On the Protonation of Fluoro Cryptands and the Possibility of CF···HN$^+$ Hydrogen Bonds

Herbert Plenio* and Ralph Diodone

Institut für Anorganische und Analytische Chemie, Universität Freiburg
Albertstrasse 21, D-79104 Freiburg, Germany
E-mail: plenio@ruf.uni-freiburg.de

Received November 28, 1996

Keywords: Fluorine / Macrocycles / Cryptands / Protonations

The protonation of several fluoro cryptands synthesized from 1,3-bis(bromomethyl)-2-fluorobenzene and diaza-macrocycles (diaza-12-crown-4, diaza-15-crown-5, diaza-18-crown-6 and 2,3-benzodiaza-15-crown-5) has been investigated by ^{1}H-, ^{13}C- and ^{19}F-NMR spectroscopy, X-ray crystal structure analysis and IR spectroscopy, with a view to detecting possible CF···HN hydrogen bonding. From the crystal structures of mono- and diprotonated 23-fluoro-4,7,20-trioxa-1,10-diazatricyclo[8.7.5.1^{12,16}]tricosa-12,14,16(23)-triene (**FN$_2$O$_3$** · H$^+$ and **FN$_2$O$_3$** · 2H$^+$) it is apparent that protonation leads to a shortening of the non-bonded nitrogen-fluorine and nitrogen-oxygen distances and consequently to O···HN hydrogen bonds. A related type of interaction involving fluorine appears possible since short N(H)···F distances (281.2–286.6 pm) with NHF angles between 130–140° are observed. A Cambridge Structural Database search was performed and 27 structures with short CF···HN contacts were found. On the other hand, IR spectra do not give any clear evidence in favor of CF···HN hydrogen bonding since the N–H vibrations in **FN$_2$O$_3$** · H$^+$ and **FN$_2$O$_3$** · 2H$^+$ as well as in **FN$_2$O$_4$** · 2H$^+$ do not experience longwave shifts relative to the N–H vibrations of the reference systems **HN$_2$O$_3$** · H$^+$, **HN$_2$O$_3$** · 2H$^+$ and **HN$_2$O$_4$** · 2H$^+$. **HN$_2$O$_3$** and **HN$_2$O$_4$** are almost identical to **FN$_2$O$_3$** and **HN$_2$O$_4$**, respectively, the only difference being that the single fluorine atom of the fluoro cryptands is replaced by hydrogen. NMR spectroscopic evidence concerning CF···HN interactions is ambiguous: (i) A spin-coupling between ^{1}H and ^{19}F (NH···F) is observed. (ii) The $^1J_{CF}$ value is reduced by up to 15 Hz upon protonation of the fluoro cryptand. (iii) An NMR competition experiment between **FN$_2$O$_3$** and **HN$_2$O$_3$** yields no evidence for an increased basicity of the fluoro cryptand. Finally, it can be stated that evidence in favor of CF···HN hydrogen bonds is inconclusive; should such an interaction exist it will certainly be very weak.

Hydrogen bonding is of fundamental importance in chemistry and biology alike[1]. Currently, the significance of such weak, non-covalent interactions is increasingly being recognized within chemistry and is now playing an ever stronger role under the label "supramolecular chemistry"[2]. This area of research was initiated through the synthesis of crown ethers and cryptands by Pedersen and Lehn[3], who also demonstrated that rather stable complexes of alkaline metal ions can be formed with macrocycle ligands via oxygen donor centers[4].

Recently, our investigations into the coordination chemistry of fluorinated macrocycles have proven that covalently-bonded fluorine can act as an efficient donor atom towards hard metal ions – in solution as well as in the solid state[5,6,7]. One of our conclusions was that, given some assistance in the form of a preorganized ligand framework, fluorine can replace oxygen donor atoms in the coordination sphere of a metal ion. A logical next step, therefore, was to investigate whether fluorine is also able to form bridging hydrogen bonds of the type CF···HN, as had already been hinted at by Glusker, Murray-Rust et al. in their 1983 landmark paper[8].

In order to assess possible fluorine-hydrogen interactions, we have investigated the protonation of several fluoro cryptands by NMR and IR spectroscopy, and by X-ray crystal structure analysis. To gain further insight into the role played by fluorine in such macrocycles, we have also studied the protonation of the closely-related parent cryptands as reference systems, which bear a hydrogen atom in the place of the single fluorine. In order to lend more support to our study, we have performed a Cambridge Structural Database search for possible CF···HN contacts.

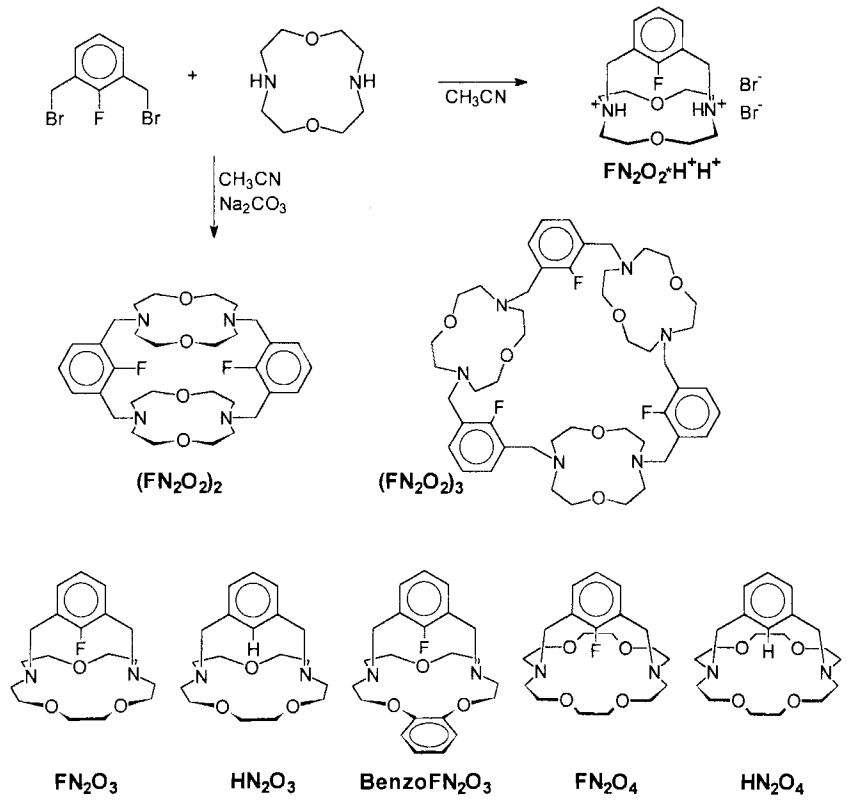
Results and Discussion

Synthesis of the Fluoro-Cryptands: The standard building block for all the fluoromacrocycles described herein was 1,3-bis(bromomethyl)-2-fluorobenzene. This was reacted with various diaza-crown ethers (diaza-12-crown-4, diaza-15-crown-5, benzodiaza-15-crown-5, diaza-18-crown-6) in acetonitrile in the presence of excess base (Scheme 1). With diaza-15-crown-5 and diaza-18-crown-6, the fluoro cryptands **FN$_2$O$_3$** and **FN$_2$O$_4$** were accessible, the syntheses of which we have described previously[5b]. The product isolated from the reaction with 2,3-benzodiaza-15-crown-5 was **BenzoFN$_2$O$_3$**[9]. The synthesis of the macrocycles **HN$_2$O$_3$** and **HN$_2$O$_4$**, which possess one hydrogen atom instead of the single fluorine atom, has also been described previously[5b]. These parent cryptands were very useful as reference compounds in the protonation experiments.

In the cryptands **FN$_2$O$_3$**, **BenzoFN$_2$O$_3$** and **FN$_2$O$_4$**, a stepwise protonation of the two nitrogen atoms is possible, since their respective basicities differ markedly[10]. For the experiments requiring pure mono- or diprotonated cryptand, a small amount of cryptand (20–30 mg) was dis-

 © VCH Verlagsgesellschaft mbH, D-69451 Weinheim, 1997 0009–2940/97/0505–0633 $ 17.50+.50/0

Scheme 1. Synthesis of the fluoro cryptands and schematic drawings of the fluoro macrocycles described previously



solved in CD_3CN in an NMR tube and titrated with trifluoromethanesulfonic acid until the ^{19}F NMR spectrum (Table 1) indicated complete conversion to the desired mono- or diprotonated ammonium salt.

The reaction of diaza-12-crown-4 with 1,3-bis(bromomethyl)-2-fluorobenzene was performed in the same manner as for the other macrocycles, but the small cryptand **FN_2O_2** could only be obtained in its diprotonated form when using a non-templating base such as DABCO. All attempts to deprotonate this ammonium salt were unsuccessful, leading either to recovery of the starting material or – when applying more harshly basic conditions – to the decomposition of the fluoro cryptand. This resistance to undergo deprotonation was not unexpected, since several other small cage-like amines, such as the [1.1.1]-cryptand described by Lehn et al.[11], the smaller bridgehead azamacrocycles described by Alder et al.[12], or more recently 1,5,9,13-tetraazatricyclo[7.7.3.3(5,13)]docosane described by Springborg et al.[13], display similar behavior. The acid/base behavior of the [1.1.1]-cryptand has been the subject of particularly detailed studies[14].

When, on the other hand, the reaction of diaza-12-crown-4 with 1,3-bis(bromomethyl)-2-fluorobenzene was performed in the presence of a templating base such as Na_2CO_3, only the higher oligomers such as the 2 + 2- and the 3 + 3-product could be isolated.

NMR Spectroscopy: The fluoro cryptands **FN_2O_3** and **FN_2O_4** and their protonation products display very complex, high-order ^1H-NMR spectra, since in the monoprotonated products every proton is magnetically and chemically unique. The ^{13}C-NMR spectra of **FN_2O_3** · H^+ and **FN_2O_4** · H^+ likewise display large numbers of signals. These observations are indicative of a localized bonding of the proton at one nitrogen.

The most salient NMR data with regard to possible $CF\cdots HN^+$ interactions are summarized in Table 1 and will be discussed now.

Table 1. Selected ^{13}C- and ^{19}F-NMR data most relevant to possible $CF\cdots HN^+$ interactions. [$\delta(^{13}C)$ *CF* is the ^{13}C-NMR shift of the carbon bonded to the fluorine atom; $\Delta\delta$ is the shift of the ^{19}F-NMR signal of the protonated ligand relative to that of the neutral cryptand; *J*(HF) is the coupling constant between the NH^+ proton and fluorine]

	^1J(CF) [Hz]	δ (^{13}C) *CF*	δ (^{19}F) ($\Delta\delta$)	*J*(HF) [Hz]
FN_2O_3	256	164.39	-109.10 (0.0)	-
FN_2O_3*H^+	250	161.90	-112.54 (-3.4)	9
FN_2O_3*$2H^+$	243.5	161.60	-116.10 (-7.0)	10.5
FN_2O_4	252	162.67	-114.38 (0.0)	-
FN_2O_4*H^+	250	-	-116.08 (-1.7)	< 7
FN_2O_4*$2H^+$	247	160.85	-119.07 (-4.7)	< 7
$BenzoFN_2O_3$	258.5	164.86	-106.41 (0.0)	-
$BenzoFN_2O_3$*H^+	251.5	163.45	-110.85 (-4.4)	8.5
$BenzoFN_2O_3$*$2H^+$	243.5	161.60	-115.19 (-8.8)	10.8

Upon addition of H^+ to the respective fluoro cryptands, the ^{19}F-NMR signals shift by up to $\Delta\delta = -8.8$ ppm relative to those of the free ligands. It may seem surprising that the addition of acid to fluoro cryptands leads to a further

shielding of the ^{19}F nuclei. However, it should be noted that this trend was predicted by deDios and Oldfield in ab initio ^{19}F-NMR shift calculations for model systems consisting of $C_6H_5F \cdot (HF)_x$[15]. It was, however, unexpected that in $\mathbf{HN_2O_3}$ and $\mathbf{HN_2O_4}$ the ^1H-NMR resonances of the hydrogen atom located in the former position of the fluorine, also experiences a pronounced upfield shift from $\delta = 8.86$ to 7.60 ($\mathbf{HN_2O_3/HN_2O_3} \cdot 2H^+$) and from $\delta = 8.41$ to 7.60 ($\mathbf{HN_2O_4/HN_2O_4} \cdot 2H^+$). This additional shielding of the nuclei is also observed in the respective ^{13}C-NMR spectra. In all cases, the changes in chemical shifts are of greater magnitude in the smaller cryptand $\mathbf{FN_2O_3}$ than in $\mathbf{FN_2O_4}$.

In the protonated products of the small cryptands $\mathbf{FN_2O_3}$ and $\mathbf{BenzoFN_2O_3}$, a significant decreases in the $^1J_{CF}$ coupling constant of up to 15 Hz relative to that of the neutral ligand is observed, whereas the larger cryptand $\mathbf{FN_2O_4}$ displays a much less pronounced decrease of only 5 Hz. In our investigation of the metal complexes with fluoro cryptands, we showed this decrease in the $^1J_{CF}$ coupling constant to be correlated with the degree of metal cation to fluorine interaction[5]. The data presented in Table 1 seem to point into the same direction.

In protonated $\mathbf{FN_2O_3}$ and $\mathbf{BenzoFN_2O_3}$, a coupling of the nuclear spins of the NH protons and the ^{19}F nucleus can be observed in the ^{19}F-NMR spectra, while in the deuterated cryptands the NMR signals lack this fine structure[16]. The ^1H-^{19}F coupling constants were determined to be close to 10 Hz by simulating the NMR spectra[17]. Such J_{FH} values are indicative of close CF···HN^+ interactions, however, caution is advisable since it is not possible to distinguish between the scalar and the dipolar component of this coupling. Somewhat unexpectedly, no such coupling was observed for $\mathbf{FN_2O_4} \cdot H^+$ and $\mathbf{FN_2O_4} \cdot 2H^+$, but in view of the rather broad lines ($\nu_{1/2} \approx 7$ Hz) it is quite possible that smaller coupling was masked by the broad signals.

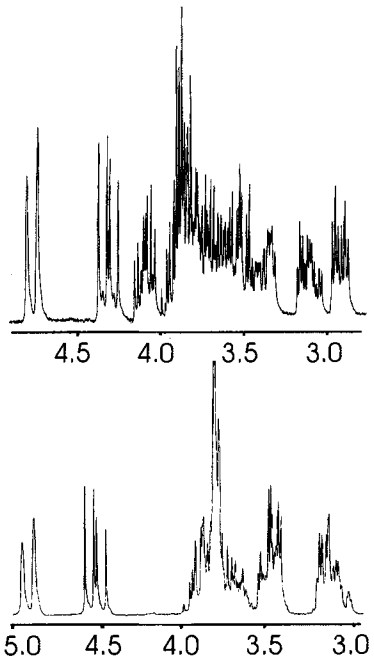
A retardation of proton-transfer kinetics, which is well-known for the [1.1.1]-cryptand, is also apparent in the reactions of $\mathbf{FN_2O_3}$ and $\mathbf{BenzoFN_2O_3}$ with acid, and can be monitored by ^{19}F-NMR spectroscopy. Whereas the formation of $\mathbf{FN_2O_3} \cdot H^+$ is still fast, the second protonation step is considerably slowed down in the presence of only a small excess of CF_3SO_3H and requires several minutes for completion. Consequently, $\mathbf{FN_2O_3}$, $\mathbf{FN_2O_3} \cdot H^+$ and $\mathbf{FN_2O_3} \cdot 2H^+$ can coexist for several minutes in CD_3CN solution. However, when carrying out the second protonation step under pseudo-first-order conditions, i.e. in a large excess of acid, the reaction is too fast to be monitored by NMR spectroscopy.

An important question to be answered regarding potential CF···HN^+ interactions concerns the basicity of the nitrogen atoms in the different cryptands described here. As soon as some sort of cooperation between a nitrogen and a fluorine occurs in the bonding of a proton, this should *invariably* lead to an increase in the basicity of this nitrogen atom with respect to that of our reference systems $\mathbf{HN_2O_3}$ or $\mathbf{HN_2O_4}$. Hence, a comparison of the base strengths of $\mathbf{FN_2O_3}$ and $\mathbf{HN_2O_3}$ might provide a simple answer to our question. Since we only expected a fairly small difference in basicity, the simple determination of the pK_b values of $\mathbf{FN_2O_3}$ and $\mathbf{HN_2O_3}$ as, for example, by potentiometric titrations would not be sufficiently precise. We therefore decided to perform an NMR competition experiment, more appropriate for measuring small differences in basicity. For such an experiment equimolar amounts of $\mathbf{FN_2O_3}$ and $\mathbf{HN_2O_3}$ were dissolved in CD_3CN in an NMR tube and an NMR titration experiment with CF_3SO_3H was carried out. In addition to knowing the concentrations of all reactants, it was also possible to cross-check the ratio of acid to fluoro cryptand by comparing the integrals of the ^{19}F-NMR resonances of the fluoro macrocycle and $CF_3SO_3^-$. By monitoring ^1H- as well as ^{19}F-NMR spectra, the relative concentrations of unprotonated, mono- and diprotonated macrocycles were known at any given time. We were, however, concerned that kinetic effects might disturb the outcome of our experiments, especially for the second protonation. Therefore, we performed our titration experiments such that in the first step exactly one equivalent of acid was added to give a 1:1:1 mixture of $\mathbf{FN_2O_3}$:$\mathbf{HN_2O_3}$:CF_3SO_3H. In the second step, the reaction mixture was titrated up to a 1:1:3 ratio. In both cases, the relative ratios of the components were checked by the ^{19}F-NMR integrals of $\mathbf{FN_2O_3}$ and CF_3SO_3H. The relative basicities were determined by comparing the ^1H- or ^{19}F-NMR integral ratios of the different protonated species.

The results of the titration experiments prove that $\mathbf{HN_2O_3}$ and $\mathbf{HN_2O_3} \cdot H^+$ are stronger bases than $\mathbf{FN_2O_3}$ and $\mathbf{FN_2O_3} \cdot H^+$, respectively, each by a factor of ca. 5(±2.5)[18]. This result may be viewed as convincing evidence against CF···HN^+ interactions, but it should be kept in mind that the outcome of this experiment is not exclusively governed by the basicity of the nitrogen atom with or without a neighbouring fluorine atom. Especially when looking at very small effects one also has to consider the slightly different conformational energies and the different electrical field effects of $\mathbf{FN_2O_3}$ and $\mathbf{HN_2O_3}$ and their protonated products. To illustrate this, the ^1H-NMR spectra of $\mathbf{FN_2O_3} \cdot 2H^+$ and $\mathbf{HN_2O_3} \cdot 2H^+$ are depicted in Figure 1. Even without assigning the resonances in the two quite complicated spectra it is evident that they are different, and hence that the conformations of the two cryptands in solution should also be different. This may not be very helpful in the context of identifying CF···HN^+ contacts, but it highlights some of the problems involved.

IR Spectroscopy: The ν(NH) vibrations produce very characteristic absorptions in the IR spectrum and should thus be diagnostic of possible CF···HN^+ interactions; any type of shared bonding of the proton between nitrogen and fluorine should lead to a longwave shift of the respective N−H stretch. The ν(NH) of the different protonated products appear at the following wavenumbers: $\mathbf{FN_2O_3} \cdot H^+$ (3143 cm^{-1}), $\mathbf{FN_2O_3} \cdot 2H^+$ (3167 cm^{-1}), $\mathbf{HN_2O_3} \cdot H^+$ (3520, 3133 cm^{-1}), $\mathbf{HN_2O_3} \cdot 2H^+$ (3520, 3142, 3122 cm^{-1}) and $\mathbf{FN_2O_4} \cdot 2H^+$ (3580, 3510, 3179 cm^{-1}), $\mathbf{HN_2O_4} \cdot 2H^+$ (3570, 3502, 3172 cm^{-1}). The shortwave absorptions around 3500 cm^{-1} give very broad bands ($\nu_{1/2} \approx 200$ cm^{-1}), while the longwave absorptions are much sharper ($\nu_{1/2} \approx$

Figure 1. ^{1}H-NMR spectra of $HN_2O_3 \cdot H^+$ (top) and $FN_2O_3 \cdot H^+$ (bottom) recorded at 200 MHz

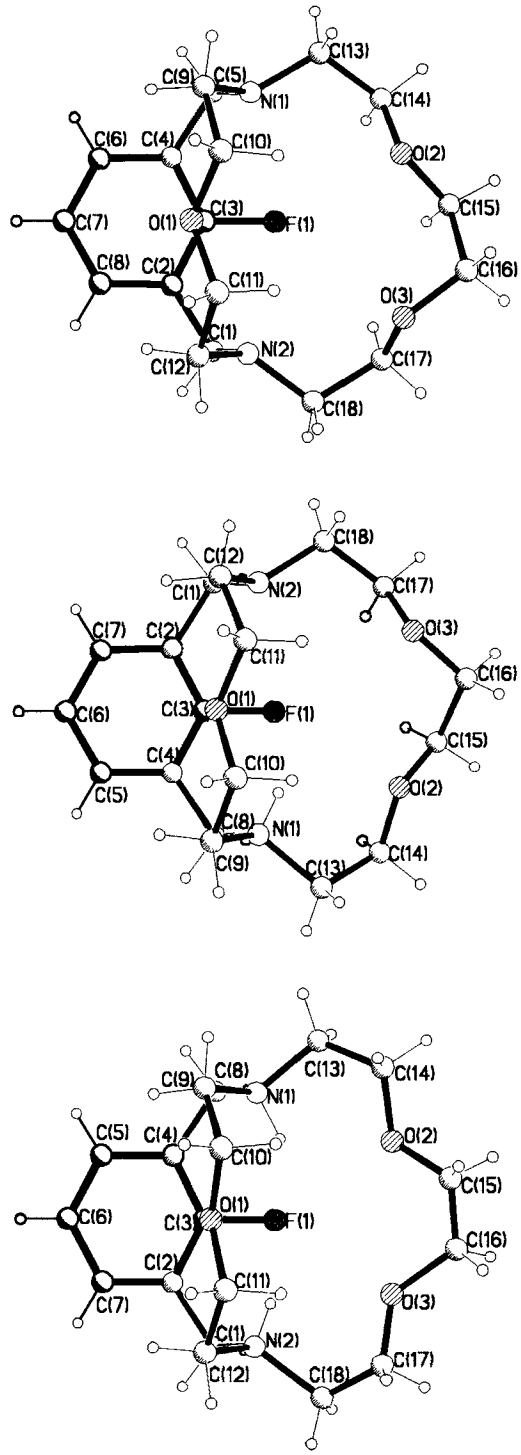


50 cm^{-1}). It is interesting to note that the aggregation state of the ammonium salts has an influence on the number of bands observed in the IR spectrum of the smaller cryptand. Nujol mulls of crystalline materials display only one sharp longwave absorption, while measurements of the pure oily materials show two IR bands[19]. Since all our X-ray crystal structures show endohedral NH bonds, we assign the shortwave band to the *endo*-NH stretch, while the *exo*-NH stretch appears at around 3500 cm^{-1}. This assignment is in accord with that made by Knöchel et al. for the protonated forms of the [1.1.1]-cryptand[20]. The higher flexibility of $FN_2O_4 \cdot 2H^+$ gives rise to the existence of *exo*- and *endo*-protonated isomers even in the solid state. The IR data reveal (with one exception) only small differences (<10 cm^{-1}) in the positions of the NH stretch between the fluorine-containing and the fluorine-free cryptands, although in all cases it is apparent that the ν(NH) of the fluorine-free cryptands exhibit a slight longwave shift. The only large difference is observed between $HN_2O_3 \cdot 2H^+$ and $FN_2O_3 \cdot 2H^+$, where the diprotonated fluoro cryptand displays a substantial long-wave shift.

In conclusion, the IR spectra provide no firm evidence in favor of CF···HN$^+$ interactions.

X-ray Crystal Structures of $FN_2O_3 \cdot H^+$ *and* $FN_2O_3 \cdot 2H^+$: In order to study the influence of protonation on the framework of a fluoro cryptand, as well as to obtain information on possible CF···HN$^+$ bridges, we have determined the structures of $FN_2O_3 \cdot H^+$ and $FN_2O_3 \cdot 2H^+$. We have already reported the crystal structures of FN_2O_3 and of $FN_2O_3 \cdot Li^+$[5b], but they are included again in the present discussion, since they are important for an understanding of the changes caused by successive protonation (Figure 2, Tables 5, 6, 7).

Figure 2. Molecular structures of FN_2O_3 (top), $FN_2O_3 \cdot H^+$ (middle) and $FN_2O_3 \cdot 2H^+$ (bottom) in the crystal (the anions ClO_4^- and $CF_3SO_3^-$ have been omitted)



Bond lengths as well as bond angles in the two new structures are unspectacular and require no discussion. In both molecules, the protons on nitrogen were localized on difference Fourier maps and were shown to reside inside the cav-

ity. This endohedral orientation of the protons is typical for protonated macrocycles and has also been found in several solid-state structures of other cryptands[21]. Since the positional parameters for the NH-protons are subject to large uncertainties, the F···H distances given here use normalized N–H bond lengths of 90 pm and are between 214–220 pm. It should also be taken into account that the N–H vectors point roughly towards the fluorine atom (NHF angles = 130–140°), which may allow for some weak, secondary interaction, especially since the nitrogen-fluorine distances in $\mathbf{FN_2O_3} \cdot H^+$ and $\mathbf{FN_2O_3} \cdot 2H^+$ are much shorter than the van der Waals distances.

Table 2. Non-bonded distances between the donor atoms in the crystal structures of $\mathbf{FN_2O_3}$, $\mathbf{FN_2O_3} \cdot H^+$, $\mathbf{FN_2O_3} \cdot 2H^+$ and $\mathbf{FN_2O_3} \cdot Li^+$

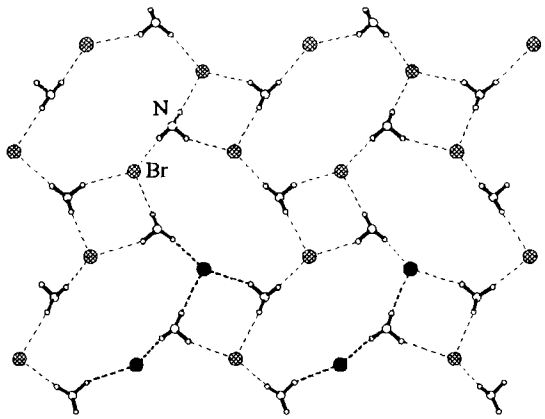
[pm]	FN_2O_3	FN_2O_3* H^+	FN_2O_3* $2H^+$	FN_2O_3*Li^+
N(1)-O(1)	296.2	282.2	281.9	280.3
N(1)-O(2)	296.2	275.9	264.5	275.8
N(1)-F(1)	291.4	281.2	286.6	284.5
N(2)-O(1)	298.3	293.5	283.2	285.6
N(2)-O(3)	298.3	298.8	269.5	277.4
N(2)-F(1)	296.5	283.6	284.2	283.8
N(1)-N(2)	476.0	468.4	466.1	445.0
O(1)-O(2)	405.2	397.3	365.8	335.3
O(1)-O(3)	409.8	403.2	362.5	325.1

It is very interesting to analyze the changes in the overall structure of the cryptand $\mathbf{FN_2O_3}$ that result from successive protonation, since this results in the addition of positive charge to the molecule. This charge is largely localized on the two nitrogen atoms and we feel that the accompanying structural changes can be best understood by analyzing the non-bonded distances of nitrogen-to-fluorine and nitrogen-to-oxygen as well as inter-oxygen and inter-nitrogen distances. These are listed in Table 2. From these data it is apparent that the addition of positive charge to the cryptand leads to a contraction of the whole molecule, as well as to a shortening of the non-bonded distances between the donor atoms. This can be understood in terms of a reduced lone-pair repulsion between nitrogen, oxygen and fluorine. The contraction of the ligand can be seen even more clearly upon averaging the respective six nitrogen-oxygen and nitrogen-fluorine distances given in Table 2. For the different compounds, the following values were calculated: $\mathbf{FN_2O_3}$ (av. 296.2 pm), $\mathbf{FN_2O_3} \cdot H^+$ (285.9 pm), $\mathbf{FN_2O_3} \cdot 2H^+$ (278.3 pm) and $\mathbf{FN_2O_3} \cdot Li^+$ (281.2 pm). In the case of $\mathbf{FN_2O_3} \cdot H^+$, the average shortening lies between that of the unprotonated and the diprotonated fluoro cryptand. It is also apparent that the contraction is greatest in the vicinity of N(1), since the proton is localized on this side of the macrocycle.

The shortening of the nitrogen-oxygen distances is much more pronounced than that of nitrogen-fluorine distances, which is not surprising since the oxygen atoms are located in a flexible oxyethylene-chain, whereas the fluorobenzene unit is fairly rigid. However, the CF···HN^+ distances found in both new structures fall within the accepted range for O···HN^+ hydrogen bonding[22].

X-Ray Crystal Structure of 2-Fluorobenzylammonium Bromide: In order to find out whether CF···HN^+ interactions are of relevance in the case of an ammonium salt, we have determined the crystal structure of protonated 2-fluorobenzylamine (Figure 3). It was hoped that the close proximity of the fluorine and the $-NH_3^+$ group in this molecule would lead to hydrogen-fluorine contacts in the solid-state structure. However, the result of the crystal structure determination shows that this idea was rather naïve, since no such contacts are observed. Instead, the molecules are packed in alternating AB layers in the crystal, with the less polar fluorophenyl units forming in one layer and the $-NH_3^+$ groups and the bromide counterions forming the other layer. Nitrogen and bromide are arranged such that there are four- and eight-membered rings, not counting the hydrogen bonds, which link the heavy atoms within this layer.

Figure 3. Packing diagram of the molecular structure of 2-fluorobenzylammonium bromide. Only the layer containing the $-NH_3^+$ groups and the Br^- ions is depicted



Crystal Structue Databank Search for Short CF···HN Contacts: To obtain more information on possible CF···HN bridges we have searched the Cambridge Structural Databank for such short contacts, thus extending a similar study performed by Glusker, Murray-Rust et al. in 1983, which found only three relevant structures[8]. Our search was limited to intermolecular CF···HN contacts with four-coordinate nitrogen (to include ammonium salts which should be better H^+ donors then amines), and to three-coordinate nitrogen. Other limitations were: non-bonded F···H distances of <250 pm, F···N distances <320 pm, insist-on-error-free and $R < 10\%$[23]. Using these restrictions, twelve X-ray crystal structures were found for four-coordinate nitrogen and fifteen data sets for three-coordinate nitrogen. In Tables 3 and 4 the data are arranged according to increasing F···N distances.

The data sets for the three- and four-coordinate nitrogen do not differ significantly in the distribution of F···N distances and, with the exception of two structures, the distributions of interatomic distances are evenly spread. Two examples displaying exceptionally short CF···HN distances were found: An F···H distance of 204 pm was reported by Collin et al. in the structure of cisapride monohydrate, a pharmaceutically active compound (KEYXOB)[49]. The second example, with an F···H distance of 205 pm, was re-

ported by Jansen and Mokros for hexakis(2-fluorophenylamino)disiloxane (KUNGIJ)[50]. The other 25 data sets might also be candidates for CF···HN interactions, even though the F···H distances are at least 15 pm longer than in the two aforementioned examples. The angles around hydrogen in all the examples are between 120–160°. While it is always dangerous to discuss hydrogen bonding on the basis of X-ray data sets, the nonbonded F···N distances are more reliable and there are eleven structures with distances shorter than the sum of the van der Waals radii of nitrogen and fluorine (302 pm)[24].

In conclusion our search has yielded 27 X-ray crystal structures which are potential candidates for CF···HN interactions. It would certainly be desirable to have neutron diffraction data of these compounds to be able to gain more conclusive information on the hydrogen positions in these molecules.

Conclusions

We have investigated the protonation of the fluoro cryptands $\mathbf{FN_2O_3}$ and $\mathbf{FN_2O_4}$ by NMR and IR spectroscopy, and by X-ray crystal structure analysis. The cryptands $\mathbf{HN_2O_3}$ and $\mathbf{HN_2O_4}$ were employed as reference systems since they differ only in that they contain a hydrogen atom in the place of the fluorine atom. These ligands were used to investigate the possibility of CF···HN hydrogen bonding. However, the results obtained were somewhat ambiguous with respect to such interactions. There is positive evidence from the X-ray crystal structures of $\mathbf{FN_2O_3} \cdot H^+$ and $\mathbf{FN_2O_3} \cdot 2H^+$, as well as from a CSD search, since several short CF···HN contacts have been found. On the other hand, a comparison of the ν(N–H) stretches in the IR spectra of $\mathbf{FN_2O_3} \cdot H^+$ and $\mathbf{FN_2O_3} \cdot 2H^+$ with those of $\mathbf{HN_2O_3} \cdot H^+$ and $\mathbf{HN_2O_3} \cdot 2H^+$ does not reveal any significant longwave shifts for the fluoro cryptands. In the NMR spectra, the typical decrease in the $^1J_{CF}$ coupling constant upon protonation, as well as the coupling between ^1H and ^{19}F is indicative of CF···HN interactions, whereas an NMR competition experiment between $\mathbf{FN_2O_3}$ and $\mathbf{HN_2O_3}$ shows the fluoro cryptand to be the slightly weaker bases.

The lack of unambiguous evidence leads us to finally conclude: Should a CF···HN^+ hydrogen bonding interaction exist, it is certainly going to be of a very weak nature.

Note added in proof (February 24, 1997): A closely related study was published very recently: J. O. Dunitz, R. Taylor, *Chem. Eur. J.* **1997**, *3*, 89.

This work was supported by the *Fonds der Chemischen Industrie*, the *Deutsche Forschungsgemeinschaft* and the *Freiburger Wissenschaftliche Gesellschaft*. We wish to thank Dr. *W. Deck*, Dipl.-Chem. *M. Ruf* and *H. G. Schmidt* for collecting the X-ray data sets, and Prof. Dr. *H. Vahrenkamp* for his support.

Experimental Section

Commercially available solvents and reagents were purified according to literature procedures. Chromatography was carried out on silica MN 60. NMR spectra were recorded at 300 K (unless otherwise noted) on a Bruker AC200 F (^1H NMR, 200 MHz; ^{13}C NMR, 50.3 MHz; ^{19}F NMR; 188.2 MHz) or a Varian Unity 300 (^1H NMR; 300 MHz; ^{13}C NMR, 75 MHz). ^1H-NMR spectra were referenced to residual H signals of the solvent; ^{13}C-NMR spectra to the respective solvent signals: $CDCl_3$ (δ = 7.26, 77.0), CD_3CN (δ = 1.93, 1.30). The ^{13}C-NMR spectra were accumulated in 32 K data files, both in the time and frequency domain, with a digital resolution of 0.7 Hz/data point. ^{19}F-NMR spectra were referenced to internal $CFCl_3$ (δ = 0). IR spectra were measured on a Bruker IFS 25 spectrometer as pure oils or as Nujol mulls. Elemental analyses were performed at the Mikroanalytisches Laboratorium der Chemischen Laboratorien, Universität Freiburg. Starting materials were available commercially or prepared according to literature procedures: 1,3-dimethyl-2-fluorobenzene[25], 1,3-bis(bromomethyl)-2-fluorobenzene[26], 1,3-diaza-18-crown-6[27], **Benzo-FN_2O_3**[9], $\mathbf{FN_2O_4}$[5b], $\mathbf{HN_2O_4}$[5b], $\mathbf{FN_2O_3}$[5b], $\mathbf{HN_2O_3}$[5b].

20-Fluoro-6,17-dioxa-3,9-diazatricyclo[9.5^{3,9}.3.1]eicosa-1(20),11,13-triene ($\mathbf{FN_2O_2}$): To a boiling mixture of DABCO (129 mg, 1.15 mmol) in acetonitrile (600 ml) was slowly added dropwise (3 ml/h) 1,7-dioxa-4,10-diazacyclodecane (100 mg, 0.754 mmol) and 1,3-bis(bromomethyl)-2-fluorobenzene (162 mg, 0.754 mmol) each in CH_3CN (50 ml). After the addition was complete, the solution was refluxed for a further 8 h. The solvent was then evaporated in vacuo and the remaining powder was dissolved in $CHCl_3$. An insoluble oily residue was dissolved by adding a small amount of acetonitrile. After 2 d, colorless crystals were obtained which were soluble in water. Yield: 60 mg (0.13 mmol) 11% $\mathbf{FN_2O_2} \cdot 2$ HBr. – ESI-MS [*m/e* (%)]: 459.1 ($M \cdot 2D^+$) (17%). – ^1H NMR (CD_3OD): δ = 3.21 (t, *J* = 7.4 Hz, 12H), 3.56 (t, *J* = 7.3 Hz, 12H), 4.64 (d, *J* = 0.7 Hz, 4H, $ArCH_2$), 7.46–7.54 (m, 1H, ArH), 7.77–7.91 (m, 2H, ArH). – ^{13}C NMR (CD_3OD): δ = 46.23, 53.49, 62.13, 117.15 (d, J_{CF} = 15.2 Hz, Ar), 127.09 (d, J_{CF} = 4.4 Hz, Ar), 139.75 (d, J_{CF} = 3.3 Hz, Ar), 162.27 (d, $^1J_{CF}$ = 253.8 Hz, Ar). – ^{19}F NMR (CD_3OD): δ = –110.26 (s). – IR (KBr): ν (cm^{-1}) 3410 s (NH).

$(\mathbf{FN_2O_2})_2$ *and* $(\mathbf{FN_2O_2})_3$: A mixture of 1,7-dioxa-4,10-diazacyclodecane (200 mg, 1.15 mmol), 1,3-bis(bromomethyl)-2-fluoroben-

Table 3. Results of the CSD search for CF···HN contacts (four-coordinate nitrogen). **AMMFAC**[31] Ammonium fluoroacetate; **BUSSIR**[32] Bis[(μ$_2$-hydroxo)ethylenediaminebis(2,2,2-trifluoro-1-(trifluoromethyl)ethoxy]aluminium, **BUTFUR**[33] DL-*threo*-beta-fluoroaspartic acid dihydrate; **BUXGOQ**[8] Bis[(–)-methylbenzylamine] monoethyl fluorocitrate; **FACECU10**[34] Bis(1,1,1,5,5,5-hexafluoropentane-2,4-dionato-*O*)bis(*N*,*N*-dimethylethylenediamine)-copper(II); **FPBXZL**[35] *B*,*B*-bis(*p*-fluorophenyl)boroxazolidine; **HAGMOR**[36] 1,4,8,11-Tetra-azoniacyclotetradecane tetrakis(trifluoroacetate); **KIKJAP**[37] Dichloro(6,6,13,13-tetrafluoro-1,4,8,11-tetraazacyclotetradecane-*N*,*N'*,*N''*,*N'''*)nickel(II); **KINWIN**[38] D-*erythro*-4-fluoroglutamic acid; **PINCUK**[39] Ethylene-1,2-diammonium-tetrakis(1,1,1,5,5,5-hexafluoro-2,4-pentanedionato-*O*,*O'*)(1,1,1,5,5,5-hexafluoro-2,4-pentane-dionato-*O*)barium; **VOYWIP**[40] Ammine-(5,7-bis(*p*-fluorophenyl)-2-phenyl-1,8-dioxa-3,4-diazaocta-2,4,6-triene-1,8-diyl-*O*,*O'*,*N*)nickel; **YAMSAG**[41] Tris-(trifluoromethyl) borane–ammine

Entry	Ref. code	F···H [pm]	F···N [pm]	FHN [°]
1	BUTFUR	237	286.0	115
2	BUXGOQ	229	286.7	124
3	KINWIN	234	287.1	124
4	PINCUK	235	294.2	123
5	YAMSAG	248	296.9	112
6	PINCUK	237	300.7	128
7	HAGMOR	235	308.7	123
8	VOYWIP	244	310.3	150
9	FACECU10	238	311.3	132
10	KIKJAP	221	312.6	138
11	AMMFAC	231	313.3	141
12	FPBXZL	236	317.2	155
13	PINCUK	246	318.9	138
14	YAMSAG	229	319.2	155
15	BUSSIR	223	319.7	167

Table 4. Results of the CSD search for CF···HN contacts (three-coordinate nitrogen). **ABDARU**[42] 1,3-Bis(trifluoromethyl)-2,4-diazabutadienylamido-*N,N''*)-(η^5-cyclopentadienyl)trimethylphosphite-ruthenium; **COGHOV**[43] Bis(perfluorophenyl)-[3-phenyl-1,4-bis(*p*-toluidino)-2,3-diazabut-1-en-1-yl-4-ylidene]gold; **CUVJOS**[44] 1-Methylhydrazinium trifluoroacetate; **DOLSEC**[45] 5-Fluoro-arabinosyl-cytosine; **GAMNUC**[46] Catena[μ_2-dimethyl-(4-amino-5-mercapto-3-trifluoromethyl-1,2,4-triazolato-*N,S*)thallium(III)]; **HEBZET**[47] (2*Z*,4*E*,6*E*)-2-Amino-8-ethyl-1,1,1-trifluoro-5-trifluoromethyl-3,4,8-triazadeca-2,4,6-triene; **HEBZOD**[48] (*Z,Z*)-2-amino-5-chloro-1,1,1,6,6,6-hexafluoro-3,4-diazahexa-2,4-diene; **KEYXOB**[49] Cisapride monohydrate; **KUNGIJ**[50] Hexakis(2-fluorophenylamino)disiloxane; **SETMAF**[51] 2-(Trifluoroacetylamino)-5,5-bis(trifluoromethyl)-1,3,4-thiadiazoline; **VICVOS**[52] 1-(Trifluoroacetyl)-2-methylhydrazine-5,10,15,20-tetrakis(heptafluoropropyl)porphyrin; **YILJUY**[53] 2-Amino-3-chloro-6-(trifluoromethyl)quinoxaline; **YESBON**[54] 5,10,15,20-Tetrakis(heptafluoropropyl)porphyrin; **YULCEN**[55] Tris(perfluorophenylthiolato)-tris(*N,N'*-dimethylthiourea-*S*)bismuth(III); **YUVNAE**[56] 1-Amino-2-[(2-tris(pentafluorophenyl)boryl)-3-cyclopropenylium]propene

Entry	Ref. code	F···H [pm]	F···N [pm]	FHN [°]
1	SETMAF	223	285.2	126
2	CUVJOS	248	285.4	102
3	DOLSEC	228	294.0	132
4	KEYXOB	204	296.6	142
5	HEBZOD	240	300.7	131
6	YUVNAE	232	304.6	138
7	VICVOS	246	306.7	116
8	YESBON	241	308.6	122
9	ABDARU	249	310.3	157
10	KUNGIJ	205	310.6	164
11	HEBZET	242	312.5	121
12	GAMNUC	243	315.3	121
13	COGHOV	234	315.5	142
14	YILJUY	225	317.1	160
15	YULCEN	248	317.4	139

zene (324 mg, 1.15 mmol) and Na_2CO_3 (280 mg, 2.3 mmol) in acetonitrile (160 ml) was heated under reflux for 24 h. The mixture was then filtered, washed with acetonitrile (25 ml) and the solvent was evaporated in vacuo. The residue was subjected to column chromatography on silica gel with cyclohexane/diethylamine (5:1) to give $(\mathbf{FN_2O_2})_2$, R_f = 0.30, and $(\mathbf{FN_2O_2})_3$, R_f = 0.36, as colorless solids. Recrystallization from cyclohexane yielded $(\mathbf{FN_2O_2})_2$ as colorless crystals.

$(\mathbf{FN_2O_2})_2$: Yield: 75 mg (0.13 mmol) 22%. – MS [*m/z* (%)]: 589 ($M \cdot H^+$) (58%). – ^{1}H NMR ($CDCl_3$): δ = 2.73 (t, *J* = 4.8 Hz, 16H, NCH_2), 3.55 (t, *J* = 4.8 Hz, 16H, OCH_2), 3.67 (s, 8H, $ArCH_2$), 6.94–7.01 (m, 2H, ArH), 7.10–7.18 (m, 4H, ArH). – ^{13}C NMR ($CDCl_3$): δ = 55.40 (d, J_{CF} = 1.6 Hz, $ArCH_2$), 55.60, 69.16, 122.91 (d, J_{CF} = 4.1 Hz, Ar), 126.25 (d, J_{CF} = 15.8 Hz, Ar), 130.99 (d, J_{CF} = 4.9 Hz, Ar), 160.78 (d, $^1J_{CF}$ = 249.6 Hz, Ar). – ^{19}F NMR ($CDCl_3$): δ –120.03 (s).

$(\mathbf{FN_2O_2})_3$: Yield: 30 mg (34 μmol) 9%. MS [*m/z* (%)]: 883 (M^+) (15%). – ^{1}H NMR ($CDCl_3$): δ = 2.76 (t, *J* = 4.2 Hz, 24H, NCH_2), 3.63–3.68 (m, 36H, $ArCH_2$ + OCH_2), 7.24–7.32 (m, 3H, ArH), 7.83–7.90 (m, 6H, ArH). – ^{13}C NMR ($CDCl_3$): δ = 52.53 (d, J_{CF} = 2.0 Hz, $ArCH_2$), 55.50, 70.05, 123.99 (d, J_{CF} = 4.2 Hz, Ar), 126.61 (d, J_{CF} = 4.2 Hz, Ar), 128.53 (d, J_{CF} = 4.7 Hz, Ar), 159.27 (d, $^1J_{CF}$ = 244 Hz, Ar). – ^{19}F NMR ($CDCl_3$): δ = –127.00 (s).

Protonation of $\mathbf{FN_2O_3}$, $\mathbf{FN_2O_4}$, $\mathbf{HN_2O_3}$ *and* $\mathbf{HN_2O_4}$: The protonated fluoro cryptands $\mathbf{FN_2O_3} \cdot H^+$, $\mathbf{FN_2O_3} \cdot 2H^+$ and $\mathbf{HN_2O_3} \cdot H^+$, $\mathbf{HN_2O_3} \cdot 2H^+$ and $\mathbf{BenzoFN_2O_3} \cdot H^+$, $\mathbf{BenzoFN_2O_3} \cdot 2H^+$ were prepared by titrating a small amount (20–30 mg) of the respective cryptands dissolved in CD_3CN in an NMR tube with trifluoromethanesulfonic acid until the appropriate ^{19}F- or ^{1}H-NMR signal (in the fluorine-free cryptands the signal of the corresponding proton was used) indicated complete mono- or diprotonation. For subsequent experiments, the solvent was removed from the respective protonated cryptand and the remaining solid or oily material was used. Single crystals of the protonated fluoro cryptands were prepared by slowly allowing diethyl ether to diffuse into solutions of the ammonium salts in acetonitrile.

$\mathbf{FN_2O_3} \cdot H^+$: ^{1}H NMR ($CD_3CN$): δ = 2.25–2.40 (m, 2H), 2.56–2.70 (m, 1H), 2.87–2.93 (dt, *J* = 8.7 Hz, 2.2 Hz, 1H), 3.0–3.4 (m, 6H), 3.48–3.89 (m, 11H), 4.01–4.24 (m, 2H), 4.77 (d, *J* = 13.2 Hz, 1H, $ArCH_2$), 7.13 (t, *J* = 7.7 Hz, 1H, ArH), 7.29–7.37 (m, 2H, ArH). – ^{13}C NMR (CD_3CN): δ = 53.98, 55.49, 58.06, 58.20, 58.66, 60.26, 63.88, 64.75, 69.72, 70.35, 70.71, 71.21, 124.86 (d, J_{CF} = 4 Hz), 131.38 (d, J_{CF} = 3.5 Hz), 133.98 (d, J_{CF} = 6.5 Hz), 161.90 (d, J_{CF} = 250 Hz).

$\mathbf{FN_2O_3} \cdot 2H^+$: ^{1}H NMR ($CD_3CN$): δ = 3.10–3.21 (m, 4H), 3.39–3.55 (m, 4H), 3.62–3.93 (m, 12H), 4.42–4.54 (m, 2H), 4.85 (d, *J* = 13.6 Hz, 2H), 7.44 (t, *J* = 7.7 Hz, 1H, ArH), 7.64–7.72 (m, 2H, ArH). – ^{13}C NMR (CD_3CN): δ = 56.92, 57.54, 59.66, 63.86, 65.38, 71.04, 120.68 (d, J_{CF} = 12 Hz), 127.86 (d, J_{CF} = 4 Hz), 135.57 (d, *J* = 4 Hz), 161.60 (d, J_{CF} = 243.5 Hz). – ^{15}N NMR (CD_3CN): δ = –335.0 (d, *J* = 2.8 Hz).

$\mathbf{HN_2O_3} \cdot H^+$: ^{1}H NMR ($CD_3CN$): δ = 2.37–3.19 (m, 6H), 3.18 (m_c, 4H), 3.38–3.90 (m, 9H), 3.95–4.08 (m, 4H), 4.77 (d, *J* = 13.6 Hz, 1H), 7.20–7.31 (m, 4H, ArH, NH^+), 8.28 (s, 1H, 2-ArH). – ^{13}C NMR (CD_3CN): δ = 55.80, 56.39, 56.63, 57.56, 58.88, 59.68, 69.61, 69.82, 70.10, 128.19, 128.46, 129.31, 130.74.

$\mathbf{HN_2O_3} \cdot 2H^+$: ^{1}H NMR ($CD_3CN$): δ = 2.90 (dt, *J* = 11.4 Hz, 3.8 Hz, 2H), 3.10 (m_c, 2H), 3.34–3.95 (m, 14H), 4.08 (m_c, 2H), 4.32 (m_c, 2H), 4.78 (d, *J* = 13.3 Hz, 2H), 6.65 (br, 2H, NH^+), 7.42 (s, 1H, ArH), 7.59 (s, 3H, ArH). – ^{13}C NMR (CD_3CN): δ = 55.50, 57.11, 59.65, 63.41, 64.61, 71.02, 129.04, 131.94, 132.79, 134.17.

$\mathbf{FN_2O_4} \cdot H^+$: ^{1}H NMR ($CD_3CN$): δ = 3.04 (br m, 8H), 3.45 (br m, 8H), 3.73 (br m, 8H), 3.96 (br m, 4H), 5.05 (br, 2H, NH^+), 7.19 (m_c, 1H, ArH), 7.40 (m_c, 2H, ArH).

Table 5. Crystallographic data for $\mathbf{FN_2O_3} \cdot H^+$, $\mathbf{FN_2O_3} \cdot 2H^+$ and *o*-Fluorobenzylammonium bromide

Compound	$\mathbf{FN_2O_3}$*$HClO_4$	$\mathbf{FN_2O_3}$*$2HCF_3SO_3$	$\mathbf{C_7H_9BrFN}$
Empirical formula	$C_{18}H_{28}ClFN_2O_7$	$C_{20}H_{29}F_7N_2O_9S_2$	C_7H_9BrFN
Molecular mass [gmol^{-1}]	438.87	638.57	206.06
Temperature [K]	293(2)	293(2)	150(2)
Crystal system	monoclinic	monoclinic	monoclinic
Space group	$P2_1/n$	$P2_1/n$	$P2_1/c$
Unit cell dimensions [pm or °]			
a	8.665(2)	12.238(2)	9.201(2)
b	11.009(2)	19.784(4)	9.614(2)
c	21.741(2)	12.592(3)	9.188(2)
α	90	90	90
β	92.99(3)	113.82(3)	105.45(3)
γ	90	90	90
Volume [Å]	2071.1(7)	2789.0(10)	783.4(3)
Z	4	4	4
Density [gcm^{-3}]	1.407	1.521	1.747
Absorption [mm^{-1}]	0.236	0.287	5.186
F(000)	928	1320	408
Crystal size [mm]	0.3 x 0.3 x 0.2	0.6 x 0.5 x 0.4	0.7 x 0.5 x 0.4
Theta range [°]	2.9-26.0	2.5-24.9	3.5-27.5
Index range (*hkl*)	-10/10, 0/13, -26/0	-14/13, -23/0, 0/14	-11/7, 0/12, -6/11
Reflections collected/independent	4177/4070	5087/ 4856	1793/1793
Data/parameters	3438/294	3406/373	1752/118
GooF	1.065	1.15	1.116
Final *R* indices [$I>2\sigma(I)$] *R*1, *wR*2	0.0445, 0.1074	0.0958, 0.2826	0.0277, 0.0655
Largest peak and hole [eÅ^{-3}]	+0.15, -0.42	+0.46, -0.39	+0.93, -0.49

$FN_2O_4 \cdot 2H^+$: ^1H NMR (CD_3CN): δ = 3.44–3.70 (m, 20H), 3.78–3.89 (m, 4H), 4.55 (dd, J = 5.0 Hz, 1.9 Hz, 4H), 6.5 (br s, 2H, NH), 7.44 (t, J = 7.8 Hz, 1H, ArH), 7.75 ("t", J = 7.6 Hz, 2H, ArH). – ^{13}C NMR (CD_3CN): δ = 54.36 (d, J_{CF} = 3 Hz, $ArCH_2$), 56.40, 63.32, 70.74, 120.02 (d, J_{CF} = 13 Hz), 127.26 (d, J_{CF} = 4.5 Hz), 136.07 (d, J_{CF} = 3.0 Hz), 160.85 (d, J_{CF} = 247 Hz).

$HN_2O_4 \cdot 2H^+$: ^1H NMR (CD_3CN): δ = 3.39–3.90 (m, 24H), 4.44 (d, J = 5.0 Hz, 4H), 6.45 (br s, 2H, NH), 7.46 (s, 1H, ArH), 7.60 (s, 3H, ArH). – ^{13}C NMR (CD_3CN): δ = 55.18, 58.37, 63.43, 71.06, 129.98, 131.44, 132.99, 133.87.

X-ray Crystal Structure Determinations (Table 5): Suitable crystals were mounted on top of a glass fibre. X-ray data were collected on an Enraf-Nonius CAD4 diffractometer using Mo-K_α radiation (71.069 pm) and a graphite monochromator. All structures were solved (SHELXS-86)[28] and refined (SHELXL-93)[29] against F^2. In the structures described, all non-hydrogen atoms were refined using anisotropic temperature coefficients. Hydrogen atoms were refined with fixed isotropic temperature coefficients (riding model), only the ammonium hydrogen atoms were localized and the positional parameters refined. An empirical absorption correction (psi-scans) was applied in all cases[30].

[1] G. A. Jeffrey, W. Saenger, *Hydrogen Bonding in Biological Structures*, Springer Verlag, Berlin **1991**.

[2] [2a] F. Vögtle, *Supramolekulare Chemie*, Teubner Verlag, Stuttgart **1993**. [2b] J.-M. Lehn, *Supramolecular Chemistry*, VCH, Weinheim **1995**. [2c] J. L. Atwood, J. E. D. Davies, D. D. Macnicol, F. Vögtle (Eds.) *Comprehensive Supramolecular Chemistry*, Pergamon Press, London **1996**.

[3] [3a] C. J. Pedersen, *Angew. Chem.* **1988**, *100*, 1053–1059; *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 1021. [3b] J.-M. Lehn, *Angew. Chem.* **1988**, *100*, 92–116; *Angew. Chem. Int. Ed. Engl.* **1988**, *27*, 89.

[4] G. Wilkinson, R. D. Gillard, J. A. McCleverty (Eds.), *Comprehensive Coordination Chemistry*, Pergamon Press, London **1987**.

[5] [5a] H. Plenio, R. Diodone, *Angew. Chem.* **1994**, *106*, 2267–2269; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 2175–2177. [5b] H. Plenio, R. Diodone, *J. Am. Chem. Soc.* **1996**, *118*, 356–367.

[6] [6a] H. Plenio, *Inorg. Chem.* **1994**, *33*, 6123–6127. [6b] H. Plenio, D. Burth, *J. Chem. Soc., Chem. Comm.* **1994**, 2297–2298. [6c] H. Plenio, R. Diodone, *Chem. Ber.* **1996**, *129*, 1211–1217.

[7] H. Plenio, R. Diodone, D. Badura, *Angew. Chem.*, **1997**, *109*, 130–132; *Angew. Chem. Int. Ed. Engl.* **1997**, *36*, 156–158.

[8] P. Murray-Rust, W. C. Stalling, C. T. Monti, R. K. Preston, J. P. Glusker, *J. Am. Chem. Soc.* **1983**, *105*, 3206–3214.

[9] H. Plenio, R. Diodone, submitted.

[10] B. Dietrich, P. Viout, J.-M. Lehn, *Macrocyclic Chemistry*, p. 301, VCH, Weinheim **1993**.

[11] [11a] P. B. Smith, J. L. Dye, J. Cheney, J.-M. Lehn, *J. Am. Chem. Soc.* **1981**, *103*, 6044–6048.

[12] [12a] R. W. Alder, S. P. East, *Chem. Rev.* **1996**, *96*, 2097–2111. [12b] R. W. Alder, R. B. Sessions, A. J. Bennet, R. E. Moss, *J. Chem. Soc., Perkin Trans. I* **1982**, 603–609.

[13] [13a] J. Springborg, U. Preetzmann, C. E. Olsen, *Acta Chem. Scand.* **1996**, *50*, 294–298. [13b] J. Springborg, P. Kofod, C. E. Olsen, H. Toftlund, I. Sotofte, *Acta Chem. Scand.* **1995**, *49*, 547–554. [13d] J. Springborg, C. E. Olsen, I. Sotofte, *Acta Chem. Scand.* **1995**, *49*, 555–563.

[14] [14a] B. G. Cox, D. Knop, H. Schneider, *J. Am. Chem. Soc.* **1978**, *100*, 6002–6007. [14b] R. Pizer, *J. Am. Chem. Soc.* **1978**, *100*, 4239–4241. [14c] J. Cheney, J. P. Kintzinger, J. M. Lehn, *Nouv. J. Chemie* **1978**, *2*, 411–418. [14d] B. G. Cox, N. van Troung, H. Schneider, *J. Chem. Soc., Perkin Trans. II* **1983**, 515–521.

[15] A. C. deDios, E. Oldfield, *Chem. Phys. Lett.* **1993**, *205*, 108–116.

[16] The coupling is not absent, it is not observed due to the unfavorable magnetogyric ratio of deuterium and the fairly broad line width of the ^{19}F-NMR signal.

[17] WIN-DAISY, Version 1.12.1995, Bruker-Franzen Analytik GmbH.

[18] By far the largest error of this experiment is introduced by problems in determining the exact values of the ^1H- and ^{19}F-NMR integrals.

[19] The rapid evaporation of the solvent from solutions of the protonated cryptands often yielded oily materials.

[20] H.-J. Brügge, D. Carboo, K. von Deuten, A. Knöchel, J. Kopf, W. Dreissig, *J. Am. Chem. Soc.* **1986**, *108*, 107–112.

[21] [21a] L. R. MacGillivray, J. L. Atwood, *J. Org. Chem.* **1995**, *60*, 4972–4973. [21b] B. G. Cox, J. Murray-Rust, P. Murray-Rust, N. van Truong, H. Schneider, *J. Chem. Soc., Chem. Comm.* **1978**, 377–379. [21c] H. Plenio, R. Diodone, *Inorg. Chem.* **1995**, *35*, 3964–3972. [21d] H. Plenio, H. El-Desoky, J. Heinze, *Chem. Ber.* **1993**, *126*, 2403–2408.

[22] C. B. Aakeröy, K. R. Seddon, *Chem. Soc. Rev.* **1993**, 397–407.

[23] Our restraints were the same as those used by Glusker, Murray-Rust *et al.* in their 1983 study (see ref. 8).

[24] A. Bondi, *J. Phys. Chem.* **1964**, *68*, 441–451.

[25] H. Plenio, R. Diodone, *Z. Naturforsch.* **1995**, *50b*, 1075–1078.

[26] M. S. Nasir, B. J. Cohen, K. D. Karlin, *J. Am. Chem. Soc.* **1992**, *114*, 2482–2491.

[27] [27a] S. Kulstad, L. A. Malmsten, *Acta Chem. Scand., Ser. B* **1979**, *33*, 469–474. [27b] S. Kulstad, L. A. Malmsten, *Tetrahedron Lett.* **1980**, *21*, 643–646.

[28] G. M. Sheldrick, *SHELXS-86, A Program for the Solution of X-Ray Crystal Structures*, Universität Göttingen **1986**.

[29] G. M. Sheldrick, *SHELXL-93, A Program for the Refinement of X-Ray Crystal Structures*, Universität Göttingen **1993**.

[30] Further details of the crystal structure investigations are available on request from the Fachinformationszentrum Karlsruhe, D-76344 Eggenstein-Leopoldshafen (Germany), on quoting the depository numbers **$FN_2O_3 \cdot H^+$** CSD-406071, **$FN_2O_3 \cdot 2H^+$** CSD-406070, *o*-fluorobenzylammonium bromide CSD-406069, the names of the authors and the journal citation.

[31] K.-T. Wie, D. L. Ward, *Acta Crystallogr. B* **1976**, *32*, 2768–2773.

[32] J.-P. Laussac, R. Enjalbert, J. Galy, J.-P. Laurent, *J. Coord. Chem.* **1983**, *12*, 133.

[33] A. M. Stern, B. M. Foxmann, A. H. Tashjian, R. H. Abeles, *J. Med. Chem.* **1982**, *25*, 544–548.

[34] M. A. Bush, D. E. Fenton, *J. Chem. Soc. A* **1971**, 2446–2450.

[35] S. J. Rettig, J. Trotter, *Acta Crystallogr. B* **1974**, *30*, 2139–2145.

[36] S. Subramanian, M. J. Zaworotko, *Can. J. Chem.* **1993**, *71*, 433–440.

[37] M. Shionoya, E. Kimura, Y. Iitaka, *J. Am. Chem. Soc.* **1990**, *112*, 9237–9245.

[38] M. Hudlicky, J. S. Merola, *Tetrahedron Lett.* **1990**, *31*, 7403–7406.

[39] L. Huang, S. B. Turnipseed, R. C. Haltiwanger, R. M. Barkley, R. E. Sievers, *Inorg. Chem.* **1994**, *33*, 798–803.

[40] K. C. Joshi, R. Bohra, B. S. Joshi, *Inorg. Chem.* **1992**, *31*, 598–603.

[41] A. Ansorge, D. J. Brauer, H. Burger, B. Krumm, G. Pawelke, *J. Organomet. Chem.* **1993**, *446*, 25–35.

[42] V. Robinson, G. E. Taylor, P. Woodward, M. I. Bruce, R. C. Wallis, *J. Chem. Soc., Dalton Trans.* **1981**, 1169–1173.

[43] R. Uson, A. Laguna, M. D. Villacampa, P. G. Jones, G. M. Sheldrick, *J. Chem. Soc., Dalton Trans.* **1984**, 2035–2038.

[44] V. E. Shklover, Yu. T. Struchkov, *Acta Cryst. C* **1985**, *41*, 734–736.

[45] G. Ferguson, S. N. Scrimgeour, J. N. Low, P. Tollin, *Acta Cryst. C* **1986**, *42*, 591–593.

[46] Y. P. Mascarenhas, I. Vencato, M. C. Carrascal, J. M. Varela, J. S. Casas, J. Sordo, *J. Organomet. Chem.* **1988**, *344*, 137–144.

[47] M. Abdul-Ghani, R. G. Pritchard, A. E. Tipping, *Acta Cryst. C* **1994**, *50*, 719–721.

[48] M. Abdul-Ghani, R. G. Pritchard, A. E. Tipping, *Acta Cryst. C* **1994**, *50*, 722–724.

[49] S. Collin, D. P. Vercauteren, G. Evrard, F. Durant, J. P. Tollenaere, H. Moereels, *J. Mol. Struct.* **1989**, *214*, 159–175.

[50] M. Jansen, I. Mokros, *Acta Cryst. C* **1993**, *49*, 119–120.

[51] G. Rabe, J. Sundermeyer, H. W. Roesky, H. G. Schmidt, M. Noltemeyer, *Chem. Ber.* **1990**, *123*, 691–696.

[52] V. E. Shklover, Y. L. Frolov, Y. T. Struchkov, *Izv. Akad. Nauk SSSR, Ser. Khim.* **1990**, 61–66.

[53] S. Iwata, M. Sakajyo, K. Tanaka, *J. Heterocycl. Chem.* **1994**, *31*, 1433–1438.

[54] S. G. DiMagno, R. A. Williams, M. J. Therien, *J. Org. Chem.* **1994**, *59*, 6943–6948.

[55] L. J. Farrugia, F. J. Lawlor, N. C. Norman, *J. Chem. Soc., Dalton Trans.* **1995**, 1163–1171.

[56] G. Erker, W. Ahlers, R. Frohlich, *J. Am. Chem. Soc.* **1995**, *117*, 5853–5854.

[96262]