

Nitrogen Pentafluoride: Covalent NF_5 versus Ionic NF_4^+F^- and Studies on the Instability of the Latter

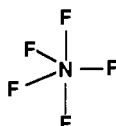
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Abstract: Recent ab initio calculations suggesting that covalent NF_5 and even NF_6^- are vibrationally stable and might be experimentally accessible prompted us to critically evaluate the presently available theoretical and experimental data for NF_5 and to carry out experiments on the stability of ionic NF_4^+F^- . It is shown that covalent NF_5 of D_{3h} symmetry and crystalline NF_4^+F^- should be of comparable energy but that covalent NF_5 should suffer from severe ligand-crowding effects that would make its synthesis experimentally very difficult. On the other hand, crystalline NF_4^+F^- should be readily accessible from the well-known solvated NF_4^+ and F^- ions. The recent discoveries of a convenient synthesis of truly anhydrous $\text{N}(\text{CH}_3)_4\text{F}$ as a source of soluble "naked" fluoride ions and of solvents which possess sufficient kinetic stability toward strong oxidizers allowed us to carry out experiments on the thermal stability of NF_4^+F^- . It is shown that at temperatures as low as -142°C crystalline NF_4^+F^- is unstable toward decomposition to NF_3 and F_2 , a process which is calculated to be exothermic by about 32 kcal mol^{-1} .

Introduction

Ever since the first successful synthesis of the NF_4^+ cation in 1966,¹ the possible existence of its parent molecule, NF_5 , has been a challenge to both experimental chemists²⁻¹⁰ and theoreticians.¹¹⁻¹⁴ Although the experimentalists have so far failed to isolate NF_5 , interest in its synthesis was renewed by recent ab initio calculations which suggested that NF_5 is a vibrationally stable molecule^{13,14} and that even NF_6^- might be structurally stable.¹⁵ Since NF_5 could exist either as a covalent, trigonal pyramidal molecule of D_{3h} symmetry

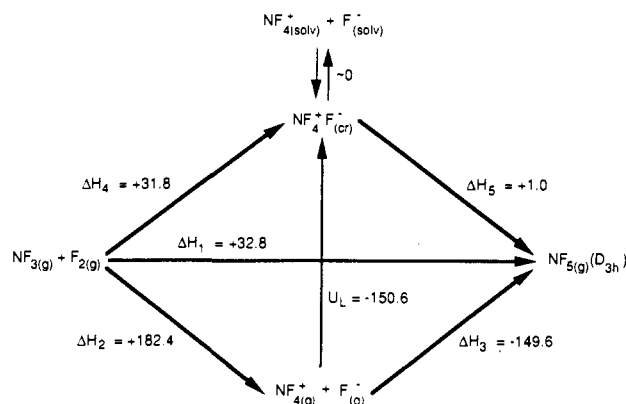


or as an ionic NF_4^+F^- salt, it was necessary to evaluate the relative energies of the two forms and their synthetic accessibility in view of previously published²⁻¹⁴ and new experimental data.

Results and Discussion

The relative energies of covalent NF_5 and ionic NF_4^+F^- with respect to each other and to NF_3 and F_2 can be estimated from a Born-Haber cycle using the following data:

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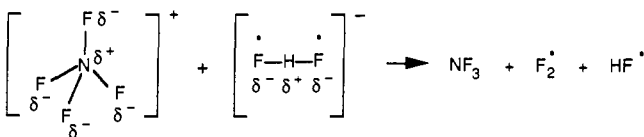


Taking the average of two values of 30.1 and $35.5\text{ kcal mol}^{-1}$ calculated^{13,14} for ΔH_1 at the MP2/6-31++G** and MP2/6-311+G* levels of theory, respectively, the formation of covalent NF_5 from NF_3 and F_2 is endothermic by about $32.8\text{ kcal mol}^{-1}$. Furthermore, the enthalpy of formation, ΔH_2 , of the free gaseous NF_4^+ and F^- ions from NF_3 and F_2 can be estimated as $+182.4\text{ kcal mol}^{-1}$ by taking the average between the values of 183.7 and $181.1\text{ kcal mol}^{-1}$ obtained by the MP2/6-31G* calculation and from a combination of the experimental values for the dissociation energy of F_2 and the first ionization potential and electron affinity of the F atom^{16,17} and the calculated F^+ affinity of NF_3 ,¹⁸ respectively. From $\Delta H_1 - \Delta H_2$, the enthalpy of formation of covalent NF_5 from gaseous free NF_4^+ and F^- ions becomes $\Delta H_3 = -149.6\text{ kcal mol}^{-1}$. The value of ΔH_4 , the enthalpy of formation of crystalline NF_4^+F^- from NF_3 and F_2 , is given by the sum of ΔH_2 and the lattice energy U_L of NF_4^+F^- . The value of U_L is the average of two previous estimates (-150.6 and $-147.0\text{ kcal mol}^{-1}$)^{9,19} and a value of $-154.1\text{ kcal mol}^{-1}$ obtained by Barlett's empirical equation,²⁰ $U_L (\text{kcal/mol}) = 556.3(V_m)^{-1/3} + 26.3$, where V_m is the sum of the molar volumes of NF_4^+ and F^- that were estimated as 64.9 and 17.5 \AA^3 , respectively, from known crystal structures.^{21,22} From $\Delta H_1 - \Delta H_4$, the energy difference between crystalline NF_4^+F^- and covalent NF_5 can then be estimated to be rather small and be of the order of about $1 \pm 6\text{ kcal mol}^{-1}$,

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considering the uncertainties in the values used for ΔH_1 , ΔH_2 , and U_L .

The following conclusions concerning the stability and synthesis of NF_5 can be drawn from the above Born-Haber cycle: (i) covalent NF_5 and ionic NF_4^+F^- are similar in energy and (ii) the formation of NF_5 from NF_3 and F_2 is endothermic by about 33 kcal mol⁻¹, an amount of energy which is slightly lower than the dissociation energy of molecular fluorine,¹⁷ i.e., 37.9 kcal mol⁻¹. The latter point suggests that, from strictly energetic considerations, covalent NF_5 should be accessible from NF_3 and two fluorine atoms. This approach has been experimentally tested using low temperature and either UV photolysis⁶ or irradiation with 3-MeV bremsstrahlung³ as the F atom sources but provided no evidence for the formation of NF_5 . This failure to produce NF_5 from NF_3 and F atoms is probably due to the steric problem of accommodating more than four fluorine ligands around the nitrogen central atom at the short N-F bond distances of 1.365 Å in NF_3 ,²³ and 1.29 Å in NF_4^+ .²¹ This difficulty has been demonstrated by a previous radiotracer study¹⁰ of the thermal decomposition of $\text{NF}_4^+\text{HF}_2^-$ containing ¹⁸F-labeled HF_2^- . It was shown that, contrary to the predictions based on bond polarities, the linear F-H-F⁻ anion exclusively attacked the fluorine ligands and not the central nitrogen atom of NF_4^+ .



This result was taken¹⁰ as evidence that at the given bond distances in NF_4^+ (~1.29 Å)²¹ the maximum coordination of nitrogen(+V) toward fluorine is 4. The accommodation of a fifth fluorine ligand at the nitrogen atom would require a significant lengthening of all N-F bonds in NF_4^+ to create enough room for a fifth fluorine ligand. The plausibility of this argument is also borne out by the results of ab initio calculations,^{13,14} which show that for more than four fluorine ligands the average N-F bond lengths increase with increasing coordination numbers. Thus, the bond lengths calculated at the MP2/6-31++G** level of theory were $\text{NF}_4^+ = 1.32$ Å,¹³ $\text{NF}_5(\text{ax}) = 1.57$ Å,¹³ $\text{NF}_5(\text{eq}) = 1.41$ Å,¹³ and $\text{NF}_6 = 1.58$ Å,¹⁵ with the NF_5 and NF_6 bond lengths being surprisingly long for highly covalent nitrogen(+V) compounds.

Further evidence for the excessive ligand crowding in NF_5 comes from the vibrational frequencies calculated¹⁴ for covalent NF_5 of D_{3h} symmetry. Depending on the level of theory used for these calculations, the frequency of the antisymmetric axial NF_2 stretching mode, ν_3 , becomes very low or even imaginary. This indicates either a small barrier along the S_3 displacement coordinate or even a spontaneous transition to an ionic C_{3v} or C_{4v} structure with one very long or ionic N-F distance. This is not surprising in view of the above Born-Haber cycle, which suggests that covalent NF_5 and ionic NF_4^+F^- should be of comparable energy. The fact that, at the higher level of theory calculations, the ionic C_{3v} structure lies higher in energy than the covalent D_{3h} structure is probably due to the fact that in these calculations only an NF_4^+F^- ion pair was considered and not a crystalline NF_4^+F^- with its full lattice energy of about 150 kcal mol⁻¹ (see above).

This situation, then, implies that for the successful syntheses of either covalent NF_5 or NF_6 from NF_3 or NF_4^+ one would first have to lengthen all the existing N-F bonds to make room for the incoming fifth and sixth ligands. This means that the synthesis of NF_5 from ground-state NF_3 or NF_4^+ , although thermodynamically feasible, should not proceed because of steric hindrance. An alternate approach would involve the use of an excited-state N-F_x precursor with longer N-F bonds.

As crystalline NF_4^+F^- is comparable in energy to covalent NF_5 but at the same time does not suffer from the steric hindrance problems of the latter, crystalline NF_4^+F^- should experimentally be easier to prepare than covalent NF_5 of D_{3h} symmetry. Since,

for a salt which is partially soluble in a given solvent, the solvation energy of its ions is comparable to its lattice energy, NF_4^+F^- (cr) might be accessible from solvated NF_4^+ and F^- ions in an essentially thermally neutral reaction. This approach avoids the endothermicity of its synthesis from NF_3 and F_2 (see above) but requires a common solvent in which both the NF_4^+ cation and the F^- anion are soluble and chemically inert. Previously, such a solvent had not been identified. The solvents generally used for NF_4^+ salts were Lewis acids, such as HF, BrF_3 , or IF_5 , that react with the strongly basic F^- anion, resulting in the formation of the corresponding complex fluoro anions.²⁴ On the other hand, the simple alkali metal fluorides are practically insoluble in all nonacidic anhydrous solvents, and only recently, the successful synthesis²² of truly anhydrous $\text{N}(\text{CH}_3)_4^+\text{F}^-$ has provided a source of highly soluble "naked" fluoride ion in combination with an oxidizer-resistant cation.^{25,26} The preferred, oxidizer-resistant solvents for $\text{N}(\text{CH}_3)_4^+\text{F}^-$ are CH_3CN and CHF_3 .²² It was therefore interesting to examine whether NF_4^+ salts could also be handled in these organic solvents and, if so, whether NF_4^+ cations and F^- anions can coexist in these solutions or will undergo the possible, exothermic ($-\Delta H_4 = -31.8$ kcal mol⁻¹) reaction to give NF_3 and F_2 . If solvated NF_4^+ and F^- will react with each other, then crystalline NF_4^+F^- should also decompose under these conditions because solvation spheres should increase the ion separation and result in an increased activation energy barrier for the fluorine elimination reaction.

The following experiments were carried out. At ambient temperature, compatibility tests of NF_4^+ salts of BF_4^- , AsF_6^- , and SbF_6^- with dry CH_3CN resulted in gentle NF_3 evolution, but at lower temperatures, good solubility and compatibility were observed by NMR spectroscopy. The lower boiling (-82.0 °C) and melting (-155 °C) CHF_3 was also found to be compatible with NF_4^+ salts, although their solubilities in this solvent were quite low. In the absence of a solvent, equimolar mixtures of NF_4BF_4 and $\text{N}(\text{CH}_3)_4\text{F}$ did not interact at 25 °C, but in CH_3CN at -31 °C or CHF_3 at -78 °C, they underwent quantitative NF_3 evolution within relatively short time periods. The F_2 evolution was not quantitative, probably due to side reactions with either the solvents or the $\text{N}(\text{CH}_3)_4^+$ cation. A reaction in CHF_3 was also carried out at -142 °C and resulted in about 10% NF_3 evolution over a time span of about 3 h. This decrease of the reaction rate at -142 °C might be partially due to the very low solubility of NF_4BF_4 in CHF_3 at this low temperature and does not necessarily reflect a substantial activation energy barrier for the $\text{NF}_3 + \text{F}_2$ elimination reaction.

Conclusions

This study allows the following conclusions to be drawn: (i) ionic and covalent NF_5 are of comparable energy; (ii) ionic NF_5 , i.e. NF_4^+F^- , should be experimentally more accessible than covalent NF_5 ; (iii) at temperatures as low as -142 °C, metathetical experiments involving solvated NF_4^+ and F^- ions resulted in NF_3 and F_2 elimination, indicating that NF_4^+F^- is unstable at or above -142 °C.

Experimental Section

Caution: Mixtures of strong oxidizers, such as NF_4^+ salts, with organic materials, such as CH_3CN or $\text{N}(\text{CH}_3)_4^+$ salts, are potentially explosive. Although no explosions were incurred in the present study, work with these materials should be carried out on a small scale with appropriate safety precautions!

Materials and Apparatus. The syntheses of anhydrous $\text{N}(\text{CH}_3)_4\text{F}^{22}$ and NF_4^+ salts^{6,24} have previously been described. CH_3CN (Baker, Bio-analyzed, having a water content of 40 ppm) was stored over P_2O_5 and freshly distilled on the vacuum line prior to its use which lowered the water content to <4 ppm. CHF_3 (Matheson) was used as received. Volatile materials were handled in a flamed-out Pyrex vacuum line equipped with greaseless Kontes Teflon valves. Solids were handled in

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the dry nitrogen atmosphere of a glovebox. Reactions involving NF_4^+ salts were carried out in $3/4$ in. o.d. Teflon-FEP ampules closed by a stainless steel valve.

The ^{19}F and ^1H NMR spectra were measured at 84.6 and 90 MHz, respectively, on a Varian Model EM390 spectrometer, with 4-mm Teflon-FEP tubes (Wilma Glass Co.) as sample containers and CFCl_3 and TMS, respectively, as internal standards, with negative shifts being upfield from the standards. Raman spectra were recorded on either a Cary Model 83 or a Spex Model 1403 spectrophotometer by use of the 488-nm exciting line of an Ar ion or the 647.1-nm line of a Kr ion laser, respectively. Baked-out Pyrex melting point capillaries were used as sample holders. Infrared spectra were recorded on a Perkin-Elmer Model 283 spectrophotometer as AgCl disks that were pressed in a Wilks minipress inside the drybox.

The $\text{NF}_4\text{BF}_4\text{-N}(\text{CH}_3)_4\text{F-CH}_3\text{CN}$ System. NF_4BF_4 (0.54 mmol) and $\text{N}(\text{CH}_3)_4\text{F}$ (0.60 mmol) were loaded inside the drybox into a $3/4$ in. Teflon-FEP ampule. On the vacuum line, dry CH_3CN (3 mL liquid) was added at -196°C , and the mixture was warmed to -31°C for 30 min. The ampule was cooled to -78°C , and the volatile material (0.45 mmol) was expanded into the vacuum line and shown by fractional condensation at -210°C and infrared spectroscopy to consist mainly of NF_3 (0.40 mmol). The mixture in the ampule was then warmed for 3 h to -31°C and for 1 h to room temperature, and an additional amount of NF_3 (0.13

mmol) was evolved. The solid residue (90.9 mg, weight calculated for 0.54 mmol of $\text{N}(\text{CH}_3)_4\text{BF}_4$ and 0.06 mmol of unreacted $\text{N}(\text{CH}_3)_4\text{F}$ = 92.9 mg) was shown by vibrational spectroscopy to consist mainly of $\text{N}(\text{CH}_3)_4\text{BF}_4$. When the reaction was repeated using a 5-fold excess of $\text{N}(\text{CH}_3)_4\text{F}$ at -31°C , the NF_3 evolution was 95% complete after 30 min.

The $\text{NF}_4\text{BF}_4\text{-N}(\text{CH}_3)_4\text{F-CHF}_3$ System. NF_4BF_4 (2.19 mmol) and $\text{N}(\text{CH}_3)_4\text{F}$ (2.24 mmol) were combined in a Teflon ampule, and CHF_3 (50.26 mmol) was added at -196°C . The mixture was warmed to -78°C for 3 h and then cooled again to -196°C , and the noncondensable gases (0.45 mmol of F_2) were measured. Subsequently, the ampule was warmed to the melting point of CHF_3 (-155°C), and the volatile material was removed in a dynamic vacuum by fractional condensation through traps kept at -186 and -210°C . The -210°C trap contained NF_3 (2.16 mmol). The solid residue, after being pumped on at room temperature (360 mg), consisted mainly of $\text{N}(\text{CH}_3)_4\text{BF}_4$ (weight calculated for 2.19 mmol of $\text{N}(\text{CH}_3)_4\text{BF}_4$ and 0.05 mmol $\text{N}(\text{CH}_3)_4\text{F}$ = 357 mg). When the reaction was repeated at -142°C , only 10% of the theoretical amount of NF_3 was evolved in 3 h.

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Conformation of Two 4'-Thio-2'-deoxynucleoside Analogs Studied by 500-MHz ^1H NMR Spectroscopy and X-ray Crystallography

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Abstract: An integrated conformational study is reported on the structurally modified nucleosides 4'-thiothymidine (**1**), an isoelectronic analogue of natural thymidine, and (*E*)-5-(2-bromovinyl)-2'-deoxy-4'-thiouridine (**2**). The conformation of **1** and **2** in D_2O solution was inferred from the vicinal proton-proton NMR coupling constants and nuclear Overhauser (*nOe*) contacts. Significant adaptations of the conventional routines for *J*-coupling analysis in nucleos(t)ide structures were necessary due to the presence of sulfur instead of $\text{O}4'$ in the thiofuranose ring. A pseudorotational equation of the form $\nu_j = a_j \nu_m \cos(P + \epsilon_j + 144^\circ(j - 2))$ was used to account for the nonequilateral nature of the 4'-thiofuranose ring. The parameter sets a_0, \dots, a_4 and $\epsilon_0, \dots, \epsilon_4$ were deduced from a set of ab initio (HF/3-21G level) molecular orbital calculations. Analysis of the *J*-coupling constants measured for **1** and **2** revealed that (i) the $\text{C}4'\text{-C}5'$ bond is primarily in the γ^+ or γ^1 conformation and (ii) the 4'-thiofuranose ring has a preference for a South-type ($\text{C}2'\text{-endo}/\text{C}3'\text{-exo}$) puckered conformation. The preference for the South conformation is slightly larger for **1** (73% at 300 K) than for **2** (66% at 300 K). The pseudorotational parameters of the South conformer are as follows: $P = 177^\circ, \nu_m = 43^\circ$ for **1**, and $P = 177^\circ, \nu_m = 44^\circ$ for **2**. The results reveal that another conformer with a North-type puckered conformation of the 4'-thiofuranose ring is also present in solution, to an extent of $\approx 27\%$ for **1** and 34% for **2** at ambient temperature. The pseudorotational parameters describing the thiofuranose conformation of the minor conformer are as follows: $P = 13^\circ, \nu_m = 45^\circ$ for **1**, and $P = 9^\circ, \nu_m = 45^\circ$ for **2**. The characterization of the minor conformer must be regarded as an essential complement to the results of X-ray crystallographic analyses. One-dimensional *nOe* measurements indicated a predominant anti conformation of the thymine base in **1** and the modified uridine base in **2**. The crystal structures of **1** and **2** were found to be grossly similar. The most important characteristics are as follows: compound **1**, $P = 177.7^\circ, \nu_m = 47.9^\circ, \chi = -144.7^\circ, \gamma = 179.5^\circ$; compound **2**, $P = 179.5^\circ, \nu_m = 48.6^\circ, \chi = -140.0^\circ, \gamma = 174.1^\circ$. Furthermore, it is concluded that the preferred conformation of **1** and **2** in solution is in close agreement with the X-ray crystal structure. The present results indicate that it is dangerous to rely solely on X-ray crystallographic information in attempts to explain or predict biological activity of modified nucleosides. The best basis for formulating structure-activity relationships for modified nucleosides is probably a combined interpretation of solid state and solution conformational data.

Introduction

The ongoing search for more active and more specific anti-(retro)viral agents has stimulated many investigations on struc-

turally modified nucleosides and nucleotides. A plethora of these compounds is known today.¹ A general conclusion emerging from

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