Reaction of diethylaminosulfur trifluoride with diols

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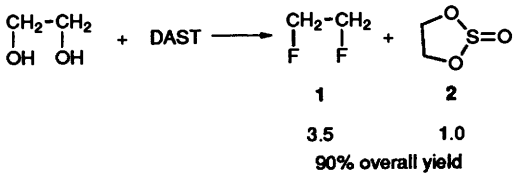
Diethylaminosulfur trifluoride (DAST) reacts with dialcohols to give difluorides, sulfite esters or cyclic ethers depending on the number of carbons separating the two alcohol groups. Vicinal and 1,3-diols give large amounts of sulfite ester products while butane-1,4-diol gives almost exclusively the cyclic ether tetrahydrofuran. Terminal dialcohols longer than four carbons give primarily difluoride products. Semiempirical calculations indicate a preference for cyclic intermediates when four or less carbons separate the two alcohol moieties. These cyclic intermediates lead directly to the cyclic ethers and sulfite ester products.

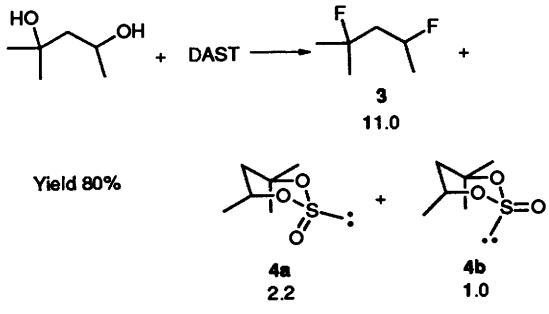
Aminosulfur trifluorides such as diethylaminosulfur trifluoride (DAST) react with alcohols to replace the hydroxy group with a fluorine.[1a,b] In polyhydroxy compounds such as sugars only one hydroxy group is usually replaced by fluorine.[1b,2] Replacement of two hydroxy groups by fluorine has been observed in a few instances.[2c] For example, Middleton reported a 70% yield of 1,2-difluoroethane (**1**) for the reaction of DAST with ethylene glycol.[1a]

Results and discussion

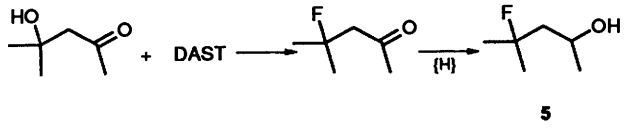
We investigated the reaction of DAST with ethylene glycol and found that ethylene sulfite (**2**) was also produced in 20% yield.



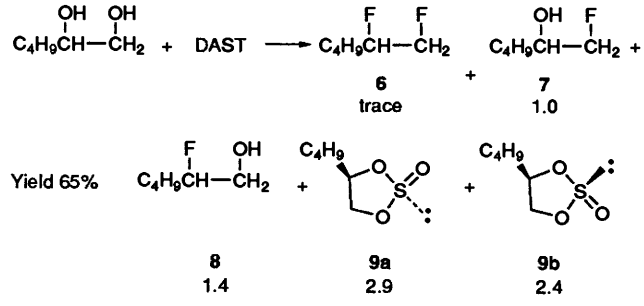
Reaction of DAST with 2-methylpentane-2,4-diol gave primarily difluoride **3** and the sulfite esters **4a, b** in 80% yield.



The fluorohydrins expected from reaction of 2-methylpentane-2,4-diol with DAST were not observed in this reaction. One of the fluorohydrins (**5**) was independently synthesized from 4-hydroxy-4-methylpentan-2-one. Fluorohydrin **5** was converted into **3** by reaction of **5** with DAST.



Sulfite esters are the major components from reaction of DAST with hexane-1,2-diol and cyclohexane-1,2-diol. Fluorohydrins **7** and **8** were converted into the difluoride **6** when excess DAST was added. Reaction of DAST with cyclohexane-1,2-diol gave fluorohydrin **12** only when less than two equivalents DAST were used. The fluorohydrin **12** was also converted into the difluoride **13** with DAST.



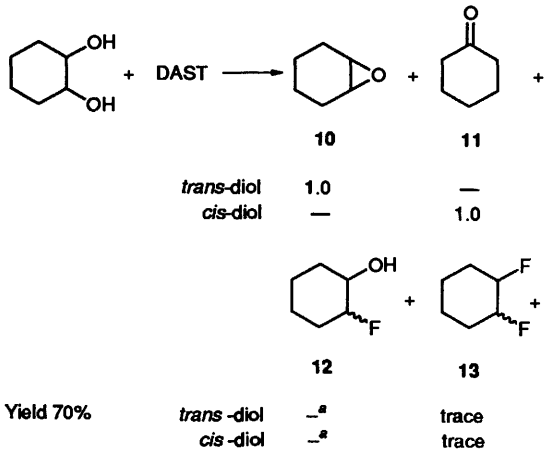
We turned our attention to reaction of DAST with primary diols. Product distributions and yields are given in Table 1. The sulfite esters were also found for reaction of DAST with ethylene glycol and propane-1,3-diol. A cyclic ether, tetrahydrofuran **21**, is the major product from butane-1,4-diol. The amount of cyclic ether decreases while the percentage of difluoride increases from butane-1,4-diol to hexane-1,6-diol (Table 1). Fluorohydrins were detected when less than 1.0 equiv. of DAST was used. These fluorohydrins were converted into the difluorides when additional DAST was added. Reactions of ethylene glycol, propane-1,3-diol and butane-1,4-diol were carried out in glyme or diglyme as the solvent since the diols were not soluble in methylene chloride. Reaction of pentane-1,5-diol in either diglyme or methylene chloride gave comparable results (Table 1). **CAUTION:** Some of these compounds are very toxic! †

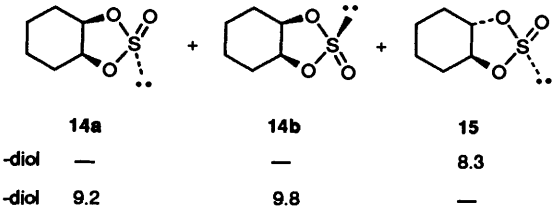
† Toxicology studies on α,ω-difluoroalkanes, ω-fluoroalkynes, ω-fluoroalkyl halides and ω-fluoro alcohols show that even-numbered carbon compounds are considerably more toxic than the odd-numbered carbon compounds. Presumably the even-numbered difluoroalkanes are metabolized to fluoroacetate. Extreme care should be exercised when working with these compounds. We worked with these compounds on small sample reactions (100–500 mg). For toxicology studies see: F. L. M. Pattison and R. E. A. Dear, *Can. J. Chem.*, 1963, **41**, 2600; F. L. M. Pattison and W. C. Howell, *J. Org. Chem.*, 1956, **21**, 748, and references therein.

Table 1 Products from DAST with terminal diols

X = Y = OH Diol	X = Y = F Difluoride[a]	X = F; Y = OH Fluorohydrin	Sulfite esters[a]	Cyclic ethers[b]	Yield (%)[c]
$n = 2$[d]	70[e]	—	20[c]	—	90
$n = 3$[f]	15	—	35	—	50
$n = 4$[d]	4	—	—	96	90
$n = 5$[d]	43	—	—	57	40
$n = 5$[g]	59	—	—	41	50
$n = 6$[g]	75	25[h]	—	0.5	60

[a] Compounds confirmed by independent synthesis. [b] Products identified by comparison of GC–MS with commercial samples. [c] Yield determined by GLC with chlorobenzene or naphthalene as an internal standard corrected for flame response. [d] Solvent diglyme. [e] Yield from ref. 2(*a*). [f] Solvent glyme. [g] Solvent methylene chloride. [h] Identified from spectral data and conversion with DAST into the difluoride.



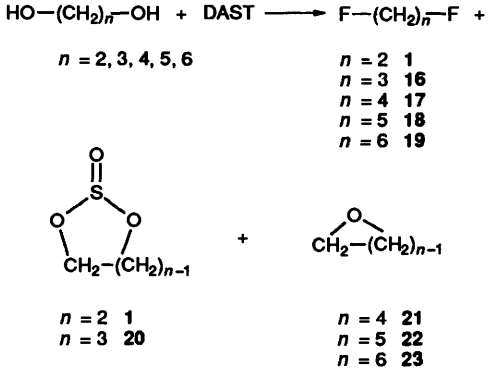


[a] The *cis* and *trans* isomers of **12** are only observed when less than two equivalents of DAST are used.

The structure of products **2**, **10**, **11**, **21**, **22** and **23** were confirmed by comparison of their GC–MS data with commercial samples. Products **1**, **3**, **4a**, **b**, **6**, **9a**, **b**, **12**, **13**, **14a**, **b**, **15**, **16**, **17**, **18**, **19** and **20** were identified by comparison of their GC–MS data with products from independent synthesis.[3–5] The difluoride **6** was independently prepared by reaction of xenon difluoride with hex-1-ene.‡

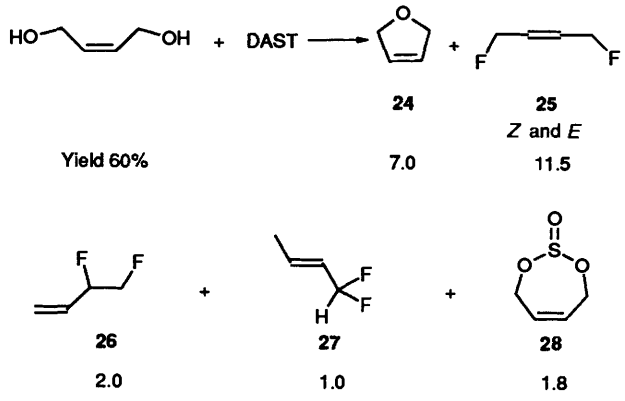
Sulfite esters **4a**, **b**, **9a**, **b**, **14a**, **b**, **15** and **20** were independently prepared by reaction of thionyl chloride with the corresponding diols.[6a,b] In the early literature these sulfite esters were characterized as a mixture of isomers. Pritchard and Laiterburg have shown that the protons (methine, methylene or methyl) of a cyclic sulfite *cis* to the S=O moiety resonate at lower fields

‡ Reaction of xenon difluoride with hex-1-ene in 2,2,2-trifluoroethanol as the solvent gives **6** as a major component in the reaction. Unpublished results.



relative to the *trans* protons.[7] We used this concept to assign the *cis* and *trans* structure of **4a**, **b**, **9a**, **b**, **14a**, **b** and **15**.

Reaction of (*Z*)-but-2-ene-1,4-diol with DAST in diglyme also gave the cyclic ether 2,5-dihydrofuran **24**, the sulfite ester **28**, and several difluorides. These products were identified by comparison of their GC–MS data with a commercial sample **24**, or prepared from reactions described in the literature. Compounds **25** and **26** were independently synthesized from reaction of xenon difluoride with buta-1,3-diene,[8] and **27** was prepared by reaction of DAST with crotonaldehyde. Compound **28** was independently synthesized from (*Z*)-but-2-ene-1,4-diol and thionyl chloride with the procedure used to prepare the other sulfite esters.[6a,b] Its structure was confirmed by NMR, IR and MS data.



We also treated tetraethylene glycol with the DAST reagent and found none of the cyclic ether or sulfite ester. The fluorohydrin **29** was converted into the difluoride **30** with subsequent reaction of DAST and chlorobenzene as an internal standard. Compound **30** was isolated by column chromatography.

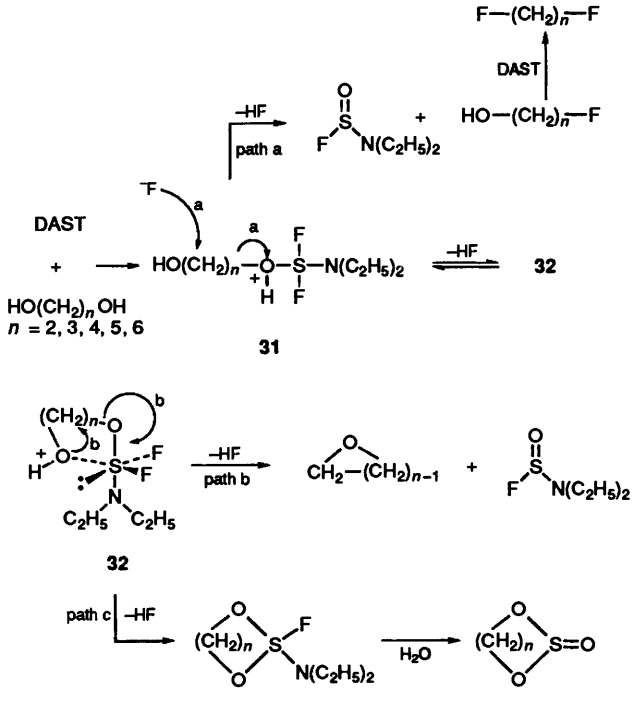
$O(CH_2CH_2OCH_2CH_2OH)_2$ + DAST ⟶ $X\text{-}(CH_2CH_2O)_3\text{-}CH_2CH_2\text{-}Y$

29 X = F; Y = OH

Yield 35%

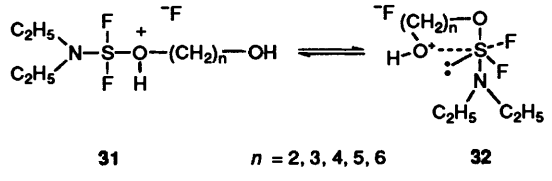
30 X = Y = F

Reaction of DAST with diols can give difluorides, cyclic ethers or sulfite esters (Scheme 1). Semiempirical calculations



Scheme 1

on the linear **31** and cyclic isomer **32** of the intermediates from reaction of DAST with terminal diols show that the free energy of the cyclic isomer is favoured for intermediates from 1,3- and 1,4-diols (Table 2).§ Thus for reaction of DAST with butane-1,4-

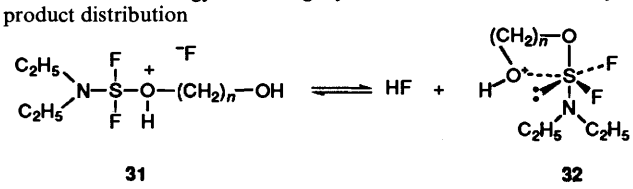


diol, collapse of the seven-membered ring (**32**, n = 4) to tetrahydrofuran (**21**) is found (Table 1). The decrease in cyclic ethers from **21** to **23** follows the decrease in the amount of cyclic intermediate **32** expected from semiempirical calculations (Table 2). An analogous cyclization to form cyclic ethers **21**, **22** and **23** was also observed for the dehydration in dimethyl sulfoxide of butane-1,4-diol, pentane-1,5-diol and hexane-1,6-diol, respectively.[9]

Even though semiempirical calculations show the cyclic intermediate (**32**, n = 3) is favoured for reaction of DAST with propane-1,3-diol, collapse to a four-membered ether (trimethylene oxide) was not observed. The cyclic intermediates (**32**, n =

§ AM1 semiempirical calculations using the SPARTAN software, Wavefunction, Inc., Irvine, CA.

Table 2 Free energy favouring cyclic intermediate **32** and cyclic product distribution



		Experimental data[b]	
n	kcal mol^{-1}[a]	% Cyclic ether	% Sulfite ester
3	−1.7	0	35
4	−3.7	96	0
5	−0.1	57	0
6	0.0	0.5	0

[a] Free energy favouring the cyclic intermediate **32**. Calculated with AM1 semiempirical calculations using the SPARTAN software, Wavefunction, Inc., Irvine, CA. [b] Percentage distribution of products.

3, 2) loses HF *via* path c in Scheme 1 to give sulfite esters **2** and **20**. Incorporation of sulfur into the final product was also observed by Coe for reaction of sulfur tetrafluoride with myo-inositol.[10]

Experimental

General Methods

DAST was purchased from Carbolabs, Inc. The remaining chemicals and solvents were obtained from Aldrich. (*Z*)-But-2-ene-1,4-diol and crotonaldehyde were distilled prior to use. NMR spectra were obtained on a Varian T60A (Point Loma Nazarene College), a Chemagnetics A200 (California State University at San Diego), a JEOL FX-90Q (Air Force Astronautics Laboratory, Edwards, CA), a Varian Unity 300 (University of San Diego). Spectra are relative to Me_4Si or $CFCl_3$. Mass spectral analyses were obtained at 70 eV on a Hewlett-Packard 5890 GC interfaced with an HP 5970A mass selective detector. Gas chromatography analysis was accomplished on an HP 5890 (fid detector) interfaced to a 3396A integrator. The GC and GC–MSD analyses were done with a 25 m Hewlett-Packard ultraperformance column of internal diameter 0.20 mm with a methyl silicone stationary phase of 0.33 μm film thickness. Infrared spectra were recorded neat with a Nicolet 620 Fourier Transform spectrometer. Gas-phase infrared were obtained on the Nicolet 620 interfaced with an HP 5890 gas chromatograph. The 25 m column for GC–FTIR analysis was identical with that used for GC and GC–MSD analyses above except for the internal diameter which was 0.3 mm.

Reaction conditions

The following reaction is representative. In a dry polypropylene bottle fitted with magnetic stirring bar and drying tube were placed 1.00 g (8.47 mmol) hexane-1,2-diol and 30 cm^3 dry (molecular sieves) methylene chloride. The mixture was cooled in an ice bath and DAST (2.74 g; 2.25 cm^3; 17.0 mmol) was added dropwise. After 30 min, 5% aqueous sodium hydrogen carbonate was added. The aqueous layer was washed with methylene chloride and the combined organic layers dried over anhydrous sodium sulfate. The mixture was concentrated with a rotary evaporator and water aspirator. Products were isolated by column chromatography on silica gel with pentane and pentane–diethyl ether as eluents. Methanol–ether was required to elute product **30** from the fluorination of tetraethylene glycol.

Reaction with ethylene glycol

Analysis by GC, initial temperature 50 °C for 1.0 min, then ramp 10 °C min^{-1} to 180 °C gave **2**, retention time 4.9 min, in 20% yield with napthalene as internal standard corrected for flame response. The product was confirmed by comparison of GC–MS data from a commercial sample of **2**. The yield of **1** was taken from the literature.[1a]

Reaction with terminal diols: propane-1,3-diol, butane-1,4-diol, pentane-1,5-diol and hexane-1,6-diol

Reactions were carried out as described above. Product distributions and yields are listed in Table 1. The presence of cyclic ethers detected (**21**, **22**, **23**) and undetected (ethylene oxide and trimethylene oxide) were demonstrated by comparison of GC–MS data with commercial samples. Sulfite ester **20** and the difluorides **16**, **17**, **18** and **19** were confirmed by comparison of spectral data with those obtained for products from independent synthesis.[3,6a,b] **Caution**: Some of these compounds are very toxic!† GC–MS data to confirm these products (**16**–**20**) with those found in our reactions are reported. GC–MS *m/z* (rel. intensity).

16: 60 (65), 59 (76), 47 (100), 33 (59). **17**: 74 (4), 73 (12), 61 (23), 59 (100), 54 (13), 47 (27), 46 (31), 41 (73), 39 (25), 33 (39), 29 (13), 28 (40), 27 (45). **18**: 88 (0.4), 75 (5), 61 (7), 55 (100), 47 (40), 42 (71), 41 (46), 39 (24), 33 (29). **19**: 102 (0.1), 82 (2), 74 (23), 69 (39), 67 (22), 59 (32), 56 (45), 55 (100), 47 (47), 41 (99), 33 (38). **20**: 122 (0.6), 92 (4), 65 (10), 58 (29), 57 (23), 43 (7), 41 (8), 32 (6), 29 (58), 28 (100), 27 (19).

Reaction of 2-methylpentane-2,4-diol

Analysis by GC, initial temperature 40 °C for 3 min, then ramp 5 °C min^{-1} to 180 °C gave products with the following retention times (min): **3** (3.4), **4a** (15.0), **4b** (15.7) in 80% yield with chlorobenzene as an internal standard. Difluoride **3** had the same GC–MS data as from independent synthesis (see below). Products **4a** and **4b** were isolated by column chromatography and their spectral data are identical with that obtained by independent synthesis.[6b]

4a δ_H(300 MHz; $CDCl_3$) 1.33 (s, 3 H), 1.34 (d, J = 6.3 Hz, 3 H), 1.74 (s, 3 H, axial methyl *cis* to S=O moiety), 1.74 (dd, J = 14.0 and 2.0 Hz, 1 H), 1.98 (dd, J = 14.0 and 11.6 Hz, 1 H) and 5.16 (dqd, J = 11.6, 6.3 and 2.0 Hz, 1 H, axial methine *cis* to S=O); δ_C(22.6 MHz; $CDCl_3$) 21.2, 28.8, 32.2, 44.0, 60.6 and 80.7; *m/z* (rel. intensity) 149 (0.1), 85 (4), 84 (1), 83 (19), 56 (63), 43 (100), 42 (31), 41 (42) and 29 (16); *m/z* (ci) 165 (M + 1). ν_{max}/cm^{-1} 2986m, 2944w, 1377m, 1214s, 1132w, 922s, 881m, 793m, 722w and 693w.

4b δ_H(200 MHz; $CDCl_3$) 1.43 (d, J = 6.2 Hz, 3 H), 1.49 (s, 3 H), 1.55 (s, 3 H, axial methyl *trans* to S=O), 1.69 (dd, J = 14.0 and 2.4 Hz, 1 H), 2.23 (dd, J = 14.0 and 12.0 Hz, 1 H) and 4.62 (dqd, J = 12.0, 6.2 and 2.4 Hz, 1 H, axial methine *trans* to the S=O). δ_C(22.6 MHz; $CDCl_3$) 22.1, 26.4, 31.5, 41.9, 70.4 and 81.7; *m/z* (rel. intensity) 149 (0.5), 85 (4), 84 (2), 83 (25), 56 (72), 43 (100), 42 (36), 41 (49) and 29 (18); *m/z* (ci) 165 (M + 1). ν_{max}/cm^{-1} 2986s, 2939m, 1377s, 1214s, 1142m, 928s, 874s, 796m and 685m.

Synthesis of 2,4-difluoro-2-methylpentane (3)

To 4-hydroxy-4-methylpentan-2-one (1.16 g, 0.010 mol) in dry methylene chloride (10 cm^3) in a dry solid CO_2 bath was added dropwise DAST (1.77 g, 0.011 mol). The mixture was warmed to 0 °C and then stirred for 10 min. Aqueous 5% sodium hydrogen carbonate was added to quench the reaction. The organic layer was separated, dried over anhydrous magnesium sulfate, and concentrated on a rotary evaporator. Analysis of the crude reaction mixture by NMR spectroscopy with benzene as an internal standard indicated a yield of 60%. Bulb-to-bulb distillation 30–33 °C (15 Torr) gave 0.46 g 4-fluoro-4-methylpentan-2-one, which was 95% pure according to GC with a retention time of 4 min; initial column temperature 50 °C for 4 min, then ramp at 10 °C min^{-1} to 180 °C. δ(300 MHz; $CDCl_3$) 1.43 (d, J = 22.0 Hz, 6 H), 2.21 (s, 3 H) and 2.76 (d, J = 17.7 Hz, 2 H); δ_F(282 MHz; $CDCl_3$) −133.7 (m); δ_C(75.4 MHz; $CDCl_3$) 26.9 (d, J = 23.8 Hz), 31.8 (s), 54.2 (d, J = 22.8 Hz), 93.8 (J = 166 Hz) and 202.6 (br s); *m/z* (rel. intensity) 103 (2), 98 (9), 61 (30), 58 (11), 56 (12) and 43 (100); ν_{max}/cm^{-1} 2990m, 2941w, 1730s, 1369m, 1214m, 1138w, 884w and 747m.

To 4-fluoro-4-methylpentan-2-one (430 mg, 3.60 mmol) in 4.0 cm^3 dry ether was added borane–dimethylamine complex (258 mg, 4.37 mmol). The mixture was stirred for 3 days and then worked up with 5% aqueous sodium hydrogen carbonate as described above. Bulb-to-bulb distillation at 40–50 °C (20–25 Torr) gave 300 mg 4-fluoro-4-methylpentane-2-ol (**5**). The following data were obtained for **5**: δ_H(300 MHz; $CDCl_3$) 1.21 (d, J = 6.2 Hz, 3 H), 1.42 (d, J = 22.0 Hz, 3 H), 1.44 (d, J = 22.0 Hz, 3 H), 1.57–1.96 (m, 2 H), 2.18 (br s, 1 H) and 4.17 (m, 1 H). δ_F(282 MHz; $CDCl_3$) −138.3 (m); δ_C(75.4 MHz; $CDCl_3$) 24.1 (s), 26.3 (d, J = 25.0 Hz), 28.3 (d, J = 24.6 Hz), 49.3 (d, J = 20.0 Hz), 64.6 (d, J = 2.7 Hz) and 97.0 (d, J = 162.1 Hz); GC–MS *m/z* (rel. intensity) 105 (0.8), 100 (0.3), 85 (15), 61 (4), 56 (100), 45 (84) and 41 (67); ν_{max}/cm^{-1} 3645w, 2985s, 2940m, 1381s, 1246w, 1160m, 1099w, 1053w and 800. To 120 mg (1.0 mmol) **5** in 0.5 cm^3 dry $CDCl_3$ at 0 °C with stirring was added DAST (175 mg, 1.1 mmol) in 0.5 cm^3 dry $CDCl_3$. After 30 min the mixture was worked up with 5% aqueous sodium hydrogen carbonate. The organic layer was separated and dried over anhydrous sodium sulfate. Compound **3** was isolated by preparative gas chromatography on a 10′ × $\frac{1}{4}$″ stainless steel column of 5% SE-30 on 80–100 Chromosorb W at 40 °C. Compound **3** was about 70% pure, the major impurity being mesityl oxide which did not interfere with the NMR analysis. The following data were obtained for **3**: δ_H(300 MHz, $CDCl_3$) 1.27 (dd, J = 24.1 and 6.2 Hz, 3 H), 1.40 (d, J = 21.1 Hz, 3 H), 1.43 (d, J = 21.1 Hz, 3 H), 2.99 (m, 2 H) and 4.92 (m, 1 H); δ_F(282 MHz; $CDCl_3$) −136.6 and −171.0; δ_C(75.4 MHz; $CDCl_3$) 25.9 (dd, J = 24.7 and 2.2 Hz), 27.3 (d, J = 25.6 Hz), 28.3 (dd, J = 24.0 and 1.5 Hz), 48.0 (dd, J = 22.6 and 20.1 Hz), 88.4 (dd, J = 164.0 and 5.8 Hz) and 94.4 (d, J = 165.4 Hz); *m/z* (rel. intensity) 107 (2), 102 (0.2), 87 (39), 61 (100), 60 (14), 59 (17), 47 (34), 42 (63), 41 (49) and 39 (19); ν_{max}/cm^{-1} 2990s, 2946m, 1383s, 1167m, 1143m, 1064w, 933w, 887w and 835w.

Reaction with hexane-1,2-diol

Analysis by GC, initial temperature 50 °C for 4 min, then ramp 10 °C min^{-1} to 180 °C gave products with the following retention times (min) **6** (4), **7** (5), **8** (6), **9a** (12), **9b** (13) in 65% yield with chlorobenzene as an internal standard. Product **6** was isolated by preparative GC at 70 °C on a 10′ × $\frac{3}{8}$″ stainless steel column of 5% Carbowax 20M on 80/100 Chromosorb G-HP. Products **7**, **8**, **9a** and **9b** were isolated by column chromatography. The following spectral data were obtained: **6** δ_H(90 MHz; $CDCl_3$) 0.93 (t, J = 5.7 Hz, 3 H), 1.2–1.6 (m, 6 H), 4.40 (ddd, J = 48, 24 and 5 Hz, 2 H) and 4.60 (ddm, J = 45–50 Hz and *ca.* 25 Hz, 1 H); δ_F(84 MHz; $CDCl_3$) −189 (m, 1 F) and −230 (tdd, 1 F). We also isolated **6** from a previous reaction of hex-1-ene with xenon difluoride in 2,2,2-trifluoroethanol as solvent.‡

† See footnote on p. 861.

‡ See footnote on p. 862.

7 δ_H(200 MHz; CCl_4) 0.93 (t, J = 6.0 Hz, 3 H), 1.2–1.7 (m, 6 H), 2.94 (s, 1 H), 3.76 (dm, J = 18 Hz, 1 H) and 4.24 (dm, J = 47 Hz, 2 H); δ_F(282 MHz; $CDCl_3$) −228.8 (td, J = 47 and 18 Hz); *m/z* (rel. intensity) 102 (0.1), 101 (0.1), 87 (32), 69 (100), 63 (25), 57 (12), 43 (36), 41 (74) and 31 (14); ν_{max}/cm^{-1} 3648w, 2967w, 2945s, 2888m, 1466w, 1384w, 1061m, 1025m, 953w and 923.

8 δ_H(200 MHz; CCl_4) 0.93 (t, J = 6.0 Hz, 3 H), 1.1–1.8 (m, 6 H), 3.41 (dd, J = 14.0 and 6.0 Hz, 2 H) and 3.80 (dm, $J \approx 40$ Hz, 1 H) and 4.80 (s, 1 H); δ_F(282 MHz; $CDCl_3$) −190 (m); *m/z* (rel. intensity) 102 (0.7), 101 (0.1), 87 (3), 69 (30), 63 (1), 57 (27), 43 (62), 41 (100) and 31 (85); ν_{max}/cm^{-1} 3649w, 2946w, 2883m, 1462w, 1384w, 1352w, 1061m, 1024m, 908w and 841w. The fluorohydrins **7** and **8** were converted into the known difluoride **6** by reaction with DAST.

9a δ_H(300 MHz; $CDCl_3$) 0.93 (t, J = 7.0 Hz, 3 H), 1.30–1.58 (m, 4 H), 1.76–2.03 (m, 2 H, $CH_2C_3H_7$ *cis* to the S=O), 4.33 (dd, J = 11.5 and 10.5 Hz, 1 H, ring methylene *cis* to S=O) and 4.44–4.54 (m, 2 H); δ_C(75.4 MHz; $CDCl_3$) 13.8, 22.4, 28.0, 33.1, 70.2 and 84.2; *m/z* (rel. intensity) 134 (0.8), 107 (61), 83 (30), 69 (24), 57 (59), 55 (39), 43 (72), 41 (100) and 29 (91); *m/z* (ci) 165 (M + 1); ν_{max}/cm^{-1} 2968m, 2948m, 1237s, 1466w, 978m, 741m and 660w. Isomer **9b** could not be obtained pure as it contained 15% **9a** after two chromatography runs. The following data were obtained: **9b** δ_H(300 MHz; $CDCl_3$) 0.93 (t, J = 7.0 Hz, 3 H), 1.29–1.53 (m, 4 H), 1.59–1.79 (m, 2 H, $CH_2C_3H_7$ *trans* to the S=O), 3.92 (dd, J = 8.2 and 7.2 Hz, 1 H, ring methylene *trans* to S=O), 4.69 (dd, J = 8.2 and 6.2 Hz, 1 H, ring methylene *cis* to S=O) and 4.93–5.03 (m, 2 H, methine *cis* to S=O); δ_C(75.4 MHz; $CDCl_3$) 13.2, 22.4, 27.5, 31.9, 71.7 and 80.2; *m/z* (rel. intensity) 134 (3), 107 (74), 83 (4), 69 (38), 57 (69), 55 (30), 43 (92), 41 (100) and 29 (99); *m/z* (ci) 165 (M + 1); ν_{max}/cm^{-1} 2970m, 2949m, 1238s, 1468w, 981m, 751m and 665w. Compounds **9a** and **9b** were also independently prepared by reaction of thionyl chloride with hexane-1,2-diol.

Reaction with *cis* and *trans*-cyclohexanediol

Analysis by GC, initial temperature 50 °C for 1 min, then ramp 10 °C min^{-1} to 180 °C gave products (70–80% yield, see the Results section for product distributions) with the following retention times (min): **10** (5.0), **11** (5.5), *cis*-**12** (5.7), *trans*-**12** (5.9), **13** (4.0), **14a** (11.4), **14b** (11.9) and **15** (11.7). The GC–MS data for **10** and **11** were identical with those obtained from commercial samples. The fluorohydrins **12** were not observed unless less than two equivalents of DAST was used. *trans*-2-Fluorocyclohexanol (**12**) was independently synthesized from cyclohexene oxide.[5] Proton and ^{19}F NMR and mass spectral data were identical with those reported in the literature.[11] The gas-phase GC/FT–IR data confirm the *trans* and *cis* structures of **12**, since the C–O, C–F and O–H stretch frequencies of the *cis* isomer are shifted to lower frequencies due to hydrogen bonding as follows: **12** *trans* [lit.,[12] ν_{max}(neat)/cm^{-1}] O–H 3645m, C–H 2950s, C–O 1084m, C–F 1039m; **12** *cis* O–H 3639m, C–H 2950s, C–O 1075m, C–F 990m.

The difluorides **13** were confirmed by treating the fluorohydrins **12** with DAST to give **13**, by independent synthesis,[4] and comparison of mass spectral data.[11b] Compounds **14a**, **14b** and **15** were isolated by column chromatography. Compound **15** was independent synthesized with thionyl chloride from *trans*-cyclohexane-1,2-diol; while **14a** and **14b** were prepared from *cis*-cyclohexane-1,2-diol.[6a,b] Spectral data for each of the three stereoisomers follow: **14a** δ_H(300 MHz; $CDCl_3$) 1.32–1.47 (m, 2 H), 1.62–1.80 (m, 2 H), 1.90–2.04 (m, 2 H), 2.17–2.32 (m, 2 H) and 4.47–4.55 (m, 2 H, methines *trans* to the S=O); δ_C(75.4 MHz) 21.1, 28.8 and 80.4; *m/z* (rel. intensity) 114 (0.6), 98 (4), 97 (12), 81 (89), 79 (31), 69 (48), 57 (32), 55 (51), 41 (100), 39 (42), 29 (68), 28 (73) and 27 (51); *m/z* (ci) 163 (M + 1); ν_{max}/cm^{-1} 2953s, 1238s, 979s, 741s and 659m.

14b (contains 7% **14a**) δ_H(300 MHz; $CDCl_3$) 1.30–1.48 (m, 2 H), 1.51–1.65 (m, 2 H), 1.68–1.80 (m, 2 H), 1.80–2.05 (m, 2 H) and 4.82–4.92 (m, 2 H, methine protons *cis* to the S=O); δ_C(75.4 MHz) 20.5, 27.6 and 78.2; *m/z* (rel. intensity) 114 (1.0), 98 (7), 97 (34), 81 (9), 79 (46), 69 (60), 57 (28), 55 (49), 41 (100), 39 (42), 29 (65), 28 (73) and 27 (53); *m/z* (ci) 163 (M + 1); ν_{max}/cm^{-1} 2957s, 1237s, 973s, 747s and 659m.

15 δ_H(300 MHz; $CDCl_3$) 1.19–1.72 (m, 4 H), 1.85–2.03 (m, 2 H), 2.28–2.40 (m, 2 H), 3.69 [ddd, J = 11.8, 9.9 and 4.1 Hz, 1 H, methine *trans* to S=O); decouple methine at 4.23 ppm, δ = 3.69 (dd, J = 11.8 and 4.1 Hz)] and 4.23 [ddd, J = 11.5, 9.9 and 4.1 Hz, 1 H, methine *cis* to S=O), decouple methine at 3.69 ppm, δ = 4.23 (dd, J = 11.5 and 4.1 Hz)]; δ_C(75.4 MHz) 23.2, 23.6, 28.3, 29.3, 80.3 and 86.4; *m/z* (rel. intensity) 114 (1.0), 98 (7), 97 (22), 81 (3), 79 (28), 69 (67), 57 (41), 55 (30), 41 (100), 39 (34), 29 (54), 28 (43) and 27 (41); *m/z* (ci) 163 (M + 1); ν_{max}/cm^{-1} 2958s, 1241s, 1024s, 742s and 641m.

Reaction with (*Z*)-but-2-ene-1,4-diol

Analysis by GC, initial temperature 40 °C for 2 min, then ramp 10 °C min^{-1} to 180 °C gave products (70% yield with cyclohexane as an internal standard, see results section for product ratios) with the following retention times (min): **24** (3.3), **25** (2.9), **26** (2.4), **27** (2.2) and **28** (19.3). Product **24** was confirmed by GC–MS and GC–FT-IR data from a commercial sample. Compounds **25** and **26** were independently synthesized by reaction of xenon difluoride with buta-1,3-diene,[8] and **27** was prepared by reaction of DAST with crotonaldehyde (see below). Compound **28** was independently synthesized from (*Z*)-but-2-ene-1,4-diol and thionyl chloride using the literature procedures for preparing sulfite esters.[6a,b] Compound **28** was isolated by distillation, bp 74–76 °C, 7.0 Torr in 35% yield. δ_H(300 MHz; $CDCl_3$) 5.82 (m, 2 H), 4.48 (m, 2 H) and 4.93 (m, 2 H); δ_C(75.4 MHz; $CDCl_3$) 60.9 and 128.7; *m/z* (rel. intensity) 134 (0.6), 104 (44), 78 (12), 70 (26), 69 (18), 55 (17), 48 (14), 42 (86), 41 (100), 40 (34), 39 (97), 29 (50), 28 (19) and 27 (34); ν_{max}(neat)/cm^{-1} 3044w, 2970w, 2935w, 2669w, 1450m, 1393w, 1203s, 1060m, 1003s, 975s, 912s, 874m, 798m, 738s, 683s and 635s.

Confirmation of 1,1-difluorobut-2-ene (27)

To 75 mg (1.0 mmol) freshly distilled crotonaldehyde and 4 cm^3 dry methylene chloride in a dry polypropylene bottle were added with stirring 345 mg (2.1 mmol) DAST. After 24 h the reaction was worked up as described in the literature.[1a] Analysis by GC, initial temperature 40 °C for 2 min, then ramp at 10 °C min^{-1} to 180 °C gave *Z*- and *E*-isomers of **27** with retention times at 2.5 and 2.6 min. No attempt was made to isolate **27**. The following data were identical with that obtained for **27** from reaction of DAST with (*Z*)-but-2-ene-1,4-diol. *m/z* (rel. intensity) (*E*)-**27** 92 (55), 77 (100), 73 (17), 71 (11), 64 (17), 53 (11), 51 (46), 46 (18), 41 (71) and 39 (72). (*Z*)-**27** 92 (58), 77 (100), 73 (16), 71 (11), 64 (18), 53 (13), 51 (50), 46 (19), 41 (85) and 39 (83). The *Z*- and *E*-isomers of **27** did not separate on the column for the GC–FT-IR. The following data were obtained on the *Z*–*E* mixture: 3012w, 2969m, 1683m, 1380m, 1124s, 1045s and 960m cm^{-1}. No attempt was made to isolate **27** pure.

Reaction with tetraethylene glycol

The reaction was carried out as described above in 35% yield determined by NMR spectroscopy with chlorobenzene as an internal standard. Fluorohydrin **29** was converted into the difluoride **30** by addition of an excess of DAST as followed by GC with chlorobenzene as an internal standard. Analysis by GC, initial temperature 60 °C with immediate ramping at 10 °C min^{-1}, to 180 °C gave **29** and **30** with retention times of 15 and 10 min, respectively. The solvent was evaporated off and the residue chromatographed on a silica gel column with pentane, ether and methanol as the eluent. The following data were

obtained for **30**: δ_H(200 MHz; $CDCl_3$) 3.58 (br d s, 8 H), 3.66 (dt, J = 27.5 and 4.4 Hz, 4 H) and 4.45 (dt, J = 47.8 and 4.4 Hz, 4 H); δ_F(282 MHz; $CDCl_3$) −223.9 (tt, J = 47.8 and 27.5 Hz); m/z (rel. intensity) $M - [^{\bullet}CH_2OH]$ 165 (0.5), 135 (1), 121 (2), 119 (2), 91 (15), 90 (9), 89 (12), 88 (4), 59 (8), 58 (7), 47 (21), 45 (100), 44 (11), 43 (14), 31 (17), 29 (14), 28 (11), 27 (12), 19 (6); ν_{max}/cm^{-1} 2954m, 2895m, 1135s and 1068m.

We were unable to isolate the fluorohydrin **29**. The following data were obtained for **29**: m/z (rel. intensity) $M - [FCH_2CH_2O^{\bullet}]$ 135 (0.5), 121 (6), 91 (35), 90 (17), 77 (4), 59 (4), 58 (0.8), 47 (39), 46 (4), 45 (100), 43 (12), 31 (14), 29 (9), 28 (9), 27 (13) and 19 (3); ν_{max}/cm^{-1} 3650w, 2950m, 2878m, 1130s and 1066m.

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