoroethane (HFC-134a) (**4**) at −78 °C were reported.[18,19] According to these preparation methods, sulfenylation of anion **3** in Et_2O of with *S*-phenyl benzenethiosulfonate[20] was carried out to give sulfide **1** in 64% yield. The corresponding sulfone **2** was obtained by oxidation of **1** with 2 equiv. of *m*-chloroperbenzoic acid (MCPBA) in 80% yield (Scheme 1).[15]



Scheme 1.

2.2. Borane-assisted radical reaction of trifluorovinyl sulfide 1 and sulfone 2

In the presence of a trace amount of oxygen, alkylboranes

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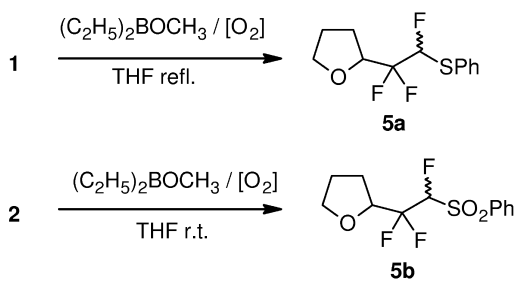
generate alkyl radicals, which abstract hydrogen from activated C–H bonds in ethers.[21] Reactivities of both trifluorovinyl compounds **1** and **2** with carbon radicals were compared by the reaction with methyl diethylboronate in THF (Scheme 2). Generated 2-oxolanyl radical reacted with **1** under refluxing to give a 1:1 diastereomer mixture of 2-substituted oxolane derivative **5a** in 76%. Similarly, sulfone **2** gave a 1:1 mixture of **5b** at room temperature in 77% yield. As expected from the reactions of geminal difluoroolefins with alkyl radicals, the addition reactions of radical to **1** and **2** were regioselective to form the new carbon–carbon bonds at the difluorinated carbons, and no regioisomers were detected. The regioselectivity was confirmed by their ^{19}F NMR spectra, in which two sets of diastereotopic fluorine signals of difluoromethylene groups were observed ($^{2}J^{19}F-^{19}F=250-270$ Hz).

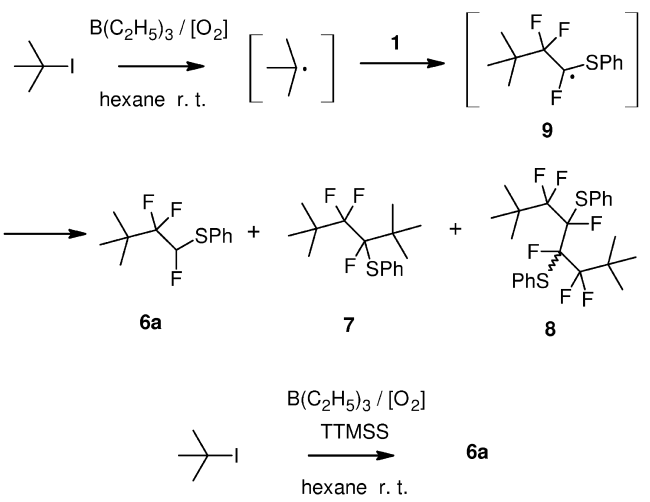


Scheme 2.

Although a competition experiment using an equimolar mixture of **1** and **2** gave a mixture of **5a** and **5b** in a 1:4 ratio and thus **2** is four times more reactive than **1**, the following radical reactions were conducted with sulfide **1** because of the comparable product yields and the shorter preparation steps.

2.3. Generation of alkyl radicals from organic halides and the reaction with thioether 1

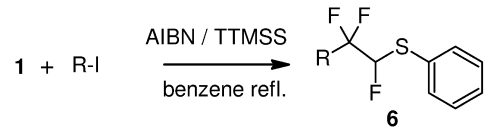
Alkyl radicals are generated from the reaction of alkyl halides and alkylborane/O_2.[22] A mixture of thioether **1**, *t*-butyl iodide, and triethylborane in hexane was stirred at room temperature in the presence of air, bearing in mind that atom-transfer reaction via alkyl radical from organic halides proceed to give olefin insertion products. However, a complex mixture of products containing several radical products such as **6a**, **7**, and **8** detected by GC–MS analysis was afforded (Scheme 3). Although these products prove that ethyl radical was generated from triethylborane and reacted with fluoroolefin **1** to give radical intermediate **9**, the radical **9** is too unreactive to abstract iodine from *t*-butyl iodide for chain propagation. When tris(trimethylsilyl)-silane (TTMSS) was added as a radical chain transfer reagent, the radical reaction proceeded smoothly to give mainly hydrogenated adduct **6a** in 65% yield.



Scheme 3.

Nevertheless, the radical reactions using $B(C_2H_5)_3$/air as the radical initiator had some problems in reproducibility particularly in the cases of primary halides. Thus, we adopted another conventional alkyl radical generation system using thermal decomposition of azobisisobutyronitrile (AIBN) under benzene reflux. The reaction was carried out by continual addition of small amounts of TTMSS and solid AIBN in every 3 min into the refluxing benzene solution of sulfide **1** and 3–5-fold excess amounts of the corresponding alkyl halide until the starting material **1** was completely consumed. In this manner, as well as *tert*-butyl iodide (entry 1) which also gave **6a** in somewhat lower yield than the reaction with $B(C_2H_5)_3$/air, primary (entries 2–4) and secondary (entries 5 and 6) halides gave adducts **6b–f** as summarized in Table 1. When TTMSS was used as the radical chain transfer reagent, a byproduct tris(trimethylsilyl)silyl halide had been often troublesome to remove from the reaction mixture. However, TTMSS was able to be readily removed by elution of the resulting benzene solution through a short column of basic alumina. While a small amount of the hydrolyzed silanol was eluted with adducts, it was readily removed by the successive chromatography on a SiO_2 column.

Table 1. Radical reaction of **1** with alkyl halides in the presence of AIBN and TTMSS



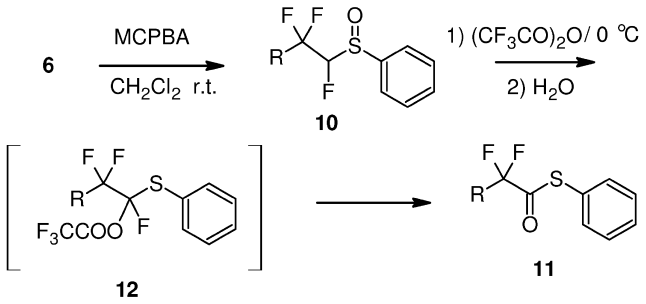
Entry	R	Product	Yield (%)
1	$(CH_3)_3C-$	**6a**	36
2	$CH_3(CH_2)_2-$	**6b**	68
3	$CH_3(CH_2)_5-$	**6c**	49
4	$CH_3(CH_2)_8-$	**6d**	67
5	$(CH_3)_2CH-$	**6e**	70
6	Cyclohexyl	**6f**	46

2.4. Conversion of radical adducts by Pummerer reaction to α,α-difluoroalkanecarboxylic acid thiol esters

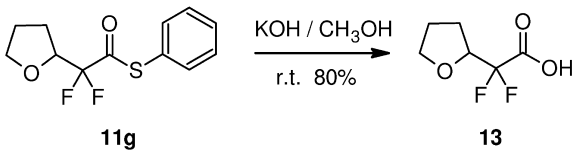
Versatility of this radical reaction depends on whether the fluorinated products can be smoothly converted into difluoroalkanecarboxylic acid derivatives, which are utilized as starting materials in various organic preparations.[23–26] The obtained α-fluorothioethers were oxidized with an equimolar amount of MCPBA at room temperature in CH_2Cl_2 to give the diastereomer mixtures of corresponding

sulfoxides **10a**–**g** as summarized in Table 2. Following Pummerer reaction with trifluoroacetic anhydride at 0 °C gave the desired α,α-difluoroalkanecalboxylic acid thiol esters **11a**–**g** after hydrolysis of the labile intermediate **12**. 2-Oxolanyl derivative **11g** was converted into the corresponding difluorocarboxylic acid **13**[10] in 80% yield on alkaline hydrolysis with KOH (Scheme 4).

Table 2. MCPBA oxidation of radical adducts followed by Pummerer reaction to thiol esters



Entry	Substrate	R	Sulfone	Thiol ester	Yield (%)
1	**6a**	$(CH_3)_3C-$	**10a**	**11a**	67
2	**6b**	$CH_3(CH_2)_2-$	**10b**	**11b**	64
3	**6c**	$CH_3(CH_2)_5-$	**10c**	**11c**	58
4	**6d**	$CH_3(CH_2)_8-$	**10d**	**11d**	41
5	**6e**	$(CH_3)_2CH-$	**10e**	**11e**	63
6	**6f**	Cyclohexyl	**10f**	**11f**	51
7	**5a**	2-Oxolanyl	**10g**	**11g**	63



Scheme 4.

In conclusion, phenyl trifluorovinyl sulfide prepared from sulfenylation of trifluorovinyllithium reacted with alkyl halides under radical reaction conditions to give difluoromethylene-containing thioether products regioselectively. Oxidation of the products followed by Pummerer reaction afforded synthetically useful α,α-difluoroalkanecarboxylic acid thiol esters.

3. Experimental

3.1. General

^{1}H NMR spectra were collected in $CDCl_3$ in the presence of TMS as an internal standard at 300 MHz. ^{19}F NMR spectra (282 MHz) were recorded in $CDCl_3$, and referenced based on internal $CF_3COOC_2H_5$ whose chemical shift was set at −75.75 ppm downfield (δ) from internal $CFCl_3$ in $CDCl_3$.

3.1.1. Phenyl trifluorovinyl sulfide (1). HFC134a (**4**) (ca. 6.0 g, 59 mmol) was liquefied at −78 °C and diluted in Et_2O (100 mL). To the Et_2O solution, BuLi (1.6 M in hexane; 62.5 mL, 100 mmol) was slowly added dropwise in 4 h at −78 °C. The resulted solution was then added dropwise into a solution of *S*-phenyl *p*-toluenethiosulfonate (12.5 g, 50 mmol) in Et_2O (300 mL) in 2 h below −45 °C. After warming up to room temperature, the resulted suspension was filtered through a bed of Celite®. The solvents of the filtrate were removed by distillation, and the residue was distilled with a glass tube oven (45 °C, 5 mm Hg) to give pure olefin **1** as colorless oil: 5.98 g (63% based on thiosulfonate); ^{1}H NMR δ 7.27–7.42 (m); ^{19}F NMR δ −88.4 (dd, J=46±2, 34±2 Hz), −106.5 (dd, J=122±2, 46±2 Hz), −149.4 (dd, J=122±2, 34±2 Hz). The NMR spectra were compatible with previously reported data.[15–17]

3.1.2. Phenyl trifluorovinyl sulfone (2). Sulfide **1** (190 mg, 1 mmol) and *m*-chloroperbenzoic acid (MCPBA) (430 mg, 2.5 mmol) was dissolved in CH_2Cl_2 (10 mL) and the mixture was stirred for 12 h at room temperature. The resulting solution was successively washed with aq. $Na_2S_2O_3$ and aq. $NaHCO_3$ solutions. Organic layer was dried over Na_2SO_4, and the solvent was removed under reduced pressure. The residue was chromatographed on a SiO_2 column (1:1 hexane–EtOAc) to give sulfone **2** as colorless oil: 176 mg (80%); ^{1}H NMR δ 7.58–7.66 (m, 3H), 7.71–7.78 (m, 2H); ^{19}F NMR δ −85.2 (dd, J=40±2, 31±2 Hz), −95.0 (dd, J=122±2, 31±2 Hz), −175.2 (dd, J=122±2, 40±2 Hz).

3.1.3. 1,1,2-Trifluoro-1-oxolan-2-yl-2-phenylsulfanylethane (5a). A mixture of **1** (380 mg, 2 mmol) and $(C_2H_5)_2BOCH_3$ THF solution (1.0 M; 10 mL, 10 mmol) was refluxed for 12 h. The solvent was removed under reduced pressure and the residue was chromatographed on a short SiO_2 column (Et_2O) to give a 1:1 diastereomer mixture of **5a** as colorless oil: 400 mg (76%); ^{1}H NMR δ 1.91–2.18 (m, 4H), 3.84–3.93 (m, 2H), 4.28–4.59 (m, 1H), 6.01 (ddd, J=52.8, 16.8, 5.4 Hz, 0.5H), 6.01 (ddd, J=51.0, 17.4, 5.4 Hz, 0.5H), 7.33–7.39 (m, 3H), 7.55–7.59 (m, 2H); ^{19}F NMR δ −118.3 (dt, J=256±2, 18±2 Hz, 0.5F), −121.5 (dtd, J=262±2, 17±2, 6±2 Hz, 0.5F), −122.7 (dtd, J=262±2, 20±2, 6±2 Hz, 0.5F), −123.5 (dtd, J=256±2, 20±2, 6±2 Hz, 0.5F), −161.8 (dt, J=55±2, 18±2 Hz, 0.5F), −168.8 (dt, J=52±2, 18±2 Hz, 0.5F); EI-MS m/z (rel. %) 262 (M^+, 67), 141 (34), 77 (31), 71 (100). Anal. Calcd for $C_{12}H_{13}F_3OS$: C; 54.95, H; 5.00. Found: C; 55.03, H; 5.04.

3.1.4. 1,1,2-Trifluoro-1-oxolan-2-yl-2-phenylsulfonylethane (5b). A mixture of sulfone **2** (220 mg, 1 mmol) and 1.0 M $(C_2H_5)_2BOCH_3$ THF solution (5 mL) **5b** was stirred at room temperature for 12 h. The resulting mixture was worked up as above to give sulfone **5b** as colorless oil: 100 mg, (34%; 77% based on the consumed sulfone **2**); ^{1}H NMR δ 1.80–2.22 (m, 4H), 3.79–3.95 (m, 2H), 4.23 (ddddd, J=24.3, 9.0, 4.8, 3.6, 1.5 Hz, 0.5H), 4.68 (ddt, J=21.6, 7.8, 5.1 Hz, 0.5H), 5.50 (ddd, J=43.5, 20.1, 0.9 Hz, 0.5H), 5.56 (ddd, J=45.0, 16.8, 6.0 Hz, 0.5H), 7.57–7.65 (m, 2H), 7.71–7.78 (m, 1H), 7.98–8.02 (m, 2H); ^{19}F NMR δ −119.3 (dtd, J=267±2, 15±2, 6±2 Hz, 0.5F), −120.9 (dddd, J=267±2, 21±2, 12±2, 6±2 Hz, 0.5F), −122.3 (ddd, J=268±2, 21±2, 15±2 Hz, 0.5F), −127.2 (ddd, J=268±2, 24±2, 9±2 Hz, 0.5F), −189.4 (dddd, J=43±2, 15±2, 8±2, 5±2 Hz, 0.5F), −196.9 (dt, J=45±2,

13±2 Hz, 0.5F); EI-MS *m/z* (rel. %) 212 (7), 141 (10), 133 (36), 78 (70), 71 (100). Anal. Calcd for $C_{12}H_{13}F_3O_3S$: C; 48.98, H; 4.45. Found: C; 48.85, H; 4.58.

3.1.5. Triethylborane-initiated radical reaction of sulfide 1 with *tert*-butyl iodide. To a mixture of **1** (95 mg, 0.50 mmol), *tert*-butyl iodide (460 mg, 2.5 mmol), and TTMSS (250 mg, 1.00 mmol), $B(C_2H_5)_3$ hexane solution (1.0 M, 0.25 mL: 0.25 mmol) was added. Then the mixture was exposed with air and stirred at room temperature. $B(C_2H_5)_3$ hexane solution (1.0 M, 0.25 mL: 0.25 mmol) was added twice into the reaction mixture at 1 and 2 h later. After 3 h stirring, the mixture was diluted with hexane and washed with saturated aq. NaCl solution. The hexane solution was dried over $MgSO_4$ and the solvent was removed under reduced pressure. The residue was chromatographed on a SiO_2 column to give 3,3,4-trifluoro-2,2-dimethyl-4-phenylsulfanylbutane (**6a**) as colorless oil: 80 mg (65%); ^{1}H NMR δ 1.15 (s, 9H), 5.90 (ddd, *J*=52.5, 19.8, 3.0 Hz, 1H), 7.35–7.38 (m, 3H), 7.56–7.59 (m, 2H); ^{19}F NMR δ −108.8 (dd, *J*=259±2, 21±2 Hz, 1F), −121.1 (dt, *J*=259±2, 18±2 Hz, 1F), −156.9 (dt, *J*=52±2, 18±2 Hz, 1F); EI-MS *m/z* (rel. %) 248 (31, M^+), 141 (100), 109 (13), 57 (35). Anal. Calcd for $C_{12}H_{15}F_3S$: C; 58.04, H; 6.09. Found: C; 58.20, H; 6.06.

3.1.6. AIBN initiated radical reaction of sulfide 1 with *tert*-butyl iodide. To a refluxing mixture of **1** (95 mg, 0.50 mmol) and *tert*-butyl iodide (0.32 mL, 2.5 mmol) in benzene (2 mL) under stirring, TTMSS (50 μL, ca. 0.16 mmol) and solid AIBN (2 mg, ca. 12 μmol) was continually added in every 3 min. The reaction was continued for 1 h. The reaction mixture was filtered through a short alumina column, and then the column was washed with hexane. After evaporation of the solvent, the residue was chromatographed on a SiO_2 column eluting with hexane to give pure **6a**: 98 mg (36%).

3.1.7. 1,2,2-Trifluoro-1-phenylsulfanylpentane (6b). The title compound was obtained as above from **1** (380 mg, 2.0 mmol) and 1-iodopropane (1.36 g, 4.0 mmol) as colorless oil: 316 mg (68%); ^{1}H NMR δ 1.00 (t, *J*=7.4 Hz, 3H), 1.59 (sex, *J*=7.4 Hz, 2H), 1.75–2.39 (m, 2H), 5.74 (ddd, *J*=53.0, 10.7, 8.0 Hz, 1H), 7.34–7.38 (m, 3H), 7.53–7.57 (m, 2H); ^{19}F NMR δ −161.6 (dt, *J*=52±2, 18±2 Hz, 1F), −108.5 (dqd, *J*=253±2, 18±2, 12±2 Hz, 1F), −106.5 (dqd, *J*=253±2, 15±2, 6±2 Hz, 1F); EI-MS *m/z* (rel. %) 234 (19, M^+), 141 (100), 109 (22), 77 (26), 51 (27). Anal. Calcd for $C_{11}H_{13}F_3S$: C; 56.39, H; 5.59. Found: C; 56.41, H; 5.77.

3.1.8. 1,2,2-Trifluoro-1-phenylsulfanyloctane (6c). The title compound was obtained as above from **1** (95 mg, 0.50 mmol) and 1-iodohexane (530 mg, 2.5 mmol) as colorless oil: 68 mg (49%); ^{1}H NMR δ 0.90 (t, *J*=6.9 Hz, 3H), 1.31–1.44 (m, 6H), 1.496–1.598 (m, 2H), 1.95–2.18 (m, 2H), 5.74 (ddd, *J*=52.8, 10.7, 8.0 Hz, 1H), 7.34–7.39 (m, 3H), 7.52–7.59 (m, 2H); ^{19}F NMR δ −161.6 (dt, *J*=54±2, 16±2 Hz, 1F), −108.5 (dqd, *J*=253±2, 21±2, 12±2 Hz, 1F), −106.5 (dqd, *J*=253±2, 18±2, 9±2 Hz, 1F); EI-MS *m/z* (rel. %) 276 (33, M^+), 141 (100), 109 (18), 77 (20), 51 (17). Anal. Calcd for $C_{14}H_{19}F_3S$: C; 60.84, H; 6.93. Found: C; 60.66, H; 7.12.

3.1.9. 1,2,2-Trifluoro-1-phenylsulfanylundecane (6d). The title compound was obtained as above from **1** (95 mg, 0.50 mmol) and 1-iodononane (640 mg, 2.5 mmol) as colorless oil: 108 mg (68%); ^{1}H NMR δ 0.88 (t, *J*=7.0 Hz, 3H), 1.13–1.42 (m, 12H), 1.54 (quint., *J*=7.4 Hz, 2H), 1.88–2.13 (m, 2H), 5.74 (ddd, *J*=52.7, 10.7, 8.0 Hz, 1H), 7.34–7.39 (m, 3H), 7.53–7.57 (m, 2H); ^{19}F NMR δ −161.6 (dt, *J*=54±2, 18±2 Hz, 1F), −108.5 (dqd, *J*=253±2, 18±2, 12±2 Hz, 1F), −106.5 (dqd, *J*=253±2, 18±2, 9±2 Hz, 1F); EI-MS *m/z* (rel. %) 319 (8, M^++1), 318 (42, M^+), 141 (100), 110 (17), 109 (19), 77 (11), 65 (11), 55 (16). Anal. Calcd for $C_{17}H_{25}F_3S$: C; 64.12, H; 7.91. Found: C; 63.90, H; 8.20.

3.1.10. 1,2,2-Trifluoro-3-methyl-1-phenylsulfanylbutane (6e). The title compound was obtained as above from **1** (95 mg, 0.50 mmol) and 2-iodopropane (430 mg, 2.5 mmol) as colorless oil: 82 mg (70%); ^{1}H NMR δ 1.09 (d, *J*=6.6 Hz, 3H), 1.10 (d, *J*=6.9 Hz, 3H), 2.31–2.52 (m, 1H), 5.82 (ddd, *J*=52.5, 14.4, 6.9 Hz, 1H), 7.36–7.38 (m, 3H), 7.55–7.59 (m, 2H); ^{19}F NMR δ −162.7 (dt, *J*=52±2, 17±2 Hz, 1F), −117.3 (dtd, *J*=253±2, 18±2, 6±2 Hz, 1F), −115.3 (dtd, *J*=253±2, 15±2, 8±2 Hz, 1F); EI-MS *m/z* (rel. %) 235 (3, M^++1), 234 (24, M^+), 141 (100), 110 (21), 109 (20), 77 (16), 65 (29), 51 (24). Anal. Calcd for $C_{11}H_{13}F_3S$: C; 56.39, H; 5.59. Found: C; 56.32, H; 5.79.

3.1.11. 1-Cyclohexyl-1,1,2-trifluoro-2-phenylsulfanylethane (6f). The title compound was obtained as above from **1** (380 mg, 2.0 mmol) and iodocyclohexane (2.10 g, 10 mmol) as colorless oil: 253 mg (46%); ^{1}H NMR δ 1.14–1.36 (m, 5H), 1.68–1.72 (m, 1H), 1.80–1.95 (m, 4H), 2.12 (m, 1H), 5.82 (ddd, *J*=52.8, 12.6, 9.3 Hz, 1H), 7.31–7.38 (m, 3H), 7.55–7.58 (m, 2H); ^{19}F NMR δ −162.9 (dt, *J*=52±2, 18±2 Hz, 1F), −116.1–114.0 (m, 2F); EI-MS *m/z* (rel. %) 274 (39, M^+), 141 (100), 110 (48), 77 (28), 55 (26). Anal. Calcd for $C_{14}H_{17}F_3S$: C; 61.29, H; 6.25. Found: C; 61.19, H; 5.94.

3.1.12. *S*-Phenyl 2,2-difluoro-3,3-dimethylbutanethioate (11a). Radical adduct **6a** (90 mg, 0.36 mmol) was dissolved in CH_2Cl_2 (2 mL). To the solution, MCPBA (74 mg, 0.43 mmol) was added in several portions. The resulting mixture was stirred for 12 h at room temperature. Then, the mixture was successively washed with 5% NaS_2O_3 solution and sat. $NaHCO_3$ solution. The CH_2Cl_2 solution was dried over $MgSO_4$, and the solvent was removed under reduced pressure to give crude sulfoxide **10a** (76 mg, 80%). Trifluoroacetic anhydride (0.5 mL) was added to the ice-cooled **10a** under stirring, and resulting mixture was stirred for 10 h at room temperature. Then, crashed ice (ca. 1 g) was added to the mixture and the mixture was stirred for 2 h. After neutralization with $NaHCO_3$, the mixture was extracted with Et_2O. The combined extracts were dried over Na_2SO_4, and the solvent was removed under reduced pressure. The residue was chromatographed on a silica gel column eluting with 5% EtOAc–hexane to give thioate **11a** as colorless oil: 59 mg (67%); ^{1}H NMR δ 1.13 (s, 9H), 7.40–7.48 (m, 5H); ^{19}F NMR δ −112.2 (s); EI-MS *m/z* (rel. %) 244 (19, M^+), 216 (11), 110 (100), 109 (50),107 (29), 87 (33), 65 (76), 59 (12), 51 (16). Anal. Calcd for $C_{12}H_{14}F_2OS$: C; 59.00, H; 5.78. Found: C; 58.89, H; 5.73.

3.1.13. *S*-Phenyl 2,2-difluoropentanethioate (11b). The title compound was obtained from radical adduct **6b** (289 mg, 1.23 mmol) as above: 180 mg (64%); ^{1}H NMR δ 0.98 (t, J=7.3 Hz, 3H), 1.55 (sex, J=7.5 Hz, 2H), 1.97–2.15 (m, 2H), 7.41–7.46 (m, 5H); ^{19}F NMR δ −103.6 (t, J=17±2 Hz); EI-MS m/z (rel. %) 230 (13, M^+),110 (100), 109 (45), 73 (16), 65 (28), 51 (12). Anal. Calcd for $C_{11}H_{12}F_2OS$: C; 57.37, H; 5.25. Found: C; 57.28, H; 5.56.

3.1.14. *S*-Phenyl 2,2-difluorooctanethioate (11c). The title compound was obtained from radical adduct **6c** (332 mg, 1.20 mmol) as above: 191 mg (58%); ^{1}H NMR δ 0.872 (t, J=6.7 Hz, 3H), 1.20–1.39 (m, 6H), 1.53 (quint, J=6 Hz, 2H), 1.98–2.15 (m, 2H), 7.33–7.44 (m, 5H); ^{19}F NMR δ −103.6 (t, J=17±2 Hz); EI-MS m/z (rel. %) 272 (7, M^+), 111 (10), 110 (100), 109 (29), 65 (10), 55 (11). Anal. Calcd for $C_{14}H_{18}F_2OS$: C; 61.74, H; 6.66. Found: C; 61.96, H; 6.99.

3.1.15. *S*-Phenyl 2,2-difluoroundecanethioate (11d). The title compound was obtained from radical adduct **6d** (114 mg, 0.36 mmol) as above: 46 mg (41%); ^{1}H NMR δ 0.86 (t, J=6.7 Hz, 3H), 1.17–1.36 (m, 10H), 1.50 (quint, J=7 Hz, 2H), 1.98–2.15 (m, 2H), 7.39–7.47 (m, 5H); ^{19}F NMR δ −103.6 (t, J=17±2 Hz); EI-MS m/z (rel. %) 314 (5, M^+), 110 (100), 109 (22), 69 (11), 57 (26), 55 (20). Anal. Calcd for $C_{17}H_{24}F_2OS$: C; 64.94, H; 7.69. Found: C; 64.85, H; 8.01.

3.1.16. *S*-Phenyl 2,2-difluoro-3-methylbutanethioate (11e). The title compound was obtained from radical adduct **6e** (100 mg, 0.43 mmol) as above: 61 mg (63%); ^{1}H NMR δ 1.08 (d, J=6.9 Hz, 6H), 2.42 (t-sep, J=15.3, 6.9 Hz, 1H), 7.38–7.58 (m, 5H); ^{19}F NMR δ −111.7 (d, J=15±2 Hz); EI-MS m/z (rel. %) 230 (18, M^+), 111 (10), 110 (100), 109 (44), 93 (17), 65 (85), 51 (14). Anal. Calcd for $C_{11}H_{12}F_2OS$: C; 57.37, H; 5.25. Found: C; 57.15, H; 5.41.

3.1.17. *S*-Phenyl 2-cyclohexyl-2,2-difluoroethanethioate (11f). The title compound was obtained from radical adduct **6f** (220 mg, 0.80 mmol) as above: 110 mg (51%); ^{1}H NMR δ 0.81–0.90 (m, 1H), 1.10–1.34 (m, 6H), 1.62–1.72 (m, 1H), 1.76–1.88 (m, 2H), 2.00–2.18 (m, 1H), 7.35–7.50 (m, 5H); ^{19}F NMR δ −110.9 (d, J=15±2 Hz); EI-MS m/z (rel. %) 270 (7, M^+), 113 (46), 110 (100), 109 (31), 93 (14), 77 (14), 73 (10), 65 (16), 51 (16). Anal. Calcd for $C_{14}H_{16}F_2OS$: C; 62.20, H; 5.97. Found: C; 62.02, H; 6.28.

3.1.18. *S*-Phenyl 2,2-difluoro-2-oxolan-2-ylethanethioate (11g). The title compound was obtained from radical adduct **5a** (210 mg, 0.80 mmol) as above: 131 mg (63%); ^{1}H NMR δ 1.86–2.28 (m, 4H), 3.86–4.00 (m, 2H), 4.46 (dtd, J=17.7, 7.2, 6.0 Hz, 1H), 7.457 (s, 5H); ^{19}F NMR δ −120.7 (dd, J=259±2, 15±2 Hz, 1F), −110.0 (dd, J=259±2, 6±2 Hz, 1F); EI-MS m/z (rel. %) 258 (17, M^+), 109 (46), 71 (100), 51 (40). Anal. Calcd for $C_{12}H_{12}F_2O_2S$: C; 55.80, H; 4.68. Found: C; 56.02, H; 4.77.

3.1.19. 2,2-Difluoro-2-oxolan-2-ylacetic acid (13). Thioate **11g** (140 mg, 0.54 mmol) and KOH (30 mg, 0.54 mmol) were dissolved in methanol (10 mL) and the mixture was stirred at room temperature for 5 h. Under reduced pressure, methanol was removed, and then after addition of water, the resulting mixture was washed with Et_2O. The aqueous layer was pored into 10% hydrochloric acid. The mixture was extracted with Et_2O and dried over $MgSO_4$. The solvent was removed under reduced pressure to give carboxylic acid **13** which was identical with an authentic sample:[10] 70 mg (78%).

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