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Preparation, Characterization, and Crystal Structures of the SO_3NHF^- and SO_3NF_2^- Ions**

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Dedicated to Dr. Carl Schack
on the occasion of his 70th birthday

Recently, a new class of materials having high-energy, *gem*-bis(difluoroamino)-substituted heterocyclic nitroamines, has gained attention for use as high-energy oxidizers: HNF⁺₂^[1,2] and TNF⁺₂^[3] have been synthesized under strongly acidic conditions from their corresponding ketone derivatives by using an excess of difluoroamine.^[4]

HNF₂ is a shock-sensitive and thermally unstable gaseous compound,^[5,6] which can be generated from different precursors, for example, tetrafluorohydrazine,^[7] *N,N*-difluoro-urea,^[8] *N,N*-difluorocarbamates,^[9] or trityldifluoroamine.^[10] Of these precursors, only trityldifluoroamine is a stable,

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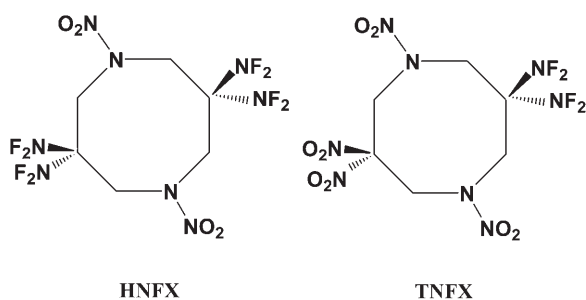
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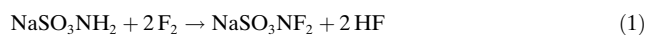


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storable solid. However, it is not useful as a general reagent for the preparation of larger quantities of *gem*-bis(difluoroamines) because its synthesis requires the use of expensive N_2F_4 , which is not commercially available and must be prepared from difluoroamine, and of equivalent amounts of mercury in an organic solvent. The use of mercury presents environmental problems, and working with N_2F_4 in an organic solvent can be hazardous. Therefore, it is highly desirable to develop a stable, solid, readily accessible difluoroamine source. Obvious candidates for HNF_2 sources are difluorosulfamate salts. Although the parent free acid HOSO_2NF_2 had been known since 1961 and has been widely used as a difluoroaminating reagent,^[11,12] no reports could be found on the existence of its salts. Herein, we report the results from two independent studies.

$\text{Na}^+\text{SO}_3\text{NF}_2^-$ was isolated by fluorinating aqueous sulfamic acid at 0°C , neutralizing the product with concentrated aqueous sodium hydroxide, filtering off the less-soluble sodium fluoride by-product, and drying the neutral solution under vacuum. This process was improved by direct fluorination of SO_3NH_2^- salts with diluted elemental fluorine in aqueous solutions at 0°C [Eq. (1)].



The reaction conditions were similar to those previously used for the fluorination of urea,^[8a] carbamates,^[9a] and sulfamide.^[13] The acidic reaction mixture was not stable above approximately 5°C , and the difluorosulfamate [Eq. (2)] rapidly hydrolyzed upon warming to ambient temperature.



The ease of this acid-catalyzed hydrolysis can account for the lack of previous reports of isolated salts of the difluorosulfamate anion. The isolation of difluorosulfamate salts required careful control of the reaction conditions and rapid removal of the water and HF by-product at 0°C in a vacuum. This method resulted in the isolation of pure, colorless NaSO_3NF_2 in 94% yield.

The dry sodium salt is stable at room temperature but decomposes when exposed to atmospheric moisture. It was stored in the dry argon atmosphere of a glove box for a period of 4 months without showing any sign of decomposition. The identity of the compound was established by the observed material balance, vibrational and multinuclear NMR spectroscopy, electronic structure calculations, and by converting

it into $[\text{PNP}][\text{SO}_3\text{NF}_2] \cdot \text{CH}_2\text{Cl}_2$ (PNP = bis(triphenylphosphoranylidene)ammonium) and determining its crystal structure.

The Raman and IR spectra of solid NaSO_3NF_2 are shown in the Supporting Information, and the observed frequencies and intensities are listed in Table 1. They were assigned by

Table 1: Comparison of observed and unscaled calculated MP2/6-311 + G(d) vibrational frequencies (cm^{-1}) and intensities for SO_3NF_2^- in point group C_s .

Mode	Approx. mode description	Observed ^{[a], [e]}		Calculated ^[b]
		IR	Raman	
a'	$\nu_1 \nu_{\text{as}} \text{SO}_3$	1309 vs	1304 [0.8]	1286 (364) [7.2 dp]
	$\nu_2 \nu_{\text{s}} \text{SO}_3$	1080 s	1089 [10.0]	1051 (59) [38 p]
	$\nu_3 \nu_{\text{s}} \text{NF}_2$	968 w	997 [4.0] 971 [0.9]	979 (72) [4.4 p]
	$\nu_4 \nu \text{SN}$	715 m	722 [5.5]	671 (64) [17 p]
	$\nu_5 \delta_{\text{as}} \text{SO}_3$	627 s 617 s	630 [1.1]	601 (140) [0.6 dp]
	$\nu_6 \delta_{\text{sciss}} \text{NF}_2$		526 [2.6]	521 (1.6) [7.3 p]
	$\nu_7 \delta_{\text{sym}} \text{SO}_3$	525 vw		501 (25) [4.6 p]
	$\nu_8 \delta_{\text{rock}} \text{SO}_3$	[c]	337 [4.3]	298 (1.6) [8.6 p]
	$\nu_9 \delta_{\text{wag}} \text{NF}_2$	[c]	264 [1.3]	224 (0.5) [2.4 p]
	$\nu_{10} \nu_{\text{as}} \text{SO}_3$	1284 vs	1267 [0.7]	1282 (362) [7.7 dp]
a''	$\nu_{11} \nu_{\text{as}} \text{NF}_2$	869 m	868 [1.6]	829 (75) [2.1 dp]
	$\nu_{12} \delta_{\text{as}} \text{SO}_3$	532 w	537 [2.0]	532 (35) [3.5 dp]
	$\nu_{13} \delta_{\text{rock}} \text{SO}_3$	[c]	390 [2.6]	325 (0.8) [0.8 dp]
	$\nu_{14} \delta_{\text{twist}} \text{NF}_2$	[c]	186 [1.3]	154 (0.02) [6.1 dp]
	$\tau \text{S-N}$	[c]	[d]	37 (0.00) [2.0 dp]

[a] As Na^+ salt. Relative Raman intensities given in brackets. [b] IR intensities given in kmol^{-1} (in parentheses) and Raman intensities given in $\text{\AA}^4 \text{amu}^{-1}$ (in brackets). [c] Not observed, IR spectrum recorded only between 4000 and 400 cm^{-1} . [d] Not observed, Raman spectrum recorded only between 3600 and 80 cm^{-1} . [e] In addition to the listed bands, IR bands at 1627 m, 1209 w, 1184 m, 565 w, and Raman bands at 1618 [0.5], 1321 [0.7], 572 [1.2] cm^{-1} were observed but were not assigned.

comparison with those calculated at the MP2^[14] level of theory with the 6-311 + G(d) basis set. Whereas the ^{19}F NMR spectrum of naturally abundant $[\text{N}^{14}]\text{NaSO}_3\text{NF}_2$ in CD_3CN gives only a broad resonance at $\delta = 34 \text{ ppm}$, the spectrum of an ^{15}N -labeled sample in the same solvent shows a sharp doublet at $\delta = 33.8 \text{ ppm}$ with $^1J(^{19}\text{F}-^{15}\text{N}) = 138 \text{ Hz}$. The ^{15}N NMR spectrum shows a sharp triplet at $\delta = -20.4 \text{ ppm}$ with the same $^1J(^{15}\text{N}-^{19}\text{F})$ coupling constant.

Colorless and air-stable $[\text{PNP}][\text{SO}_3\text{NF}_2]$ was obtained by neutralizing the fluorination reaction mixture, adding PNP^+Cl^- , and extracting with methylene chloride [Eq. (3)]. Single crystals of $[\text{PNP}][\text{SO}_3\text{NF}_2] \cdot \text{CH}_2\text{Cl}_2$ suitable for X-ray crystal structure determination were obtained by recrystallization from CH_2Cl_2 .



$[\text{PNP}][\text{SO}_3\text{NF}_2] \cdot \text{CH}_2\text{Cl}_2$ crystallizes in the triclinic space group $P\bar{1}$. The X-ray structure analysis reveals the presence of two isolated $[\text{PNP}]^+$ and $[\text{SO}_3\text{NF}_2]^-$ units together with two disordered CH_2Cl_2 molecules in the unit cell (packing diagrams are given in the Supporting Information). The

closest F...H and O...H contacts between neighboring cations and anions are 2.682 Å and 2.349 Å, respectively. The dimensions of the SO₃N skeleton of the SO₃NF₂[−] ion (Figure 1) are more similar to those of sulfamic acid^[15] than

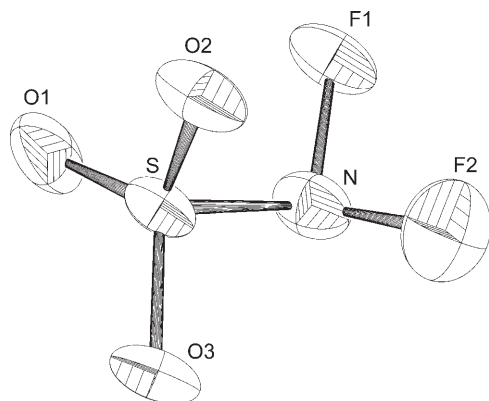
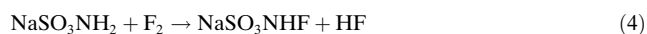


Figure 1. ORTEP drawing of the anion of [PNP][SO₃NF₂]·CH₂Cl₂. Thermal ellipsoids are shown at the 50% probability level. Bond lengths [Å] and angles [°]: S–O1 1.428(4), S–O2 1.424(3), S–O3 1.424(3), S–N 1.772(4), F1–N 1.412(5), F2–N 1.463(6); O1–S–O2 114.7(2), O1–S–O3 116.1(2), O2–S–O3 116.8(2), O1–S–N 100.1(2), O2–S–N 106.1(2), O3–S–N 99.3(2), F1–N–F2 99.0(3), F1–N–S 104.5(3), F2–N–S 99.6(3).

to the ones reported for salts with the SO₃NH₂[−] ion.^[16] Estimations of the double-bond character of the S–N bond are frequently made by comparison of the observed lengths with that predicted from Pauling's covalent radii (1.74 Å)^[17] or with the bond length in sulfamic acid (1.772(1) Å).^[15b] In the solid state, the latter has the zwitterionic structure ⁺NH₃–SO₃[−], which possesses a formal S–N single bond. The observed S–N bond length in SO₃NF₂[−] (1.772(4) Å) is similar to that in sulfamic acid and larger than the typical values found in the SO₃NH₂[−] ion (1.64 Å). The S–O bond lengths (1.428(8) Å and 1.424(3) Å) are shorter than the values reported for sulfamates (1.44–1.45 Å)^[16] and sulfamic acid (1.438(1) Å, 1.436(1) Å, and 1.435(1) Å).^[15b] The average O–S–O and O–S–N angles (115.9° and 101.8°, respectively) are in good agreement with those reported for sulfamic acid.

The marked differences in the S–N and S–O bond lengths between SO₃NF₂[−] and SO₃NH₂[−] can be readily reconciled by the large difference between the electronegativity values of hydrogen and fluorine. The strongly electron withdrawing fluorine atoms pull some of the negative charge away from the oxygen atoms, thereby increasing the S=O double-bond character and shortening the S–O bonds. By contrast, the electron-donating hydrogen atoms increase the electron density on the nitrogen atom, which passes it on to the S=O bonds. This results in partial N=S double bond character and increased negative charge on the oxygen atoms with concomitant lengthening of the S–O bonds.

When only one equivalent of fluorine was used in the fluorination reaction of SO₃NH₂[−], the SO₃NHF[−] ion was formed [Eq. (4)].



Colorless and somewhat moisture sensitive NaSO₃NHF was obtained when the acidic reaction mixture was evaporated in a vacuum at 0°C. The compound was identified and characterized by its vibrational spectra and by its crystal structure as the salt [PPh₄][SO₃NHF]. The Raman and IR spectra of NaSO₃NHF are shown in Supporting Information, and the observed frequencies and intensities are listed in Table 2 and were assigned by comparison with those calculated at the MP2^[11] level of theory with the 6-311 + G(d) basis set.

Table 2: Comparison of observed and unscaled calculated MP2/6-311 + G(d) vibrational frequencies (cm^{−1}) and intensities for SO₃NHF[−] in point group C₁.

Mode	Approx. mode description	Observed ^{[a],[d]}		Calculated ^[b]
		IR	Raman	(IR) [Raman]
ν ₁	ν NH	3100 s, br	3000 [1.3]	3481 (2.4) [69]
ν ₂	δ _{sciss} HNF	1522 w		1410 (30) [2.8]
ν ₃	ν _{as} SO ₃	1242 vs	1246 [1.3]	1270 (368) [7.3]
ν ₄	ν _{as} SO ₃	1213 vs	1225 [1.2]	1240 (401) [7.1]
ν ₅	ν _s SO ₃ /δ _{wag} NH	1064 s	1065 [10.0]	1041 (82) [27]
ν ₆	ν _s SO ₃ /δ _{wag} NH	1021 m	1014 [5.9]	1033 (45) [18]
ν ₇	ν NF	863 m	869 [4.3]	923 (38) [14]
ν ₈	ν SN	602 s	602 [5.0]	699 (161) [16]
ν ₉	δ _{as} SO ₃	590 s		584 (66) [4.5]
ν ₁₀	δ _{as} SO ₃	497 w	466 [2.6]	520 (26) [3.4]
ν ₁₁	δ _{sym} SO ₃	477 w	445 [3.0]	509 (26) [5.9]
ν ₁₂	δ _{rock} SO ₃	438 w	424 [3.7]	371 (0.1) [4.7]
ν ₁₃	δ _{rock} SO ₃		411 [3.0]	343 (8.1) [2.6]
ν ₁₄	δ _{wag} NF		[c]	215 (1.2) [1.1]
ν ₁₅	τ S–N		[c]	118 (1.9) [0.4]

[a] As Na⁺ salt. Relative Raman intensities given in brackets. [b] IR intensities given in km mol^{−1} (in parentheses) and Raman intensities given in Å⁴ amu^{−1} (in brackets). [c] Not observed, IR spectrum recorded only between 4000 and 400 cm^{−1}. [d] In addition to the listed bands, IR bands at 1313 m, 1168 s, 1082 s, 918 m, 897 m, 773 m, 731 s, 617 m and Raman bands at 1168 [1.0], 1153 [1.0], 913 [1.2], 666 [1.0] cm^{−1} were observed but were not assigned.

The [PPh₄][SO₃NHF] salt was obtained by metathesis in the same manner as shown in Equation (3). It crystallizes in the triclinic space group *P* $\bar{1}$. The X-ray structure analysis reveals the presence of two nonequivalent [PPh₄]⁺ and [SO₃NHF][−] units (packing diagrams are shown in the Supporting Information). One SO₃NHF[−] ion could be refined well, but the SO₃ group of the second ion is disordered. This results in a relatively high *R* factor of 8.16% for the refined structure. The closest F...H and O...H contacts between neighboring cations and anions are 2.566 Å and 2.373 Å, respectively. The ordered SO₃NHF[−] ion is depicted in Figure 2. The observed S–N bond length in SO₃NHF[−] (1.694(5) Å) lies between those observed for SO₃NF₂[−] (1.772(4) Å) and SO₃NH₂[−] (1.64 Å). This situation is in accord with the expectation that the electronic effect of an -NHF group is intermediate between those of an -NF₂ and an -NH₂ group.

The presence of one hydrogen atom and one fluorine atom attached to the same nitrogen atom was further established by proton and fluorine NMR spectroscopy. The

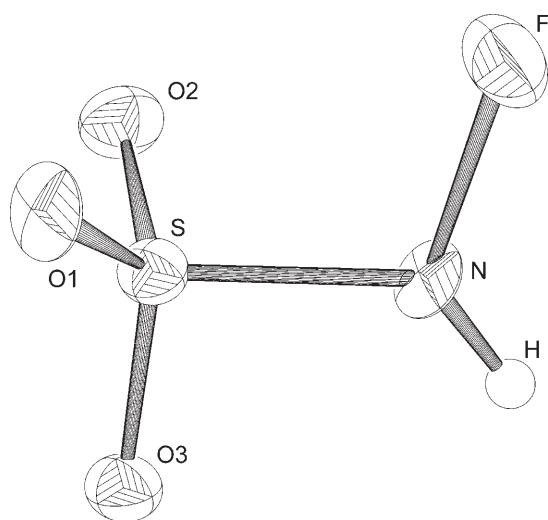


Figure 2. ORTEP drawing of the anion of $[\text{PPh}_4][\text{SO}_3\text{NHF}]$. Thermal ellipsoids are shown at the 50% probability level. Selected bond lengths [Å] and angles [°]: S–O1 1.433(4), S–O2 1.457(4), S–O3 1.447(3), S–N 1.694(5), F1–N 1.474(5), O1–S–O2 114.4(2); O1–S–O3 115.3(2), O2–S–O3 114.1(2), O1–S–N 108.5(2), O2–S–N 104.3(2), O3–S–N 98.0(2), F–N–S 106.4(3).

proton and fluorine spectra showed doublets at $\delta = 8.69$ and -103.0 ppm, respectively, with the same $^2J(^1\text{H}-^{19}\text{F})$ coupling constant (49 Hz).

The utility of NaSO_3NF_2 as an alternative source of difluoroamine in organic difluoroamination reactions was demonstrated by the transformation of carbonyl into *gem*-bis(difluoroamino) groups. Qualitative reactions of acetone, cyclohexanone, 3-pentanone, and 1-acetylpiperidin-4-one with the reagent in approximately 100% H_2SO_4 and 30% oleum showed formation of the expected *gem*-bis(difluoroamino)alkane by ^1H , ^{13}C , and ^{19}F NMR spectroscopy. In the case of 1-acetylpiperidin-4-one, only the oxygen atom of the ring-carbonyl group was replaced, whereas the carbonyl oxygen atom of the acetyl group did not react. A quantitative comparison was conducted by using 1,3-dibromoacetone as a model ketone. 1,3-Dibromo-2,2-bis(difluoroamino)propane was formed in 38% yield by using NaSO_3NF_2 in anhydrous H_2SO_4 containing approximately 1% SO_3 . This compares with a yield of 37% for conventional difluoroamination (HNF_2 in oleum) of 1,3-dibromoacetone.

Experimental Section

Materials and Apparatus (USC): All reactions were carried out in teflon-FEP ampules closed by stainless steel valves or pyrex glass vessels closed by grease-free Kontes glass-teflon valves. Volatile materials were handled in stainless steel/teflon-FEP^[18] or pyrex glass vacuum lines. Nonvolatile solids were handled in the dry argon atmosphere of a glove box. Infrared spectra were recorded in the range 4000–400 cm^{-1} on a Midac, M Series, FT-IR spectrometer using KBr pellets. The pellets were prepared inside the glove box using an Econo mini-press (Barnes Engineering Co.) and transferred in a closed container to the spectrometer before placing them quickly into the sample compartment, which was purged with dry nitrogen to minimize exposure to atmospheric moisture and potential hydrolysis of the sample. Raman spectra were recorded on a Bruker Equinox 55

FT-RA spectrometer using a Nd-YAG laser at 1064 nm with power levels of 100–200 mW and pyrex melting-point capillary tubes as sample containers. NMR spectra were recorded unlocked on Bruker AMX 500 and Varian Mercury/VX 400 NMR spectrometers at room temperature. The ^{19}F and ^{15}N NMR spectra were referenced to external samples of CFCl_3 and nitromethane, respectively.

The starting materials $\text{H}_2\text{NSO}_3\text{H}$, H_2SO_4 , $[\text{P}(\text{C}_6\text{H}_5)_4]\text{Cl}$, $[\text{PNP}]\text{Cl}$, NaOH (all Aldrich), $^{15}\text{N}_2$ urea (MSD Isotopes), and fluorine (Air Products and Chemicals Inc.) were used without further purification. Solvents were dried by standard methods and freshly distilled prior to use. NaSO_3NH_2 was obtained by neutralization of HSO_3NH_2 with NaOH . $^{15}\text{N}[\text{HSO}_3\text{NH}_2]$ was prepared from $^{15}\text{N}_2$ urea and H_2SO_4 according to a modified literature method.^[19]

NaSO_3NHF (USC): A solution of NaSO_3NH_2 (0.380 g, 3.19 mmol) in water (4 mL) was placed into a teflon-FEP ampule equipped with a teflon-coated magnetic stirring bar and a teflon gas-inlet tube. After cooling to 0°C, fluorine (3.19 mmol; 10% v/v in nitrogen) was introduced at a rate of 110 mL min^{-1} . The reaction mixture was pumped to dryness at 0°C, leaving behind a colorless solid (0.391 g; weight calcd for 3.19 mmol $\text{NaSO}_3\text{NHF} = 0.437$ g).

$[\text{PPh}_4][\text{SO}_3\text{NHF}]$ (USC): A solution of NaSO_3NH_2 (0.695 g, 5.00 mmol) in water (10 mL) was placed into a teflon-FEP ampule equipped with a magnetic stirring bar and a teflon gas-inlet tube. After cooling to 0°C, fluorine (5.00 mmol; 10% v/v in nitrogen) was introduced at a rate of 110 mL min^{-1} . The reaction mixture was neutralized by adding cold solid NaHCO_3 and filtered through a cold porcelain frit. A cold solution of PPh_4Cl (5.00 mmol) in water (50 mL) was added to the clear filtrate. The resulting milky solution was extracted three times with 50 mL of cold CH_2Cl_2 . The combined organic phases were dried over MgSO_4 and pumped to dryness at ambient temperature, leaving behind a colorless solid (2.039 g; weight calcd for 5.00 mmol $\text{PPh}_4\text{SO}_3\text{NHF} = 2.267$ g). Crystals were grown from a solution in CH_2Cl_2 by slow evaporation of the solvent with a stream of dry nitrogen.

NaSO_3NF_2 (USC): A solution of NaSO_3NH_2 (0.236 g, 1.98 mmol) in water (7 mL) was placed into a teflon-FEP ampule equipped with a magnetic stirrer and a teflon gas-inlet tube. After cooling to 0°C, fluorine (10% v/v in nitrogen) was introduced at a rate of 110 mL min^{-1} . After 45 min, the fluorination was discontinued, and the reaction mixture pumped to dryness at 0°C, leaving behind a colorless solid (0.288 g; weight calcd for 1.98 mmol $\text{NaSO}_3\text{NF}_2 = 0.307$ g).

NaSO_3NF_2 (TPL): Sulfamic acid (16.42 g, 0.169 mol) was dissolved in H_2O (30 mL), and NaOH (8.1 g, 0.20 mol) was added. Fluorine (10% v/v in nitrogen) was bubbled through the solution at 0°C. The progress of the fluorination of sulfamate was monitored by ^{19}F NMR spectroscopy of reaction aliquots to observe the conversion of monofluorosulfamate ($\delta = -102.1$ ppm vs. external CFCl_3 in $[\text{D}_6]\text{acetone}$) into difluorosulfamate ($\delta = 36.6$ ppm). After 1.5 h, the fluorination was complete, and the cloudy mixture was neutralized with concentrated aqueous NaOH . The NaF precipitate was removed by filtration. On the basis of its ^{19}F NMR spectrum, the filtrate appeared to be a 96:4 mixture of NaSO_3NF_2 and NaF . The viscous filtrate was quickly dried at room temperature in a vacuum desiccator over excess P_2O_5 . After 24 h, ^{19}F NMR spectroscopy of the dried solid showed the same $\text{SO}_3\text{NF}_2^-/\text{F}^-$ ratio as the initial filtrate.

$[\text{A}][\text{SO}_3\text{NF}_2]$ (A = PNP, PPh_4 , AsPh_4) (USC): A solution of NaSO_3NH_2 (0.357 g, 3.00 mmol) in water (10 mL) was placed into a teflon-FEP ampule equipped with a magnetic stirring bar and a teflon gas-inlet tube. After cooling to 0°C, fluorine (10% v/v in nitrogen) was introduced at a rate of 110 mL min^{-1} . After 60 min, the fluorination was discontinued, and the reaction mixture was neutralized by adding cold solid NaHCO_3 . The reaction mixture was filtered through a cold porcelain frit, and a cold aqueous solution of 3.00 mmol A^+Cl^- was added to the clear filtrate. The resulting milky solution was extracted three times with 10 mL of cold CH_2Cl_2 . The combined organic phases were dried over MgSO_4 and pumped to

dryness at ambient temperature, leaving behind colorless solids ([PPh₄][SO₃NF₂]: 1.283 g, calcd weight for 3.00 mmol = 1.414 g; [AsPh₄][SO₃NF₂]: 1.466 g, calcd weight for 3.00 mmol = 1.543 g; [PNP][SO₃NF₂]: 2.071 g, calcd weight for 3.00 mmol = 2.011 g). Crystals were grown from a solution in CH₂Cl₂ by slow evaporation of the solvent with a stream of dry nitrogen.

2,2-Bis(difluoroamino)propane and 1-acetyl-4,4-bis(difluoroamino)piperidine (USC): NaSO₃NF₂ (2.5 equiv.) was added in increments at 4 °C to a vigorously stirred mixture of CDCl₃ (1.5 mL), 30 % oleum (1.5 mL), and the ketone starting material (1.0 mmol). Immediate gas evolution was observed. After 15 min, the upper organic phase was analyzed by ¹⁹F, ¹H, and ¹³C NMR spectroscopy, showing the formation of the desired *gem*-bis(difluoroamines).

1,3-Dibromo-2,2-bis(difluoroamino)propane (TPL): 1,3-Dibromoacetone (24.72 g, 0.114 mol) was added to a mixture of sodium difluorosulfamate (61 g, ≤ 0.39 mol) in sulfuric acid (310 mL) containing approximately 1 % SO₃ (made from 30 % oleum plus concd H₂SO₄) plus 100 mL dichloromethane. The reaction mixture was stirred for 4 days at 0 °C, quenched in water, neutralized, and extracted with dichloromethane. Removal of the solvent produced 13.2 g of solute, the major constituent of which was 1,3-dibromo-2,2-bis(difluoroamino)propane (38 % crude yield). Three short-path distillations (room temperature at 1–3 Torr) produced material that was > 95 % pure (elemental analysis and ¹H NMR) with residual 1,3-dibromoacetone as the main impurity. ¹H NMR spectroscopy (200 MHz, CDCl₃, TMS): δ = 3.98 ppm (quint., 1.25 Hz). ¹³C{¹H} NMR spectroscopy (CDCl₃): δ = 23.75 (quint., 5.5 Hz), 99 ppm (m). ¹⁹F NMR spectroscopy (CDCl₃): δ = 29.9 ppm (s). ¹H NMR spectroscopy (C₆D₆): δ = 3.24 ppm (quint., 1.27 Hz). ¹³C NMR spectroscopy (C₆D₆): δ = 23.69 (quint., 5.7 Hz), 95.37 ppm (quint., 6.4 Hz). ¹⁹F NMR spectroscopy (C₆D₆): δ = 30.26 ppm (s). Elemental analysis calcd for (0.953)C₃H₄F₄N₂Br₂ + (0.047)C₃H₄Br₂O: C 12.08, H 1.35, N 8.78, F 23.83; found: C 12.12, H 1.30, N 8.93, F 23.53 %.

Theoretical Methods: The molecular structures and harmonic vibrational frequencies were calculated by using second-order many-body perturbation theory^[14] (denoted as MP2, but also known as MBPT(2)) and a 6-311 + G(d) basis set. Hessians (energy second derivatives) were calculated for the final equilibrium structures to determine if they were minima (positive definite hessian) or *n*th-order transition states (“*n*” negative eigenvalues). All calculations were performed by using the electronic structure code GAMESS.^[20]

X-ray structure determination: The collection, reduction, and processing of X-ray data was described previously.^[21] Crystal data for C₃₇H₃₂Cl₂F₂N₂O₃P₂S: *M*_r = 755.55, triclinic, space group *P*1̄, *a* = 11.8650(12), *b* = 11.9167(12), *c* = 14.5180(15) Å, α = 66.755(2), β = 68.964(2), γ = 71.034(2)°, *V* = 1719.7(3) Å³, *F*(000) = 780, ρ_{calcd} (*Z* = 2) = 1.459 g cm^{−3}, μ = 0.395 mm^{−1}, approximate crystal dimensions 0.29 × 0.21 × 0.05 mm³, θ range = 1.58 to 27.49°, index ranges −15 ≤ *h* ≤ 12, −15 ≤ *k* ≤ 12, −18 ≤ *l* ≤ 18, MoKα (λ = 0.71073 Å), *T* = 133(2) K, 10657 measured reflections, of which 7433 (*R*_{int} = 0.0487) were unique, data to parameters ratio = 16.9:1, final *R* indices [*I* > 2σ(*I*): *R*1 = 0.0731, *wR*2 = 0.1949, *R* indices (all data): *R*1 = 0.1087, *wR*2 = 0.2102, GOF on *F*² = 1.012.

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CCDC-274108 and -274109 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge

from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

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