Dinitrogen Difluoride Chemistry. Improved Synthesis of cis- and trans-\( \text{N}_2\text{F}_2 \), Synthesis and Characterization of \( \text{N}_2\text{F}^+\text{SnF}_9 \), Ordered Crystal Structure of \( \text{N}_2\text{F}^+\text{SnF}_{11} \), High-Level Electronic Structure Calculations of cis-\( \text{N}_2\text{F}_2 \), trans-\( \text{N}_2\text{F}_2 \), \( \text{F}_2\text{N}^=\text{N} \), and \( \text{N}_2\text{F}^+ \), and Mechanism of the trans-cis Isomerization of \( \text{N}_2\text{F}_2 \) (Preprint)

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N2F+ salts are important precursors in the synthesis of N5+ compounds, and better methods are reported for their larger scale production. A new, marginally stable N2F+ salt, N2F+Sn2F9-, was prepared and characterized. An ordered crystal structure was obtained for N2F+Sn2F11-, resulting in the first observation of individual N=N and N-F bond distances for N2F+ in the solid phase. The observed N=N and N-F bond distances of 1.089(9) and 1.257(8) Å, respectively, are among the shortest experimentally observed N-N and N-F bonds. High-level electronic structure calculations at the CCSD(T) level with correlation-consistent basis sets extrapolated to the complete basis limit show that cis-N2F2 is more stable than trans-N2F2 by 1.4 kcal/mol at 298 K. The calculations also demonstrate that the lowest uncatalyzed pathway for the trans-cis isomerization of N2F2 has a barrier of 60 kcal/mol and involves rotation about the N=N double bond. This barrier is substantially higher than the energy required for the dissociation of N2F2 to N2 and 2 F. Therefore, some of the N2F2 dissociates before undergoing an uncatalyzed isomerization, with some of the dissociation products probably catalyzing the isomerization. Furthermore, it is shown that the trans-cis isomerization of N2F2 is catalyzed by strong Lewis acids, involves a planar transition state of symmetry Cs, and yields a 9:1 equilibrium mixture of cis-N2F2 and trans-N2F2. Explanations are given for the increased reactivity of cis-N2F2 with Lewis acids and the exclusive formation of cis-N2F2 in the reaction of N2F+ with F-. The geometry and vibrational frequencies of the F2N=N isomer are also calculated and imply strong contributions from ionic N2F+-F- resonance structures, similar to those in F3NO and FNO.

14. ABSTRACT

15. SUBJECT TERMS
Dinitrogen Difluoride Chemistry. Improved Syntheses of cis– and trans–$N_2F_2$, Synthesis and Characterization of $N_2F^+$Sn$_2F_9$-, Ordered Crystal Structure of $N_2F^+$Sb$_2F_{11}$-, High-Level Electronic Structure Calculations of cis-$N_2F_2$, trans-$N_2F_2$, F$_2$N=N, and N$_2F^+$, and Mechanism of the trans-cis Isomerization of N$_2F_2$† (Preprint)

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†This paper is dedicated to the memory of Ira B. Goldberg
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Abstract

N$_2$F$^+$ salts are important precursors in the synthesis of N$_5^+$ compounds, and better methods are reported for their larger scale production. A new, marginally stable N$_2$F$^+$ salt, N$_2$F$^+$Sn$_2F_9$-, was prepared and characterized. An ordered crystal structure was obtained for N$_2$F$^+$Sb$_2F_{11}$-, resulting in the first observation of individual N≡N and N-F bond distances for N$_2$F$^+$ in the solid phase. The observed N≡N and N-F bond distances of 1.089(9) and 1.257(8) Å, respectively, are among the shortest experimentally observed N-N and N-F bonds. High-level electronic structure calculations at the CCSD(T) level with correlation-consistent basis sets extrapolated to the complete basis limit show that cis-N$_2$F$_2$ is more stable than trans-N$_2$F$_2$ by 1.4 kcal/mol at 298 K.

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The calculations also demonstrate that the lowest uncatalyzed pathway for the trans-cis isomerization of N$_2$F$_2$ has a barrier of 60 kcal/mol and involves rotation about the N=N double bond. This barrier is substantially higher than the energy required for the dissociation of N$_2$F$_2$ to N$_2$ and 2 F. Therefore, some of the N$_2$F$_2$ dissociates before undergoing an uncatalyzed isomerization, with some of the dissociation products probably catalyzing the isomerization. Furthermore, it is shown that the trans-cis isomerization of N$_2$F$_2$ is catalyzed by strong Lewis acids, involves a planar transition state of symmetry $C_s$, and yields a 9:1 equilibrium mixture of cis-N$_2$F$_2$ and trans-N$_2$F$_2$. Explanations are given for the increased reactivity of cis-N$_2$F$_2$ with Lewis acids and the exclusive formation of cis-N$_2$F$_2$ in the reaction of N$_2$F$^+$ with F. The geometry and vibrational frequencies of the F$_2$N=N isomer have also been calculated and imply strong contributions from ionic N$_2$F$^+$ F$^-$ resonance structures, similar to those in F$_3$NO and FNO.
Introduction

Polynitrogen compounds possess high energy and hold great potential as propellants and explosives. In 1999, the isolation of an exciting new polynitrogen compound, N$_5^+$AsF$_6^-$, was reported. The synthesis of N$_5^+$AsF$_6^-$ and other N$_5^+$ salts was achieved by reacting N$_2$F$^+$ salts with HN$_3$ in a suitable solvent. The following 5-step process, originally used for generating the required N$_2$F$^+$ salt (Scheme 1), was expensive, time consuming and sometimes gave undesirable by-products.

\[
\text{C}_x + \text{AsF}_5 \rightarrow \text{C}_x\cdot\text{AsF}_5 \quad (x = 10-12) \quad (1)
\]

\[
2\text{C}_x\cdot\text{AsF}_5 + \text{N}_2\text{F}_4 \rightarrow 2\text{C}_x^+\text{AsF}_6^- + \text{trans-N}_2\text{F}_2 \quad (2)
\]

\[
\text{trans-N}_2\text{F}_2 + \text{AsF}_5 \rightarrow \text{N}_2\text{F}^+\text{AsF}_6^- \quad (3)
\]

\[
\text{N}_2\text{F}^+\text{AsF}_6^- + \text{NaF} \rightarrow \text{NaAsF}_6 + \text{cis-N}_2\text{F}_2 \quad (4)
\]

\[
\text{cis-N}_2\text{F}_2 + \text{MF}_5 \rightarrow \text{N}_2\text{F}^+\text{MF}_6^- \quad (5)
\]

Scheme 1

The synthesis of N$_2$F$^+$ salts required the commercially unavailable N$_2$F$_2$. The latter can exist as both a cis– and a trans–isomer, but only the cis–isomer reacts readily at ambient or sub-ambient temperatures with strong Lewis acids to form the desired N$_2$F$^+$ salts. Both isomers are planar, with $C_{2v}$ symmetry for the cis– and $C_{2h}$ symmetry for the trans–isomer. The cis–isomer has been reported to be thermodynamically slightly more stable than the trans–isomer. While most preparative methods for N$_2$F$_2$ result in mixtures of both isomers, its most convenient synthesis involving the reduction of N$_2$F$_4$ with graphite/AsF$_5$ intercalates, produces only the less reactive trans–isomer which must then be converted into the cis–isomer. Although trans–cis isomerization has been reported to occur above 225 °C in a copper flow tube, the uncatalyzed
reaction has a very high activation energy barrier with calculated values\textsuperscript{4} ranging from 65 to 85 kcal mol\textsuperscript{-1}. However at these temperatures, the thermal decomposition of N\textsubscript{2}F\textsubscript{2} to NF\textsubscript{3}, N\textsubscript{2} and F\textsubscript{2} proceeds quite readily. Therefore, the high temperature gas phase isomerization must compete with the decomposition reaction which might result in autocatalysis and renders the isomerization reaction difficult to control. A reported experimental barrier\textsuperscript{7} of only 32 kcal mol\textsuperscript{-1} for the gas phase isomerization reaction is suspect\textsuperscript{8} and needs verification. Isomerizations at temperatures below 225 °C involve long induction periods of weeks or months consistent with the calculated high barriers and the possible need for creating first catalytically active metal fluoride surfaces by the reaction of some fluorine decomposition product with metal components. Therefore, finding convenient and reproducible isomerization conditions was important for scale-up reactions. In the past\textsuperscript{1,9}, this problem had been overcome by reacting \textit{trans}–N\textsubscript{2}F\textsubscript{2} with the strong Lewis acid AsF\textsubscript{5} under carefully controlled conditions, 75 °C and elevated pressure, to give N\textsubscript{2}F\textsuperscript{+}AsF\textsubscript{6}\textsuperscript{−}. Subsequent displacement reactions of the resulting N\textsubscript{2}F\textsuperscript{+}AsF\textsubscript{6}\textsuperscript{−} with a strong Lewis base, such as FNO or alkali metal fluorides in HF solution, resulted in the exclusive formation of \textit{cis}–N\textsubscript{2}F\textsubscript{2}, thus providing a high-yield but cumbersome method for the synthesis of pure \textit{cis}–N\textsubscript{2}F\textsubscript{2}, which then could be used for the synthesis of N\textsubscript{2}F\textsuperscript{+} salts other than AsF\textsubscript{6}\textsuperscript{−}.

Further drawbacks of the previous process\textsuperscript{1} were the use of expensive Highly Oriented Pyrolytic Graphite (HOPG) for preparing the AsF\textsubscript{5} intercalate and the need for long reaction times, stoichiometric amounts of AsF\textsubscript{5} and an extra step, the displacement reaction. In this paper experimental solutions are presented which mitigate these problems. Using high-level quantum chemical calculations, a better understanding of the underlying chemistry was also gained and some of the questions concerning the mechanism and thermodynamics of the N\textsubscript{2}F\textsubscript{2} \textit{trans}–\textit{cis}
isomerization \(^9\) were answered. With the crystal structure of \(\text{N}_2\text{F}^+\text{Sb}_2\text{F}_{11}^-\), the first ordered structure of an \(\text{N}_2\text{F}^+\) salt was determined and the synthesis of the new \(\text{N}_2\text{F}^+\text{Sn}_2\text{F}_9^-\), is communicated. In addition, a theoretical study of the \(\text{F}_2\text{N}=\text{N}\) isomer was carried out, resulting in the prediction of an unusual structure with highly ionic N-F bonds, similar to those found in \(\text{F}_3\text{NO}^{10}\) and \(\text{FNO}^{11,12}\).

**Experimental Section**

**Caution!** Some of the compounds used in this study are strong oxidizers and anhydrous HF is corrosive and can cause severe burns on contact with skin. Recommended safety precautions include the wearing of face shields, leather gloves and protective leather clothing.

**Materials and Apparatus:** Arsenic pentafluoride (Advanced Research Chemicals) and \(\text{N}_2\text{F}_4\) (Air Products) were purified by fractional condensation prior to use. Fluorine (Allied Chemical) and antimony pentafluoride (Ozark Mahoning) were used as received. Powdered natural graphite flakes (Asbury Graphite Mills, No. 3243 50-60 µ) were treated with 360 torr of fluorine gas to remove traces of moisture and reactive impurities before their intercalation with \(\text{AsF}_5\). Hydrogen fluoride (Matheson Co.) was dried over \(\text{BiF}_3\) as described earlier.\(^{13}\) Due to the corrosive and hazardous nature of the compounds used during this work, a stainless steel Teflon-FEP vacuum line, fitted with Hoke valves, was used.\(^{14}\) The vacuum line and all reaction vessels were passivated with \(\text{ClF}_3\) prior to use. Pressures were measured with a Heise-Bourdon tube-type gauge (0-1500 mm ± 0.1%). All non-volatile materials were handled in the inert atmosphere of a glove box.

Infrared spectra were recorded on a Mattson Galaxy FTIR spectrometer. The Raman spectra were measured either on a Cary Model 83GT spectrometer using the 488-nm line of an
Ar-ion laser or on a Bruker Equinox 55 spectrometer using the 1064 nm line of a Nd-Yag laser. The infrared spectra of gaseous samples were taken using a Monel IR cell equipped with a stainless steel valve and AgCl windows. The spectra of solid samples were recorded as powders pressed between AgCl or AgBr windows.

The single crystal X-ray diffraction data were collected on a Bruker 3-circle platform diffractometer equipped with a SMART CCD (charge coupled device) detector with the χ-axis fixed at 54.74° and using MoKα radiation (λ = 0.71073 Å) from a fine-focus tube. This diffractometer was equipped with an LT-3 apparatus for low-temperature data collection using controlled liquid nitrogen boil off. Single crystals were selected in a glovebox, equipped with a CCD camera mounted microscope, and immersed in a culture slide’s cavity containing PFPE (perfluoropolyether) oil. The culture slide was then taken out of the glovebox, and a suitable crystal was scooped out with a magnetic Cryoloop and mounted in a cold nitrogen stream on the magnetic goniometer head. Cell constants were determined from 90 30-sec frames. A complete hemisphere of data was scanned on omega (0.3°) with a run time of 30-sec per frame at a detector resolution of 512 x 512 pixels using the SMART software. A total of 1271 frames were collected in three sets. A final set of 50 frames, identical to the first 50 frames, was also collected to determine if any crystal decay had occurred. The frames were then processed on a PC by using the SAINT software to give the hkl file corrected for Lp/decay. The absorption correction was performed using the SADABS program. The structures were solved by the direct method using the SHELX-90 program and refined by the least squares method on F2, SHELXL-97, incorporated in SHELXTL Suite 5.10 for Windows NT. All atoms were refined anisotropically. For the anisotropic displacement parameters, the U(eq) is defined as one third of the trace of the orthogonalized Uij tensor.
**Intercalation of Graphite with AsF₅.** Natural graphite flakes (120 g, 1 mol based on C₁₀) were loaded into a prepassivated 1 L Monel cylinder, which was then attached to a steel vacuum line and evacuated. Teflon filters were used to prevent any graphite powder from being blown into the line. About 25 mmol of fluorine gas was slowly bled into the evacuated cylinder. After keeping the cylinder for 12 h at room temperature, unreacted fluorine was pumped off and passed through a –196 °C trap followed by a soda-lime scrubber. The volatiles trapped at –196 °C, consisted mainly of CO₂, CF₄, SiF₄, HF, and a trace of C₂F₆. Then, AsF₅ (173 g, 1.02 mol) was slowly bled at room temperature into the reactor, and a rapid pressure drop indicated the onset of intercalation. The total AsF₅ addition took about 2 h, after which the AsF₅ uptake became negligible. At this point, the cylinder was cooled to –196 °C and the remaining AsF₅ was condensed in. The cylinder was warmed to room temperature for ~72 h after which time the volatiles were pumped off through a –196 °C trap. The contents of this trap consisted of small amounts of AsF₃, CF₄ and SiF₄ and showed only traces of AsF₅. The graphite showed a weight gain of 141g (0.83 mol of AsF₅) indicative of a first stage intercalate having the approximate composition C₁₂AsF₅. This intercalate was subsequently used to reduce the N₂F₄ to N₂F₂.

In a separate experiment, the cylinder was heated to 45 °C after condensing the AsF₅ onto the graphite. This resulted in a lower weight uptake and the generation of large amounts of AsF₃ along with other decomposition products. Therefore, heating must be avoided when carrying out the intercalation reaction.

**Reduction of N₂F₄ with the Graphite Intercalate.** This reaction was carried out as described by Selig,⁵ but the reaction time was reduced to ~38 h as opposed to ~5 days. In a typical experiment, 200 mmol of N₂F₄ was condensed at –196 °C into an evacuated 300 mL stainless steel reactor containing 138 mmol of C₁₂AsF₅. The cylinder was allowed to warm
slowly to room temperature and kept at this temperature for 38 h. Noncondensible material, mainly nitrogen gas, was removed by evacuating the reactor at –196 °C. The room temperature volatiles were fractionated through traps held at –156 and –196 °C. The –156 °C trap contained \textit{trans}-N$_2$F$_2$ (194.5 mmol, ~97% yield based on N$_2$F$_4$), while the –196 °C trap contained some NF$_3$ and CF$_4$.

**Isomerization Reactions of trans–N$_2$F$_2$.** A reaction between \textit{trans}–N$_2$F$_2$ (103 mmol) and SbF$_5$ (19.42 mmol) was carried out in a 100 mL Monel cylinder for 6 days at room temperature. The cylinder was then cooled to –196 °C and checked for any non-condensable material. None was detected. It was then kept in a –64 °C bath, and the volatiles were pumped through traps held at –156 and –196 °C. Nothing was trapped at –156 °C, and the –196 °C trap contained mainly \textit{cis}–N$_2$F$_2$ (~75 mmol) and smaller amounts of \textit{trans}–N$_2$F$_2$, NF$_3$ and CF$_4$. In the reactor, a white solid remained consisting of N$_2$F$^+$/Sb$_2$F$_{11}^-$ (~3.5g).

In another experiment, a 30 mL passivated 316-stainless steel cylinder was loaded in the glove box with AlF$_3$ (0.7mmol) and attached to the vacuum line. The cylinder was evacuated and treated with 800 torr of F$_2$ for 16 h at room temperature. After removal of the F$_2$, the cylinder was cooled to –196 °C, evacuated, and \textit{trans}–N$_2$F$_2$ (12.1 mmol) was condensed in. The reactor was allowed to warm to room temperature and then heated in an oil bath to 55 °C for 16 h, cooled to room temperature. It was checked for any non-condensable material at –196 °C, but none was detected. The room-temperature volatiles (12.0 mmol) were trapped at –196 °C and consisted of \textit{cis}–N$_2$F$_2$ (90 %), \textit{trans}–N$_2$F$_2$ (10 %) and a trace of NF$_3$.

When this experiment was repeated under identical conditions in a prepassivated 316-stainless steel reactor but in the absence of AlF$_3$, identical results (90 % \textit{cis}– and 10 % \textit{trans}–N$_2$F$_2$) were obtained.
However, when the experiment was scaled up to 40 mmol of trans–N$_2$F$_2$ in the same size 30 mL prepassivated 316-stainless steel cylinder, a strongly exothermic reaction occurred upon insertion into the oil bath at 55 °C, resulting in a sharp temperature rise and complete decomposition of the trans–N$_2$F$_2$ to NF$_3$, N$_2$ and F$_2$.

In a separate experiment, a 10 mL Teflon-FEP reactor, containing 30 mg of AlF$_3$, was loaded with trans–N$_2$F$_2$ (0.77 mmol) and heated to 55 °C for 16 h, resulting in a 90 % conversion of trans–N$_2$F$_2$ to cis–N$_2$F$_2$.

In a similar experiment in a Teflon reactor but in the absence of AlF$_3$, no isomerization of trans–N$_2$F$_2$ was observed.

**Preparation of N$_2$F$^+$SbF$_6^-$ and N$_2$F$^+$Sb$_2$F$_{11}^-$.** In order to obtain well-defined stoichiometries, exact amounts of SbF$_5$ and cis–N$_2$F$_2$ were combined in anhydrous HF solution. For this purpose, a prepassivated Teflon ampule, equipped with a stainless steel Hoke valve and a Teflon coated magnetic stirring bar, was loaded in the glove box with SbF$_5$ (20.3 mmol), attached to the vacuum line and evacuated at –196 °C. Anhydrous HF (~2 mL) was condensed into the ampule, and the reaction mixture was allowed to warm to ambient temperature to dissolve the SbF$_5$. The ampule was cooled to –196 °C, and a slight excess of cis–N$_2$F$_2$ (~22 mmol) was added. The ampule was allowed to warm slowly toward room temperature and then stirred vigorously for about 10 min. The volatiles were pumped off at –64 °C for 2 h until a constant weight was attained, leaving behind a white free flowing powder. The observed weight gain (5.71 g) corresponded to the formation of 20.2 mmol of N$_2$F$^+$SbF$_6^-$ (99.7% yield based on SbF$_5$).

The N$_2$F$^+$Sb$_2$F$_{11}^-$ salt was prepared in a similar manner by reacting 3.1 mmol of SbF$_5$ with 3.1 mmol of N$_2$F$^+$SbF$_6^-$ in ~2 mL of HF. N$_2$F$^+$Sb$_2$F$_{11}^-$ was obtained as a white flaky solid in
quantitative yield. The infrared and Raman spectra of these compounds agreed well with those reported in literature.\textsuperscript{9,21-25}

**Synthesis of $N_2F^+Sn_2F_9^-$**. When anhydrous HF suspensions of SnF$_4$ were treated for several days at ambient temperature in either Teflon-FEP ampules or 316-stainless steel cylinders with a two- to four-fold molar excess of $cis$–N$_2$F$_2$, white solid residues were obtained upon removal of the volatile products. Based on the observed material balances, the combining ratios of SnF$_4$ : $cis$–N$_2$F$_2$ were always very close to 2 : 1. The Raman and infrared spectra of these solids showed the presence of bands due to N$_2$F$^+$ cations\textsuperscript{9,21-25} and tin fluoride anions.\textsuperscript{26-28} Therefore, the empirical composition of these solids is best described as N$_2$F$^+Sn_2F_9^-$. In one instance, a solid was obtained with a composition closer to 1:1, the vibrational spectra of which showed the presence of trapped $cis$–N$_2$F$_2$,\textsuperscript{29} indicating that salts richer in N$_2$F$^+$, such as N$_2$F$^+SnF_5^-$, are thermally unstable at room temperature and decompose with the evolution of $cis$-N$_2$F$_2$.

**Crystal Structure Determination of $N_2F^+SbF_6^-$**. Single crystals of N$_2$F$^+SbF_6^-$ were grown from HF solutions at \(-45\) °C in a Teflon-FEP ampule. The solvent was slowly removed by distillation in a static vacuum into a \(-78\) °C trap. Suitable crystals were selected in the drybox and mounted as described in the Experimental Section. The diffraction data indicated no crystal decay during the data collection, but the nylon loop was charred when the mounted crystal was allowed to warm to room temperature. The intensity statistics and E-values did not provide an unambiguous choice of space groups in the orthorhombic crystal system. Systematic absences, \textit{i.e.}, absence of $h+k = \text{odd}$ reflections, however, clearly indicated a C-centered lattice. The structure could be solved in both centrosymmetric ($Cmmm$) and non-centrosymmetric space groups ($C222$ and $Amm2$). The $Cmmm$ and $C222$ space groups placed the central nitrogen atom,
bonded to one other atom – nitrogen or fluorine, of the $N_2F^+$ cation on a mirror plane, thereby
generating disorder in the N-N-F bonds. The structure was refined with nitrogen and fluorine
atoms on the same sites with equal occupancy factors. This model failed to give the individual
N-N and N-F bond distances and, therefore, provided information only on the $r_{N-N} + r_{N-F}$
distances. Both these space groups refine the structure to the same $R$-value of 3.9% and similar
structural parameters were obtained. The final choice of $Cnmm$ to be the correct space group
was made on the basis that this space group has higher symmetry and only half of the parameters
need to be refined. An alternate choice of the $Amm2$ space group was rejected although it
allowed the determination of individual N-N and N-F bonds, because the atoms did not have
good thermal values and the $R$-value was considerably higher.

**Crystal Structure Determination of $N_2F^+Sb_2F_{11}^-$**. The $N_2F^+Sb_2F_{11}^-$ crystals obtained
from the reaction of $trans$–$N_2F_2$ with SbF$_5$ at room temperature were used for this diffraction
study. A suitable single crystal was mounted using a Cryoloop as described above. The intensity
statistics, i.e., $E^2-1$ values, indicated a centrosymmetric space group for $N_2F^+Sb_2F_{11}^-$. Furthermore, the absence of $0 \ k \ 0$ ($k$ = odd) and $h0l$ reflections ($h+l$ = odd) showed the presence
of a 2$_1$ screw axis and an $n$-glide plane parallel and perpendicular to the $b$-axis, respectively. The
space group was thus unambiguously assigned as $P2_1/n$.

**Computational Methods.** The computational approach developed at The University of
Alabama and Washington State University for the prediction of accurate molecular
thermochemistry was used to predict the heats of formation and important energetic features of
these compounds.$^{30-32}$ The approach is based on calculating the total atomization energy of a
molecule and using this value with known heats of formation of the atoms to calculate the heat of
formation at 0 K. The approach starts with coupled cluster theory with single and double
excitations and includes a perturbative triples correction (CCSD(T)), combined with the correlation-consistent basis sets extrapolated to the complete basis set (CBS) limit to treat the correlation energy of the valence electrons. This is followed by a number of smaller additive corrections including core-valence interactions and relativistic effects, both scalar and spin-orbit. The zero point energy can be obtained from experiment, theory, or a combination of the two. Corrections to 298 K can then be calculated by using standard thermodynamic and statistical mechanics expressions in the rigid rotor-harmonic oscillator approximation and appropriate corrections for the heat of formation of the atoms.

The standard aug-cc-pVnZ basis sets were used for N and F and abbreviated as aVnZ. Only the spherical component subset (e.g., 5-term d functions, 7-term f functions, etc.) of the Cartesian polarization functions were used. All CCSD(T) calculations were performed with the MOLPRO-2002 program system on an SGI Altix computer, the Cray XD-1, the dense memory Linux cluster at the Alabama Supercomputer Center, or the Dell Linux cluster at The University of Alabama. For the open shell atomic calculations, the restricted method for the starting Hartree-Fock wavefunction was used and then the spin restriction in the coupled cluster portion of the calculation was relaxed. This method is conventionally labeled R/UCCSD(T).

The geometries were optimized at the CCSD(T) level with the aVDZ and aVTZ basis sets except for N2F where only the aVDZ geometry was obtained. The aVTZ geometries were then used in single point CCSD(T)/aVQZ calculations. The zero point energies (ΔE_{ZPE}) were calculated at the CCSD(T)/aVTZ level without scaling. For the CBS estimates, a mixed exponential/Gaussian function of the form

\[ E(n) = E_{CBS} + B e^{-(n-1)} + C e^{-(n-1)^2} \]  

(6)
was used, where \( n = 2 \) (aVDZ), 3 (aVTZ), and 4 (aVQZ). Core-valence (CV) calculations were carried out at the CCSD(T) level with the weighted CV basis set cc-pwCVTZ.\(^{44}\) The atomic spin-orbit corrections are \( \Delta E_{SO}(O) = 0.22 \), \( \Delta E_{SO}(F) = 0.39 \), and \( \Delta E_{SO}(F^+) = 0.48 \) kcal/mol, respectively, taken from the tables of Moore.\(^{45}\) \( \Delta E_{SR} \) was evaluated by using expectation values for the two dominant terms in the Breit-Pauli Hamiltonian, the so-called mass-velocity and one-electron Darwin (MVD) corrections from configuration interaction singles and doubles (CISD) calculations\(^ {46} \) with the aVTZ basis set at the appropriate optimized geometry. By combining the computed \( \Sigma D_0 \) values, given by the following expression,

\[
\Sigma D_0 = \Delta E_{elec}(CBS) - \Delta E_{ZPE} + \Delta E_{CV} + \Delta E_{SR} + \Delta E_{SO}
\]

with the known heats of formation at 0 K for the elements, the \( \Delta H_{f,0K} \) values can be derived. The heats of formation of N and F are \( \Delta H_{f,0K}(N) = 112.53 \) kcal/mol and \( \Delta H_{f,0K}(F) = 18.47 \) kcal/mol.\(^ {47}\) Heats of formation at 298 K were obtained by following the procedures outlined by Curtiss et al.\(^ {38}\)

**Results and Discussion**

**Preparation of the Graphite-AsF\(_5\) Intercalate.** The first step in the generation of \( N_2F^+ \) salts is the formation of a first stage intercalate of AsF\(_5\) in graphite (Eq. 1). If HOPG (Highly Oriented Pyrolytic Graphite) is used, the intercalation is sluggish and requires several weeks to go to completion. Not only is HOPG very expensive, it is also difficult to grind. Replacing the HOPG graphite with finely powdered natural flake graphite (particle size of 50-60 µ), which is commercially available for about one dollar per pound, proved to be a highly efficient and economical method for preparing the required intercalate. In all the intercalation experiments performed during this work, the graphite powder was pretreated with small amounts of ambient
pressure F₂ gas to remove impurities and traces of moisture. The major volatile products observed during this treatment were CF₄ and SiF₄. In different runs of the intercalation reaction, carried out at room temperature with reaction times of 2-3 days, the composition of the first-stage intercalate based on AsF₅ uptake corresponded to CₓAsF₅ (x = 10.4-12.0). Furthermore, it was found that mild warming of the reaction cylinder to ~40 °C accelerated the intercalation, but also resulted in the formation of significant amounts of CF₄ and AsF₃ due to the oxidation of the graphite by AsF₅. Therefore, heating of the cylinder to accelerate the intercalation rate should be avoided. As reported earlier, AsF₃ does not form a stable intercalate with graphite.⁵

Synthesis of trans-N₂F₂. Our method for the preparation of trans-N₂F₂ was based on the work of Münch and Selig,⁵ and involved the reduction of N₂F₄ with the graphite/AsF₅ intercalate (Eq. 2). Without careful temperature control, varying amounts of N₂, F₂ and NF₃ were obtained with traces of SiF₄ and CF₄ as by-products. However, addition of the N₂F₄ at −196 °C, followed by slow and controlled warm up and use of the small particle size, natural flake graphite intercalate, resulted in a fast and quantitative reduction of the N₂F₄ to trans-N₂F₂ without formation of NF₃, N₂ and F₂. The quantitative formation of trans-N₂F₂ also eliminated its difficult separation from unreacted N₂F₄. No cis–N₂F₂ was observed in all of these reactions.

Münch and Selig reported⁵ that the reaction of first stage graphite/AsF₅ intercalate with N₂F₄ was complete after one mole of N₂F₄ was converted per mole of intercalated AsF₅. We examined the stoichiometry of this reaction by adding the N₂F₄ in increments to the first stage intercalate and analyzing the products after each N₂F₄ addition. Contrary to the report by Münch and Selig,⁵ we found that 1 mol of intercalate was able to quantitatively reduce somewhat more than 1.5 mol of N₂F₄ to trans–N₂F₂. This demonstrates that equation (2) is a poor description of this reaction and that the graphite structure is also being fluorinated (Eq. 8).
2 C_{12} \cdot \text{AsF}_5 + 3 \text{N}_2 \text{F}_4 \rightarrow 2 \text{C}_{12} \text{F}_2^+ \text{AsF}_6^- + 3 \text{trans–N}_2 \text{F}_2 \quad (8)

**Reaction of N\textsubscript{2}F\textsubscript{2} with Lewis Acids and its trans–cis Isomerization.** In the previous study,\textsuperscript{9} excess trans–N\textsubscript{2}F\textsubscript{2} was reacted with AsF\textsubscript{5} at 70 °C for 3 days to give yields of N\textsubscript{2}F\textsuperscript{+}AsF\textsubscript{6}\textsuperscript{-} of about 80\% (Eq. 3). In this study, it was found that by cutting the reaction time in half, the yield of N\textsubscript{2}F\textsuperscript{+}AsF\textsubscript{6}\textsuperscript{-} could be increased to >99\%, based on the amounts of AsF\textsubscript{5} used, and the decomposition of N\textsubscript{2}F\textsubscript{2} to NF\textsubscript{3}, N\textsubscript{2} and F\textsubscript{2} was suppressed. By adding the required amount of NaF to the cylinder containing the N\textsubscript{2}F\textsuperscript{+}AsF\textsubscript{6}\textsuperscript{-}, condensing in HF and shaking it vigorously at room temperature, quantitative yields of cis–N\textsubscript{2}F\textsubscript{2} were obtained (Eq. 4), which can then be converted readily to other N\textsubscript{2}F\textsuperscript{+} salts, such as N\textsubscript{2}F\textsuperscript{+}SbF\textsubscript{6}\textsuperscript{-}, by reaction with the corresponding Lewis acid (Eq. 5).

When either N\textsubscript{2}F\textsuperscript{+}Sb\textsubscript{2}F\textsubscript{11}\textsuperscript{-} is the desired product or the loss of some N\textsubscript{2}F\textsubscript{2} in the form of N\textsubscript{2}F\textsuperscript{+}Sb\textsubscript{2}F\textsubscript{11}\textsuperscript{-} can be tolerated, steps (3) and (4) can be greatly simplified by replacing the stoichiometric amount of AsF\textsubscript{5} required for (3) by catalytic amounts of SbF\textsubscript{5}, thus avoiding the use of large amounts of expensive AsF\textsubscript{5} and eliminating the need for heating and for the displacement step (4). Thus, when trans–N\textsubscript{2}F\textsubscript{2} was reacted for 6 days at room temperature with catalytic amounts of SbF\textsubscript{5}, the 9 : 1 cis–trans–N\textsubscript{2}F\textsubscript{2} equilibrium was established, while the catalytic amount of SbF\textsubscript{5} was converted to N\textsubscript{2}F\textsuperscript{+}Sb\textsubscript{2}F\textsubscript{11}\textsuperscript{-} (Eq. 9). The N\textsubscript{2}F\textsuperscript{+}Sb\textsubscript{2}F\textsubscript{11}\textsuperscript{-} was characterized by vibrational spectroscopy and its crystal structure (see below).

\[
\text{trans–N}_2\text{F}_2 + 2 \text{SbF}_5 \rightarrow \text{N}_2\text{F}^+\text{Sb}_2\text{F}_{11}^- + \text{cis–N}_2\text{F}_2
\quad (9)
\]

The most effective catalysts, however, were found to be either 10-20 mol\% of commercial AlF\textsubscript{3}, which had been pretreated with elemental F\textsubscript{2} gas at 60 °C, or the surfaces of 316-stainless steel cylinders, which had been passivated with strong fluorinating agents, such as
F₂ or ClF₃. Running these isomerization reactions at 55 °C for 15 h, the limiting thermodynamic cis–trans equilibrium³,⁴⁸ of 9 : 1 can successfully be reached. Examination of the used AlF₃ catalyst by Raman spectroscopy at room temperature showed no evidence for the presence of N₂F⁺ salts or retention of N₂F₂ by AlF₃. Furthermore, the catalyst was reusable and not consumed. We have also demonstrated that heating alone in the absence of a catalyst, i.e., using an all Teflon reactor under the same conditions, did not result in isomerization.

Since N₂F₂ is thermodynamically unstable with respect to its decomposition products NF₃, N₂ and F₂,³ and stainless steel is a relatively poor thermal conductor, heating of steel cylinders, overloaded with N₂F₂, can lead to exothermic, uncontrolled thermal decomposition of the N₂F₂. Such an event was observed by us when a 30 mL prepassivated stainless steel reactor, loaded with 40 mmol of trans–N₂F₂, was immersed into a 55 °C oil bath, resulting in a run-away exothermic decomposition reaction of all the N₂F₂ present. In a second case, a similarly overloaded reactor, but this time in the presence of catalytic amounts of SbF₅, also underwent N₂F₂ decomposition. The generated heat and pressure were sufficient to effect the reaction of SbF₅ with the NF₃ and F₂ decomposition products to yield NF₄⁺Sb₃F₁₆⁻ according to (10).⁴⁹

\[
3 \text{SbF}_5 + \text{NF}_3 + \text{F}_2 \rightarrow \text{NF}_4^+\text{Sb}_3\text{F}_{16}^-
\]  

It should be noted that the catalytic effect of prepassivated steel on the isomerization had already been mentioned more than 40 years ago,⁴⁸,⁵₀ but has been widely ignored in subsequent work.

**Structural Investigations of N₂F⁺SbF₆⁻ and N₂F⁺Sb₂F₁₁⁻.** The N₂F⁺ cation has been the subject of various spectroscopic, structural and theoretical investigations.³,⁹,²¹-²⁴,⁵¹-⁵⁷ The most interesting features are the unusually short N-N and N-F bond lengths of 1.1034(5) and 1.2461(10) Å, respectively, observed by Botschwina et al. for the free gaseous ion using millimeter-wave spectroscopy.⁵² The shortest experimentally observed N-N bond distance is
1.09277(9) Å in N\textsubscript{2}H\textsuperscript{+}.\textsuperscript{58} Christe et al. have previously determined the crystal structure of N\textsubscript{2}F\textsuperscript{+}As\textsubscript{6}F\textsubscript{-}.\textsuperscript{9} The compound crystallized in the centrosymmetric space group C2\textit{m} where the N≡N and N-F bonds were disordered, and it was not possible to measure the bond lengths of each bond individually. The same disorder problem affects the crystal structure of N\textsubscript{2}F\textsuperscript{+}S\textsubscript{b}F\textsubscript{6}\textsuperscript{-} in the present study, and only the sum of the N-N and N-F bond distances (2.340(9) Å) can be determined. Details on the disordered N\textsubscript{2}F\textsuperscript{+}S\textsubscript{b}F\textsubscript{6}\textsuperscript{-} structure are given in the Supplementary Material.

The crystal structure of N\textsubscript{2}F\textsuperscript{+}S\textsubscript{b}F\textsubscript{11}\textsuperscript{-} (Tables 1, 2 and S4) is ordered and allows the determination of the individual N-N and N-F bond lengths. This structure can be considered a true representation of the N\textsubscript{2}F\textsuperscript{+} cation in the solid-state and the linearity of the N-N-F bond is not automatically generated by symmetry as in the case of N\textsubscript{2}F\textsuperscript{+}MF\textsubscript{6}\textsuperscript{-} (M = As or Sb) salts. The structure (Fig. 1) was solved in the \textit{P}2\textsubscript{1}/\textit{n} space group and all of the atoms showed excellent thermal behavior. A final \textit{R} value of 3.76\% was obtained with no appreciable residual electron density left over, which would indicate some disorder. The sum of the N-N and N-F bond distances of 2.346(9) Å (Table 3) is in excellent agreement with the observed spectroscopic gas phase value of 2.3495 Å.\textsuperscript{52} In N\textsubscript{2}F\textsuperscript{+}S\textsubscript{b}F\textsubscript{11}\textsuperscript{-}, the N-F distance of 1.257(8) Å is somewhat longer and the N-N distance of 1.089(9) Å is slightly shorter than those (1.2461 and 1.1034 Å, respectively,) of gaseous N\textsubscript{2}F\textsuperscript{+}.\textsuperscript{52} The N≡N distance in N\textsubscript{2}F\textsuperscript{+}S\textsubscript{b}F\textsubscript{11}\textsuperscript{-} can, therefore, be considered to be among the shortest, if not the shortest, experimentally observed N-N bond lengths. For comparison, the N≡N bond distances in N\textsubscript{2} and HN\textsubscript{2}\textsuperscript{+} are 1.0976(2) and 1.09277(9) Å, respectively.\textsuperscript{58,59}

Fig. S3 depicts the packing diagram of N\textsubscript{2}F\textsuperscript{+}S\textsubscript{b}F\textsubscript{11}\textsuperscript{-}. The N\textsubscript{2}F\textsuperscript{+} cation lies between the Sb-F-Sb bend of the S\textsubscript{b}F\textsubscript{11}\textsuperscript{-} anion at an angle of 68.4° with respect to the mean plane containing the
F6-Sb1-F7-Sb2-F12 atoms. As in the case of N2F+SnF6−, no close contacts are found to and from the N2F+ cation.

The geometry of the Sb2F11− anion also deserves a special comment. The Sb-F-Sb bridge is bent with an angle of 145.2(2)° and coplanar with the terminal fluorines, F6 and F12, which are eclipsed. The equatorial fluorine atoms of each SbF5 group are staggered with a twist angle of ~31° (Fig. 2). The large variation in the structures of Sb2F11− anions in different compounds is due to its ease of deformation by crystal packing effects.60,61

**Synthesis and Properties of N2F+Sn2F9−.** The only room-temperature stable N2F+ salts, previously reported were those derived from AsF5 and SbF5, while BF3 and PF5 do not form stable N2F+ salts.3,9 Since SnF4, with a pF− value of 9.8,62,63 is a stronger Lewis acid than either BF3 or PF5 and can form stable N2F3+ and NF4+ salts,26,27 it was interesting to explore the interaction between SnF4 and cis–N2F2. Because SnF4 is a highly polymeric solid, the reactions were carried out in anhydrous HF solution. It was found that SnF4 reacts with excess cis–N2F2 in a 2 : 1 mole ratio giving white solids with the empirical composition N2F+Sn2F9− (Eq. 11).

\[
\text{cis–N2F2} + 2 \text{SnF4} \rightarrow N2F+Sn2F9− \quad (11)
\]

The products were characterized by vibrational spectroscopy (Figure S4, Table 4). They showed the three characteristic N2F+ bands and bands of variable intensities in the regions characteristic for Sn(IV) fluoride anions26-28 indicating the presence of polyanions of variable composition and structure. The N2F+ bands also showed some splittings of variable intensities indicative of the presence of more than one form of the counterion. A similar observation for the existence of polymeric tin fluoride anions of different composition has previously been made in our study of N5+SnF5 where the “SnF5−” anion was shown28 by multinuclear NMR spectroscopy to be present as a mixture of Sn2F10− and Sn4F20−. The preferred formation of Sn2F9− can be explained by the
fact that monomeric SnF$_4$ is a weaker Lewis acid than its oligomers, in accord with our general
finding that oligomeric Lewis acids are stronger acids than their monomers.$^{62,63}$ Therefore, Sn$_2$F$_9^-$
salts are more stable than SnF$_5^-$ salts, which in turn are more stable than SnF$_6^{2-}$ salts. This was
also demonstrated by us by carrying out metathetical reactions between N$_2$F$^+$SbF$_6^-$ and either
CsSnF$_5$, Cs$_2$SnF$_6$ or Na$_2$SnF$_6$ in HF solution, which gave no evidence for the formation of stable
N$_2$FSnF$_5$ or (N$_2$F)$_2$SnF$_6$ salts, but produced only some N$_2$F$^+$Sn$_2$F$_9^-$.

Further experimental evidence for the instability of N$_2$F$^+$SnF$_5^-$ was obtained in one
instance when a product with a composition closer to 1 : 1 was accidentally obtained from the
reaction of excess cis–N$_2$F$_2$ with SnF$_4$ in HF solution, when the removal time of unreacted N$_2$F$_2$
was shortened and the spectra of the solid product were immediately recorded (Fig. 3). These
vibrational spectra showed the presence of anion bands resembling more closely those previously
observed$^{28}$ for SnF$_5^-$ in N$_5^+$SnF$_5^-$ and a set of bands due to cis–N$_2$F$_2$ trapped within the solid (Fig.
3). Their frequencies are very close to those of free gaseous cis–N$_2$F$_2$,$^{29}$ however, the rotational P
and R branches, characteristic for the free gas, are missing. This demonstrates that N$_2$FSnF$_5$
decomposes at room temperature to N$_2$FSn$_2$F$_9$ and cis–N$_2$F$_2$ (Eq. 12).

$$2 \text{N}_2\text{F}^+\text{SnF}_5^- \rightarrow \text{N}_2\text{F}^+\text{Sn}_2\text{F}_9^- + \text{cis–N}_2\text{F}_2$$ (12)

The Sn$_2$F$_9^-$ anion most likely does not have a monomeric structure. Because tin prefers a
coordination number of 6 towards fluorine, a monomeric anion would require three fluorine
bridges, that is, the sharing of a common face. Based on the similarity of the coordination
chemistry of Sn(IV) and Ti(IV) and the failure, despite of intensive efforts, of Mazej and
Goreshnik$^{64}$ to find the corresponding triply-bridged monomeric Ti$_2$F$_9^-$ anion, its existence in tin
chemistry is equally unlikely. Depending on the counter ion, they only found either tetrameric,
pseudo-tetrahedral Ti$_4$F$_{18}^{2-}$ or polymeric, infinite double chain (Ti$_2$F$_9^-)_n$ anions. Based on the
complexity of our observed vibrational spectra, the analogy with the titanium system and our previous findings for SnF$_5^-$, it is very likely that Sn$_2$F$_9^-$ is also present as an oligomer or polymer.

**Computational Results.** Since precise experimental measurements of some of the thermodynamic properties of N$_2$F$_2$ and its isomerization process are very difficult due to its high reactivity and the small differences in the values between the two isomers, high-level electronic structure calculations can provide better values than experiment. A previous molecular orbital study by Lee and coworkers showed$^4$ that the calculated values strongly depend on the level of correlation treatment and the basis set. It was, therefore, desirable to perform these calculations at the highest available level.

Our calculated CCSD(T)/aVTZ value (Table 3) for the $r_{\text{N=N}}$ distance in N$_2$F$^+$ is larger by 0.021 Å as compared to the experimental gas phase structure$^{52}$ and $r_{\text{N-F}}$ is shorter than experiment by 0.010 Å. The calculated $r_e$ of N$_2$ ($^4\Sigma_g^+$) is 1.104 Å at this level$^{65}$ compared to the experimental value$^{66}$ of 1.0977 Å, a discrepancy of 0.006 Å. The calculated CEPA-1/[8,4,2,1] values$^{52}$ of $r_{\text{N=N}} = 1.1040$ Å and $r_{\text{N-F}} = 1.2521$ Å for N$_2$F$^+$ are in somewhat better agreement with experiment than the CCSD(T)/aVTZ values. The anharmonic vibrational frequencies of N$_2$F$^+$, reported$^9$ previously as well as in the current work, are in excellent agreement with the calculated CCSD(T)/aVTZ harmonic frequencies (Table 4). The largest discrepancy was found for the F–N=N bend ($\pi$ mode), which was calculated to be 20 cm$^{-1}$ higher than the experimental value. Our calculated harmonic frequencies are also within about 20 cm$^{-1}$ of the anharmonic CEPA-1 values.$^{52}$

The experimental geometries of *cis*– and *trans*–N$_2$F$_2$ have been reported from electron diffraction (*cis* and *trans*)$^{67}$ and microwave spectroscopy (*cis*)$^{68}$ studies. Our CCSD(T)/aVTZ values for *cis*–N$_2$F$_2$ are in good agreement with the microwave structure$^{68}$ with the calculated
\( r_{\text{N=N}} \) and \( r_{\text{N-F}} \) distances being 0.011 Å and 0.003 Å, respectively, longer than the experimental values (Table 5). Our CCSD(T)/aVTZ values for \textit{cis}– and \textit{trans}–\( \text{N}_2\text{F}_2 \) are also in good agreement with the electron diffraction structures,\(^{67}\) with the predicted \( r_{\text{N-F}} \) distances of both isomers being shorter than the experimental values. Comparison of the microwave and electron diffraction structures suggests that the electron diffraction \( r_{\text{N-F}} \) distances are too long. The calculations do reproduce the electron diffraction difference for the N-N bond lengths in the two isomers but not the difference in the N-F bond lengths. The substantial change in the \( \angle \text{FNN} \) for the \textit{cis}- and \textit{trans}-isomers of about 10° is reproduced by the calculations. The anharmonic vibrational frequencies of \textit{cis}–\( \text{N}_2\text{F}_2 \) and \textit{trans}–\( \text{N}_2\text{F}_2 \) have also been reported,\(^{69,\,70}\) and agree well with our calculated CCSD(T)/aVTZ harmonic frequencies, with the largest discrepancy of 32 cm\(^{-1}\) found for the highest frequency \( a_1 \) mode of \textit{cis}\(-\text{N}_2\text{F}_2 \) (Table 6).

The calculated heats of formation are given in Table 7. The components for the atomization energies are given in the Supporting Information. We predict \textit{cis}\(-\text{N}_2\text{F}_2 \) to be more stable than \textit{trans}\(-\text{N}_2\text{F}_2 \) by 1.4 kcal/mol at 298 K, consistent with other calculated values\(^{4}\) and the experimental equilibrium measurements of Pankratov and Sokolov who found that within experimental error this value was close to zero.\(^{48}\) We note that the current calculations are the most reliable values reported so far. Our calculated heat of formation of the less stable \textit{trans}–\( \text{N}_2\text{F}_2 \) is within 0.1 kcal/mol of the reported experimental value.\(^{43}\) However, our calculated value for \textit{cis}–\( \text{N}_2\text{F}_2 \) is 1.7 kcal/mol higher than the reported experimental value,\(^{47}\) due to the smaller calculated energy of isomerization.

In contrast to the small energy difference between the \textit{cis}- and the \textit{trans}-isomers which also represents the heat of isomerization, the activation energy barriers for the uncatalyzed isomerization of the free molecule are very high involving transition states which, depending on
the isomerization mechanism and the level and basis set used for the calculation, are at least 60 kcal/mol above the ground state. Two different mechanisms can be envisioned for the uncatalyzed trans-cis isomerization.

The first mechanism involves rotation about the N=N double bond resulting in a transition state of $C_2$ symmetry.

The calculated $^3B$ $C_2$ minimum energy structure with a dihedral F-N-N-F angle of 89.8 ° (Table 6) lies 59.6 kcal/mol above the cis-isomer at 0 K. This represents the lower limit to the isomerization barrier on the singlet surface. The value of ~60 kcal/mol for rotation about the N=N bond is consistent with the value expected for the C=C $\pi$-bond.\(^7\)

The second mechanism involves the in-plane inversion of one fluorine ligand with a transition state of $C_s$ symmetry.

It has a structure similar to that of the N$_2$F$^+$ cation with a significantly shortened N-F bond of 1.30 Å, a very short N-N bond of 1.15 Å, and an F-N-N angle of 170 °. The second N-F bond is elongated to 1.72 Å. This transition state has an imaginary frequency of 883i cm$^{-1}$ and lies 68.7 kcal/mol above the ground state. Thus, contrary to our previous speculation,\(^9\) the
mechanism involving rotation about the N-N bond is energetically favored over the in-plane rearrangement of fluorine ligands, just as in an olefin with a comparable double bond.

Our high-level calculations for the isomerization barriers of the free N₂F₂ molecule are not expected to be in error by more than 1 to 2 kcal/mol and provide convincing evidence that the barrier is at least 60 kcal/mol. This result is in contrast to the previous CISD and CCSD calculations which are too high by up to 20 kcal/mol, and the shock tube measurements which reported an experimental barrier of 32 kcal/mol for this process. This value is probably highly inaccurate, considering the great technical difficulties involved in making such a measurement for thermally labile molecules, and should be disregarded. This type of error is consistent with those found in similar shock tube experiments. This explanation is supported by an analysis of the bond dissociation energies in N₂F₂. The N₂F radical is barely stable with respect to loss of an F atom, so N₂F₂ will lose the second F atom as soon as the first N-F bond is broken. The energy for the reaction cis-N₂F₂ → N₂ + 2F is only 18.2 kcal/mol at 0 K. Hence, it is possible that isomerization was also occurring by a dissociation/association process. An FN=NF double bond dissociation is highly unlikely because its energy, defined by the reaction N₂F₂ → 2NF, is 93 kcal/mol at 0 K, using ΔHf(NF) = 55.6 kcal/mol. This value is substantially higher than the C=C bond dissociation energy in C₂F₄, defined by the reaction C₂F₄ → 2¹CF₂ which is 68 kcal/mol. In view of the relatively low thermal stability of N₂F₂ and the high barriers for the uncatalyzed isomerizations, the uncatalyzed isomerizations of trans-N₂F₂ are of lesser practical interest.

The F⁺ affinity of N₂ (calculated using the experimental value of ΔHf₀k(F⁺) = 419.40 kcal/mol) is 127 kcal/mol at 0 K and falls in the lower range of the Christe/Dixon oxidizer strength scale with values that are bracketed by those of OF₂ (122 kcal/mol) and BrF₃O (131
kcal/mol). This confirms the experimental observations that N$_2$F$^+$ is a very powerful oxidative fluorinorator.

Contrary to our previous conclusion that Lewis acids do not catalyze the isomerization, the results from the present study prove that strong Lewis acids do indeed catalyze this process. The catalytic effect of the Lewis acids can be readily understood by the similarity of the C$_s$ transition state structure of the uncatalyzed isomerization with that of the N$_2$F$^+$ cation. The interaction of trans–N$_2$F$_2$ with a strong Lewis acid is likely to stretch one N-F bond, while at the same time shortening the other N-F bond as well as the N-N bond and increasing their F-N-N angle. This interaction greatly reduces the energy required for reaching the C$_s$ transition state. It is also easy to understand that increasing Lewis acidity strength lowers the barrier and the required isomerization temperature. Therefore, both cis–N$_2$F$_2$ and trans–N$_2$F$_2$ can react with strong Lewis acids to give N$_2$F$^+$ salts. The only difference is that the cis–isomer is more reactive. This increased reactivity of the cis-isomer can be readily explained. In both N$_2$F$_2$ isomers, each nitrogen atom possesses a sterically active free valence electron pair. The transformation of N$_2$F$_2$ to N$_2$F$^+$, requires the conversion of the N=N double bond into a N≡N triple bond by an overlap of electrons from these two free valence electron pairs. Obviously, this overlap is greatly facilitated in cis-N$_2$F$_2$ where these free pairs are on the same side of the molecule.

Another characteristic of the N$_2$F$_2$ reaction chemistry is the exclusive formation of cis-N$_2$F$_2$ when N$_2$F$^+$ reacts with F$^-$ (Eq. 4). Why does one not obtain the typical 9:1 mole ratio of cis-N$_2$F$_2$ : trans-N$_2$F$_2$, observed for the trans-cis isomerization reactions? This feature can be readily explained by the charge distribution in N$_2$F$^+$. The central N atom carries the formal positive charge and, therefore, F$^-$ attacks exclusively the central N atom, generating an F$_2$NN intermediate which rearranges itself by an in-plane $\alpha$-fluorine migration to cis-N$_2$F$_2$. 
Because of the involvement of the $\text{F}_2\text{N}=\text{N}$ isomer in this reaction, it was interesting to explore this isomer in more detail. It lies 14.3 kcal/mol above the cis-isomer at 298 K, explaining its tendency to rearrange to the energetically favored cis-$\text{N}_2\text{F}_2$. Its calculated geometry and vibrational spectra are given in Tables 5 and 6, respectively. No experimental data are known for this isomer, and the spectrum originally attributed\textsuperscript{75} to $\text{F}_2\text{N}=\text{N}$ by Sanborn is that of cis-$\text{N}_2\text{F}_2$.\textsuperscript{3}

Compared to cis-$\text{N}_2\text{F}_2$ and trans-$\text{N}_2\text{F}_2$, the calculated N-N bond length in $\text{F}_2\text{N}=\text{N}$ is dramatically shortened by about 0.10 Å, while the N-F bond lengths are increased by about 0.06 Å.

Similarly, the N-N stretching frequency is increased by about 500 cm\textsuperscript{-1}, while the NF\textsubscript{2} stretching frequencies are decreased by an average of about 300 cm\textsuperscript{-1}, indicating that in $\text{F}_2\text{N}=\text{N}$, strong contributions from the following resonance structures must be invoked to describe its bonding appropriately.

This strong contribution from highly polar N-F bonds resembles those encountered for F\textsubscript{3}NO\textsuperscript{10} and FNO.\textsuperscript{11,12}
The driving forces behind these highly unusual resonance structures for nitrogen fluorides and oxofluorides is the desire of fluorine, which is more electronegative than oxygen or nitrogen, to carry the negative charges.

Conclusions

The present work describes improved methods for the synthesis of $N_2F^+$ salts, which are the key precursors to novel high energy density materials, such as $N_5^+$ salts. Important improvements include the use of cheap natural graphite flakes in place of expensive highly oriented pyrolytic graphite (HOPG) for the preparation of the first stage graphite-$AsF_5$ intercalate and of better catalysts for the $N_2F_2$ trans–cis isomerization, the elimination of extra reaction steps and significant reductions in the reaction times required for the synthesis of $N_2F^+$ salts, from several weeks to several days. Also, the first ordered crystal structure of an $N_2F^+$ salt was obtained, thus providing individual $N≡N$ and $N-F$ bond lengths for a direct comparison with the free molecule. These bonds are among the shortest experimentally observed $N≡N$ and $N-F$ bond lengths. Furthermore, the new $N_2F^+$ salt, $N_2F^+Sn_2F_9^-$, has been synthesized and characterized. High-level correlated molecular calculations were carried out and show that $cis$-$N_2F_2$ is more stable than $trans$-$N_2F_2$ by 1.4 kcal/mol at 298 K. In addition, the calculations demonstrate that
the lowest-energy uncatalyzed isomerization pathway involves rotation about the N=N double bond and has a barrier of 60 kcal/mol. This rotation barrier is substantially above the energy required for the dissociation of N₂F₂ to N₂ and 2F. Therefore, some of the N₂F₂ can dissociate before undergoing uncatalyzed isomerization resulting in autocatalysis by the decomposition products. It is shown that the trans-cis isomerization of N₂F₂ is catalyzed by strong Lewis acids, most likely involves a planar transition state of symmetry C₃, and yields a 9:1 equilibrium mixture of cis-N₂F₂ and trans-N₂F₂. Explanations are given for the increased reactivity of cis-N₂F₂ with Lewis acids and the exclusive formation of cis-N₂F₂ in the reaction of N₂F⁺ with F⁻. The geometry and vibrational frequencies of the F₂N≡N isomer have also been calculated and imply strong contributions from ionic N₂F⁺ F⁻ resonance structures.

Acknowledgment. We gratefully acknowledge financial support of this work by the Air Force Office of Scientific Research, DARPA, the Office of Naval Research, the National Science Foundation, and the Department of Energy. DAD is indebted to the Robert Ramsay Endowment of the University of Alabama.

Supporting Information Available. Crystal data and structure refinement for N₂F⁺SbF₆⁻ (Table S1); atomic coordinates (x 10⁴) and equivalent isotropic displacement parameters (Å² x 10³) for N₂F⁺SbF₆⁻ (Table S2); bond lengths and angles for N₂F⁺SbF₆⁻ (Table S3); atomic coordinates (x 10⁴) and equivalent isotropic displacement parameters (Å² x 10³) for N₂F⁺Sb₂F₁₁⁻ (Table S4); CCSD(T)/aVnZ total energies (E₉₅) as a function of the basis set (Table S5); components for calculated atomization and reaction energies in kcal/mol (Table S6); ORTEP plot for N₂F⁺SbF₆⁻ with thermal ellipsoids at 30% probability level (Figure S1); packing diagram of N₂F⁺SbF₆⁻ along the c-axis (Figure S2); packing diagram of N₂F⁺Sb₂F₁₁⁻ along the a-axis (Figure S3); IR and Raman spectra of N₂FSn₂F₉ (Figure S4); and X-ray crystallographic file in CIF format for
the structure determinations of N$_2$FSbF$_6$ and N$_2$FSb$_2$F$_{11}$. This material is available free of charge via the internet at http://pubs.acs.org.
References


17. SADABS, Program for absorption correction for area detectors, Version 2.01, Bruker AXS, Madison, WI (2000).


37. McQuarrie, D. A. *Statistical Mechanics*, University Science Books: Sausalito, CA, **2001**.


**Table 1.** Crystal data and structure refinement for N$_2$F$^+$Sb$_2$F$_{11}^-$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical formula</td>
<td>F12 N2 Sb2</td>
</tr>
<tr>
<td>Formula weight</td>
<td>499.52</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>-35 (2)</td>
</tr>
<tr>
<td>Space group</td>
<td>$P2_1/n$</td>
</tr>
<tr>
<td>Unit cell dimensions</td>
<td></td>
</tr>
<tr>
<td>$a$ (Å)</td>
<td>7.558(2)</td>
</tr>
<tr>
<td>$b$ (Å)</td>
<td>9.926(2)</td>
</tr>
<tr>
<td>$c$ (Å)</td>
<td>14.103(2)</td>
</tr>
<tr>
<td>$\beta$ (°)</td>
<td>99.59(1)</td>
</tr>
<tr>
<td>Volume (Å$^3$)</td>
<td>1043.2(4)</td>
</tr>
<tr>
<td>$Z$</td>
<td>4</td>
</tr>
<tr>
<td>$D_{\text{calc}}$ (g/cm$^3$)</td>
<td>3.181</td>
</tr>
<tr>
<td>Absorption coefficient (cm$^{-1}$)</td>
<td>0.5329</td>
</tr>
<tr>
<td>Final $R$ indices [I&gt;2sigma(I)]</td>
<td>$R1 = 0.0376$</td>
</tr>
<tr>
<td></td>
<td>$wR2 = 0.0895$</td>
</tr>
<tr>
<td>$R$ indices (all data)</td>
<td>$R1 = 0.0388$</td>
</tr>
<tr>
<td></td>
<td>$wR2 = 0.0903$</td>
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**Table 2.** Bond lengths and angles for N$_2$F$^+$Sb$_2$F$_{11}$.

<table>
<thead>
<tr>
<th>Bond Lengths (Å)</th>
<th>Bond Angles (°)</th>
<th>Torsion Angles (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sb(1)-F(3)</td>
<td>1.868(4)</td>
<td>Sb(2)-F(7)-Sb(1)</td>
</tr>
<tr>
<td>Sb(1)-F(2)</td>
<td>1.873(4)</td>
<td>F(8)-Sb(2)-F(7)</td>
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<tr>
<td>Sb(1)-F(6)</td>
<td>1.879(4)</td>
<td>Sb(2)-F(7)-Sb(1)</td>
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<tr>
<td>Sb(1)-F(5)</td>
<td>1.887(4)</td>
<td>F(8)-Sb(2)-F(7)</td>
</tr>
<tr>
<td>Sb(1)-F(4)</td>
<td>1.894(4)</td>
<td>Sb(2)-F(7)</td>
</tr>
<tr>
<td>Sb(1)-F(7)</td>
<td>2.077(4)</td>
<td>F(12)-Sb(2)-F(7)</td>
</tr>
<tr>
<td>Sb(2)-F(9)</td>
<td>1.865(4)</td>
<td>F(9)-Sb(2)-F(8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F(11)-Sb(2)-F(8)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F(10)-Sb(2)-F(10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F(8)-Sb(2)-F(10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F(9)-Sb(2)-F(10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F(11)-Sb(2)-F(10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F(11)-Sb(2)-F(12)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>F(10)-Sb(2)-F(12)</td>
</tr>
</tbody>
</table>

**Bond Angles (°)**

<table>
<thead>
<tr>
<th>Bond Angles (°)</th>
<th>Torsion Angles (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(2)-N(1)-F(1)</td>
<td>179.2(7)</td>
</tr>
<tr>
<td>F(3)-Sb(1)-F(2)</td>
<td>89.6(2)</td>
</tr>
<tr>
<td>F(3)-Sb(1)-F(6)</td>
<td>95.9(2)</td>
</tr>
<tr>
<td>F(2)-Sb(1)-F(6)</td>
<td>95.2(2)</td>
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<td>F(3)-Sb(1)-F(5)</td>
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<td>89.8(2)</td>
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<tr>
<td>F(6)-Sb(1)-F(5)</td>
<td>92.0(2)</td>
</tr>
<tr>
<td>F(3)-Sb(1)-F(4)</td>
<td>90.8(2)</td>
</tr>
<tr>
<td>F(2)-Sb(1)-F(4)</td>
<td>170.3(2)</td>
</tr>
<tr>
<td>F(6)-Sb(1)-F(4)</td>
<td>94.4(2)</td>
</tr>
<tr>
<td>F(5)-Sb(1)-F(4)</td>
<td>88.5(2)</td>
</tr>
<tr>
<td>F(3)-Sb(1)-F(7)</td>
<td>87.56(18)</td>
</tr>
<tr>
<td>F(2)-Sb(1)-F(7)</td>
<td>87.55(19)</td>
</tr>
<tr>
<td>F(6)-Sb(1)-F(7)</td>
<td>175.64(17)</td>
</tr>
<tr>
<td>F(5)-Sb(1)-F(7)</td>
<td>84.56(18)</td>
</tr>
<tr>
<td>F(4)-Sb(1)-F(7)</td>
<td>82.80(17)</td>
</tr>
<tr>
<td>F(9)-Sb(2)-F(7)-Sb(1)</td>
<td>-154.8(4)</td>
</tr>
</tbody>
</table>
F(11)-Sb(2)-F(7)-Sb(1)       25.1(4)
F(6)-Sb(1)-F(7)-Sb(2)        -19(3)
F(5)-Sb(1)-F(7)-Sb(2)        -56.9(4)
F(4)-Sb(1)-F(7)-Sb(2)        32.2(4)
F(10)-Sb(2)-F(7)-Sb(1)     -64.1(4)
F(12)-Sb(2)-F(7)-Sb(1)       26.8
F(3)-Sb(1)-F(7)-Sb(2)        123.3(4)
F(2)-Sb(1)-F(7)-Sb(2)        -147.0(4)
Table 3. Calculated and experimental bond distances (Å) for \( \text{N}_2\text{F}^+ \).

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Method</th>
<th>( r_{\text{N}\equiv\text{N}} )</th>
<th>( r_{\text{N}-\text{F}} )</th>
<th>( \Sigma(r_{\text{N}\equiv\text{N}} + r_{\text{N}-\text{F}}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{N}_2\text{F}^+\text{AsF}_6^- )</td>
<td>x-ray(^9)</td>
<td>(1.099)(^a)</td>
<td>(1.217)(^a)</td>
<td>2.316 (12)</td>
</tr>
<tr>
<td>( \text{N}_2\text{F}^+\text{SbF}_6^- )</td>
<td>x-ray(^9)</td>
<td>(1.110)(^a)</td>
<td>(1.230)(^a)</td>
<td>2.340 (9)</td>
</tr>
<tr>
<td>( \text{N}_2\text{F}^+\text{Sb}<em>2\text{F}</em>{11}^- )</td>
<td>x-ray(this work)</td>
<td>1.089 (9)</td>
<td>1.257 (8)</td>
<td>2.346 (9)</td>
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<tr>
<td>( \text{N}_2\text{F}^+(\text{gas}) )</td>
<td>Millimeter spectroscopy(^49)</td>
<td>1.1034</td>
<td>1.2461</td>
<td>2.3495</td>
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<tr>
<td>( \text{N}_2\text{F}^+(\text{gas}) )</td>
<td>CCSD(T)/aVTZ</td>
<td>1.1246</td>
<td>1.2357</td>
<td>2.360</td>
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<tr>
<td>( \text{N}_2\text{F}^+(\text{gas}) )</td>
<td>CEPA-1/[8,4,2,1] (^49)</td>
<td>1.1040</td>
<td>1.2521</td>
<td>2.3561</td>
</tr>
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</table>

\(^a\) Obtained by partitioning the experimentally observed sum in the same ratio as that calculated at the LDFS2 level.