

$^2\Delta\text{H}(\text{D})$ and $^1\Delta\text{N}(\text{D})$ Isotope Effects on Nuclear Shielding of Ammonium Ions in Complexes with Crown Ethers and Cryptands

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One-bond deuterium isotope effects on nitrogen nuclear shielding, $^1\Delta\text{N}(\text{D})$ and two-bond isotope effects at ^1H nuclear shielding, $^2\Delta\text{H}(\text{D})$, have been investigated in a series of inclusion complexes. The hosts comprise, SC-24, [2.2.2], [2.2.1], [2.2.1]D, [2.2] DD, K5, 18-crown-6 and 18-crown-6 tetracarboxylic acid. The structure of the host [2.2.1] is discussed based on isotope effects and ^1H chemical shifts, and an interesting exchange reaction is observed between CDCl_3 and ammonium ions in the [2.2.1] complex. The counterion dependence is shown to be zero for ammonium ions fully included in cages such as SC-24 and [2.2.2] and for 18-C-6(COOH)₄. For cryptands and podands such as [2.2.1] and K5 a weak counterion dependence of $^2\Delta\text{H}(\text{D})$ opposite to that found for ammonium ions in water is observed, while $^1\Delta\text{N}(\text{D})$ and ^{15}N chemical shifts depend very strongly on the counterions, as also found for ammonium ions in water solution. The anilinium ion shows effects similar to those observed for the ammonium ion.

$^1\Delta\text{N}(\text{D})$ isotope effects correlate well with δN , and $^2\Delta\text{H}(\text{D})$ correlate with δNH . The correlation between $^1\Delta\text{N}(\text{D})$ and $^2\Delta\text{H}(\text{D})$ is different for ammonium ions in water and ions included in crowns, cryptands or podands. This shows that different mechanisms are operating. The $^2\Delta\text{H}(\text{D})$ isotope effects and δNH chemical shifts depend on the distance to the nearest acceptor (oxygen or nitrogen), and they also depend on the type of acceptor. $^2\Delta\text{H}(\text{D})$ isotope effects are found to be a good gauge of $\text{N}\cdots\text{N}$ or $\text{N}\cdots\text{O}$ distances of the inclusion complexes. The $^2\Delta\text{H}(\text{D})$ isotope effects vary with temperature, but the dramatic changes in the ^1H NMR spectra of the host are not reflected in the isotope effects. The one-bond couplings, $^1J(\text{N}, \text{H})$, correlate with $^2\Delta\text{H}(\text{D})$. The variations are much larger for the cryptands than found in water solutions.

$^1\Delta\text{N}(\text{D})$ and $^2\Delta\text{H}(\text{D})$ are calculated in $\text{NH}_3\text{D}\cdots\text{NH}_3$ complexes using the *ab initio*/LORG method. $^1\Delta\text{N}(\text{D})$ increases with an increase in the distance $R_{\text{N}\cdots\text{N}}$, and $^2\Delta\text{H}(\text{D})$ changes from negative to positive values for longer $R_{\text{N}\cdots\text{N}}$ values. Both isotope effects depend on R as $1/r^2$, where r is the distance from the nitrogen of ammonia to the midpoint of the N–D bond.

The finding that ammonium ions rotate fast in water,^{1–3} despite rather strong hydrogen bonds to water, has aroused much theoretical interest.^{4–6} Several models for solvent structures have been suggested, including a model with five water molecules in the first coordination sphere.³

Ammonium ions included in crown ethers and cryptands show fast rotation for most hosts, but slow rotation for the complexation optimised host, SC-24.⁷ The majority of the cryptands except SC-24 have a rather loose structure and show dramatic conformational

changes with temperature.^{7,8} The inclusion of ammonium ions and other cations and the related topics of molecular recognition have attracted much interest,^{9–18} and inclusion complexes with alkylammonium ions have also been studied.^{19–21} Deuterium isotope effects on ^1H and ^{15}N nuclear shielding have been investigated in great detail^{22–26} and have also been subject to theoretical calculations.^{27,28}

The small magnitude of $^1\Delta\text{N}(\text{D})$ of ammonium ions compared to ammonia is partly due to hydrogen bonding.^{25,26} The two-bond isotope effects on ^1H chemical shifts, $^2\Delta\text{H}(\text{D})$, are found to be negative.²⁹ Experiments showed $^2\Delta\text{H}(\text{D})$ to be most negative at infinite dilution.²⁶

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The theoretical calculations suggest that ${}^2\Delta H(D)$ should become more negative with decreasing N...O distance. They also suggest that a positive isotope effect is expected if the ammonium ion is bare.^{27,28} In addition, non-directional hydrogen bonds do not lead to negative two-bond isotope effects. The negative value of ${}^2\Delta H(D)$ of the ammonium ion can be ascribed to electric field effects from the water molecules. The effects of a water molecule and that of a unit negative charge are in several aspects similar.²⁷

The angular and distance dependence, as well as the dependence on the nature of the hydrogen bond acceptor, needs further experimental investigation.

In order to shed more light on these questions we have investigated deuterium isotope effects of partially

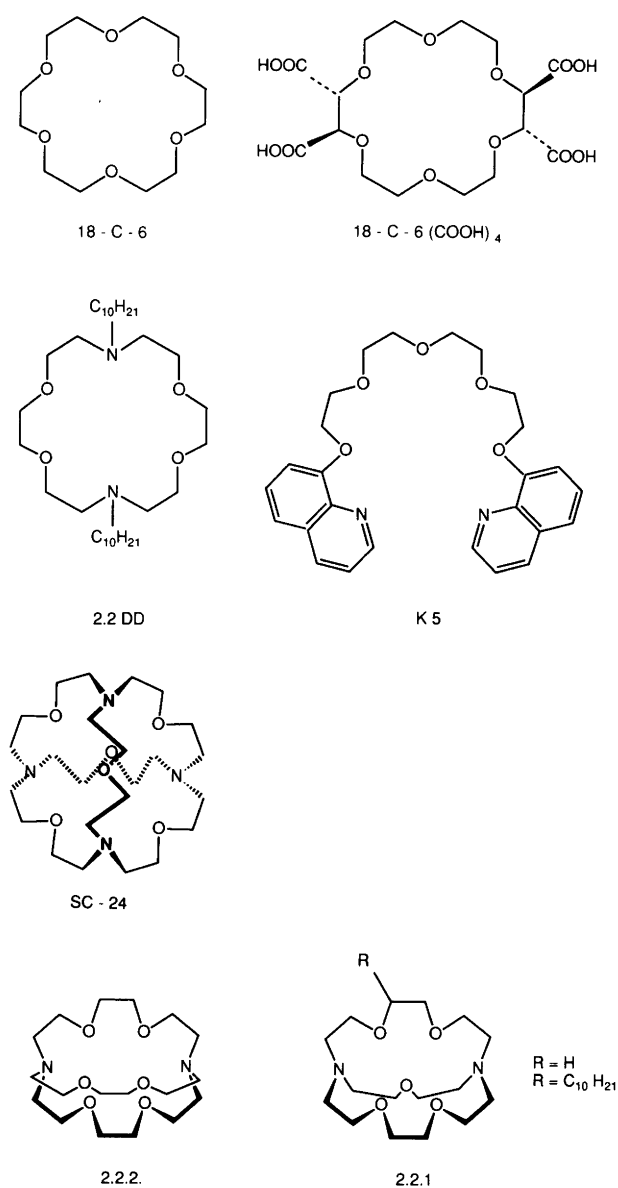


Fig. 1. List of investigated crown ethers, cryptands and podands together with abbreviations and signs used in graphs. For [2.2.1]D, R = C₁₀H₂₁.

deuteriated ammonium ions complexed with several crown ethers (18-C-6 and 18-C-6(COOH)₄, cryptands (SC-24, [2.2.2], [2.2.1], [2.2.1]D and [2.2] DD) and the podand (K5) at different temperatures and for different ammonium salts (Fig. 1). The studies also comprise ¹H NMR spectra of complexes between ammonium ions and cryptands such as K5, [2.2] DD and [2.2.1]D not previously published. In addition, the complex between the anilinium ion and 18-C-6 has been studied.

Results

The experiments in water have mostly been made with ¹⁴NH₄⁺ ions.^{25,26} This is possible because of the high symmetry of the solvent sphere. However, with the crown ethers and cryptands it is essential to use ¹⁵NH₄⁺ ions, as the ¹⁴N ion would give broad lines due to quadrupole effects³⁰ caused by the lower symmetry of these inclusion sites.

The experiments have been carried out in either CDCl₃ or CD₂Cl₂. The latter is preferable for work at low temperatures, but also because it is more inert (see later). The appearance of the spectra is as shown in Fig. 2. The splitting due to the ¹J(N, H) coupling is almost invariable (72–74.3 Hz). The ¹H spectra show geminal HD couplings of ~1.55 Hz. These couplings gradually disappear as the temperature is lowered owing to quadrupole decoupling.³⁰ The temperature dependence of this disappearance varies slightly from complex to complex as seen from Fig. 2. For the [2.2.1] complex the point of disappearance is at a slightly lower temperature (~230 vs.

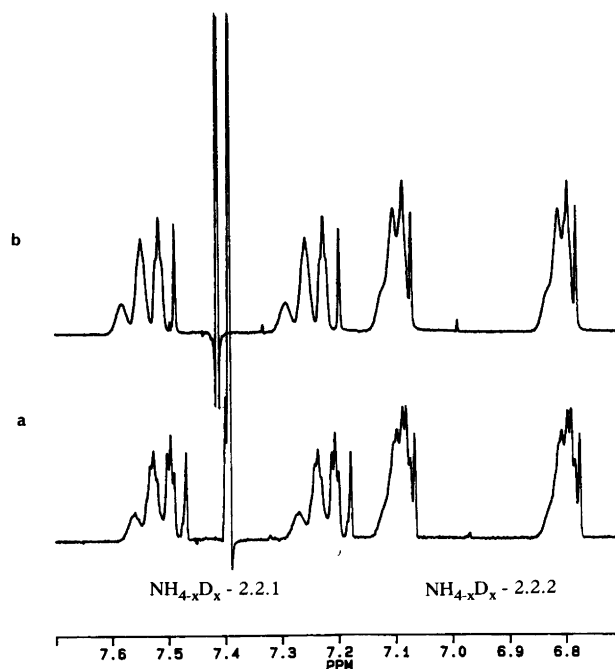


Fig. 2. ¹H NMR spectra of the ammonium ion in a solution containing 0.095 mmol ¹⁵NH₄NO₃ (partially deuteriated), 0.098 mmol [2.2.1] and 0.049 mmol [2.2.2] in 0.5 ml CDCl₃ (a) at 270 K and (b) 240 K.

~ 237 K for CD_2Cl_2 vs. CDCl_3). A similar trend is seen for 18-C-6.

Exchange must be slow in order to measure small deuterium isotope effects. Exchange is suppressed in water solution by acidification.²⁶ Lowering of the temperature was necessary in order to observe isotope effects in the following cases: for the complexes of K5 and [2.2.1] dissolved in CDCl_3 the temperature had to be lowered to 270 K, and for [2.2] DD a lowering of the temperature to 250 K was necessary. For the [2.2] DD ammonium iodide complex no well resolved ^1H spectra could be observed. The anilinium nitrate complex with 18-C-6 had to be cooled to 210 K to obtain well resolved ^1H spectra. The anilinium ion forms a somewhat weaker complex,³¹ as it is a much stronger acid. Resonances from both the free cryptand itself and the complex are seen simultaneously for SC-24 and [2.2.2]. This is not the case for the other cryptands.

The [2.2.1]D complex shows the interesting feature that two sets of $\text{NH}_x\text{D}_{4-x}$ resonances are observed in the ratio of $\sim 2 : 1$. For the ^{15}N resonance the minor species cannot be observed with certainty. Two sets of proton resonances are not observed for [2.2.1], and this can be ascribed to the long chain, which probably can only be in an equatorial position. This favours the complex with hydrogen bonds to oxygen at the end of the molecule opposite to the R substituent.

$^2\Delta\text{H}(\text{D})$. The two-bond isotope effects for the isotopomers are given in Table 1. They are not fully additive. They become larger for the heavier isotopomers, as found in water solutions.^{23,26} For the complexes with SC-24, [2.2.2] and 18-C-6(COOH)₄ no counterion dependence is observed. For 18-C-6 a decrease is seen on going from ammonium nitrate to ammonium iodide, as also found in water solution. Addition of tetrabutylammonium iodide (TBAI) as an iodide source leads to a decrease that is roughly proportional to the concentration of TBAI. For [2.2.1] and K5 a numerical increase is seen. An increase is also found on addition of TBAI to the [2.2.1]- NH_4NO_3 complex.

The temperature dependence of the $^2\Delta\text{H}(\text{D})$ isotope effects has also been studied. For [2.2.1] and [2.2] DD a small numerical increase is observed upon lowering the temperature (Table 1). For SC-24 a small decrease is found. The remaining complexes show no definite temperature dependences. The values for $^2\Delta\text{H}(\text{D})_1$ are seen to vary considerably compared to the value at infinite dilution in water, -0.019 ppm/ D_1 . The value for the [2.2.1]- NH_4I complex is -0.026 ppm/ D_1 at 270 K and -0.036 ppm/ D_1 for K5, but only -0.010 ppm for the 18-C-6(COOH)₄ complex (Table 1). For ease of comparison $^2\Delta\text{H}(\text{D})_1 = \delta\text{NH}_4^+ - \delta\text{NH}_3^+\text{D}$ is given, as this is known for all complexes. $^2\Delta\text{H}(\text{D})$ isotope effects are slightly different in chloroform and in methylene chloride. The more negative value is found in the latter solvent (Table 1). The deuteriated anilinium ion complexed with 18-C-6 gave a $^2\Delta\text{H}(\text{D})_1$ value of -0.0185 ppm at 210 K.

$\delta\text{N}^1\text{H}$. The proton chemical shift of the NH group varies from 6.77 ppm for SC-24 to 8.23 ppm for K5 (270 K; CD_2Cl_2). The chemical shifts show some temperature variation, which can be divided roughly into three categories: for [2.2.2], [2.2] DD and 18-C-6 a high-field shift of $\sim 9 \times 10^{-4}$ ppm/ $^\circ$ is observed, a similar low-field shift is observed for [2.2.1], and a low-field shift of 1.66×10^{-3} ppm/ $^\circ$ is measured for K5.

$^1\Delta\text{N}(\text{D})$. The ^{15}N spectra were recorded using the INEPT³² technique optimized for $^1\text{J}(\text{N}, \text{H})$. The ND_4^+ species was thus not observed. In the text $^1\Delta\text{N}(\text{D})_1$ isotope effects are discussed, and $^1\Delta\text{N}(\text{D})_2$ and $^1\Delta\text{N}(\text{D})_3$ are given in Table 2. $^1\Delta\text{N}(\text{D})_{\text{tot}}$ can easily be estimated, as the $^1\Delta\text{N}(\text{D})_i$ are shown to vary in a regular manner.²⁶ The one-bond isotope effect at nitrogen is independent of counterions in the SC-24, [2.2.2] and 18-C-6(COOH)₄ complexes, whereas 18-C-6, [2.2.1] and K5 show a counterion dependence similar to that observed in water.²⁶

$\delta^{15}\text{N}$. ^{15}N chemical shifts are given in Table 2. They are seen to be independent of counterion for SC-24, [2.2.2] and 18-C-6(COOH)₄. A similar trend was also observed for $^1\Delta\text{N}(\text{D})$. 18-C-6, [2.2.1] and K5 show a six to eight ppm difference between the nitrate and the iodide with the latter to lowest field.

$^1\text{J}(^{15}\text{N}, ^1\text{H})$. The one-bond couplings, $^1\text{J}(^{15}\text{N}, ^1\text{H}_4)$, are seen to vary from 74.25 Hz for the 18-C-6(COOH)₄ complex to 72 Hz for the K5 complex in the following order: 18-C-6(COOH)₄ > SC-24 > 18-C-6 > [2.2.2] > [2.2.1] > K5 (Tables 1 and 2). The one-bond couplings of the complexes are rather insensitive to counterions and vary only moderately with temperature. Slight variation are found in $^1\text{J}(\text{N}, \text{H})$, depending on the number of deuteriums. The values shown in the tables are $^1\text{J}(^{15}\text{N}, ^1\text{H}_4)$ values.

Correlations. $^1\Delta\text{N}(\text{D})$ and ^{15}N chemical shifts are seen to correlate well for the crown ethers, the cryptands and the podands (Fig. 3). A similar correlation was found for ammonium salts in water solution.²⁷ $^2\Delta\text{H}(\text{D})$ and δNH likewise correlate. Counterion dependence causes a certain scatter in the latter correlation (Fig. 4). A plot of $^1\text{J}(\text{N}, \text{H})$ vs. $^2\Delta\text{H}(\text{D})_1$ shows a good correlation for SC-24, [2.2.2], [2.2.1] and K5. The values for ammonium ions in water fall outside this line, as also do data for the 18-C-6(COOH)₄ complex and to a certain extent data for 18-C-6. The data for the ions in water, now including the CF_3COO^- ion, roughly fall on separate lines corresponding to each particular anion. Some scatter is observed, probably owing to the different amounts of acid added. The variation in $^1\text{J}(\text{N}, \text{H})$ is greatest for the oxygen-containing ions NO_3^- , ClO_4^- and CF_3COO^- (Fig. 5).

A plot of $^1\Delta\text{N}(\text{D})$ vs. $^2\Delta\text{H}(\text{D})$ for the ammonium ions in water shows a good correlation (Fig. 6). A correlation

Table 1. NH chemical shifts^a and two-bond isotope effects, ²ΔH(D).^a

Host	¹⁵ NH ₄ X	Addition	Solvent	Temperature/K	δH (ppm)	² ΔH(D) ₁ ^e	² ΔH(D) ₂	² ΔH(D) ₃	¹ J(N, H) /Hz	² J(H, D) ^g /Hz
18-C-6 (0.1)	NO ₃ (0.1)	—	CDCl ₃	282	7.02 ^b	-17.5	-19.2	— ^c	73.3	1.61
18-C-6 (0.1)	NO ₃ (0.1)	—	CDCl ₃	228	7.03(5) ^b	-16.0	-17.7	-20.3(5)	73.3	— ^d
18-C-6 (0.1)	NO ₃ (0.1)	—	CD ₂ Cl ₂	300	7.01 ^b	-18.7	— ^c	— ^c	73.3	— ^d
18-C-6 (0.1)	NO ₃ (0.1)	—	CD ₂ Cl ₂	283	—	-19.2	-21.0	— ^c	73.2	1.56
18-C-6 (0.1)	NO ₃ (0.1)	—	CD ₂ Cl ₂	263	—	-18.9	-20.3	— ^c	73.1	1.56
18-C-6 (0.1)	NO ₃ (0.1)	—	CD ₂ Cl ₂	228	—	-19.0	-21.2	-23.1(5)	73.1	— ^d
18-C-6 (0.196)	NO ₃ (0.099)	—	CDCl ₃	300	7.00	-18.6	-20.1	-22.3	73.3	1.61
18-C-6 (0.196)	NO ₃ (0.099)	TBAI (0.044)	CDCl ₃	300	6.97	-16.5	-18.1	-20.3	73.4	1.62
18-C-6 (0.196)	NO ₃ (0.099)	TBAI (0.087)	CDCl ₃	300	6.96	-15.8	-17.2	-19.0	73.4	1.66
18-C-6 (0.196)	NO ₃ (0.099)	TBAI (0.168)	CDCl ₃	300	6.94	-15.0	-16.4	— ^c	73.4	1.66
18-C-6 (0.196)	NO ₃ (0.099)	TBAI (0.222)	CDCl ₃	300	6.94	-14.8	-15.5	— ^c	73.5	1.63
18-C-6 (0.101)	I ⁻ (0.104)	—	CDCl ₃	282	6.96	-12.1	— ^c	— ^c	73.3	1.45
SC-24 (0.01)	NO ₃ (0.01)	—	CDCl ₃	300	6.77	-14.3	-15.8	— ^c	73.0	— ^d
SC-24 (0.01)	NO ₃ (0.01)	—	CDCl ₃	282	6.69	-12.9	-15.2	-16.7	73.2	— ^d
SC-24 (0.01)	NO ₃ (0.01)	—	CDCl ₃	270	6.77	-13.4	— ^c	— ^c	73.0	— ^d
SC-24 (0.01)	NO ₃ (0.01)	—	CDCl ₃	260	6.75	-13.2(5)	— ^c	— ^c	73.0	— ^d
SC-24 (0.01)	NO ₃ (0.01)	—	CDCl ₃	240	6.72	—	—	—	—	— ^d
2.2.2 (0.081)	NO ₃ (0.081)	—	CDCl ₃	300	6.92	-15.0	-16.7(5)	-18.7	72.8	1.69
2.2.2 (0.081)	NO ₃ (0.081)	—	CDCl ₃	283	6.90	-14.8	-16.7	— ^c	72.8	1.68
2.2.2 (0.081)	NO ₃ (0.081)	—	CDCl ₃	263	6.89	-14.9	-16.5	— ^c	72.7	1.48
2.2.2 (0.081)	NO ₃ (0.081)	—	CDCl ₃	243	6.89	-14.3	-16.3	— ^c	72.7	— ^d
2.2.2 (0.081)	NO ₃ (0.081)	—	CDCl ₃	233	6.89	-14.4	-16.9	— ^c	72.7	— ^d
2.2.2 (0.15)	NO ₃ (0.15)	—	CD ₂ Cl ₂	270	6.90	-14.4	-16.3	-18.4	72.7	1.67
2.2.2 (0.15)	NO ₃ (0.15)	—	CD ₂ Cl ₂	230	6.91	-14.7	-16.7	-18.6(5)	72.7	— ^d
2.2.2 (0.15)	NO ₃ (0.15)	—	CD ₂ Cl ₂	200	^c	— ^c	-17.5	-19.8	72.6	— ^d
2.2.2 (0.15)	NO ₃ (0.15)	—	CDCl ₃	270	6.92	-14.5	-16.8	— ^c	72.7	1.60
2.2.2 (0.15)	NO ₃ (0.15)	TBAI (0.042)	CDCl ₃	270	6.92	-14.6	-16.9	— ^c	72.8	1.61
2.2.2 (0.15)	NO ₃ (0.15)	TBAI (0.100)	CDCl ₃	270	6.92	-14.5	-16.7(5)	— ^c	72.8	1.62
2.2.2 (0.10)	I ⁻ (0.10)	—	CDCl ₃	300	6.89	-14.9	-16.6	-18.7	72.7	1.66
2.2.1 (0.196)	NO ₃ (0.192)	—	CDCl ₃	300	7.30	— ^d	— ^d	— ^d	72.8	— ^d
2.2.1 (0.196)	NO ₃ (0.192)	—	CDCl ₃	287	7.30	-26.4	-28.9	-31.3	72.6	— ^d
2.2.1 (0.196)	NO ₃ (0.192)	—	CDCl ₃	270	7.32	-27.3	-29.7	-32.8(5)	72.6	1.56
2.2.1 (0.196)	NO ₃ (0.192)	—	CDCl ₃	250	7.34	-27.8	-31.0(5)	-34.2	72.7	1.41
2.2.1 (0.196)	NO ₃ (0.192)	—	CDCl ₃	231	7.35	-29.1	-32.6	-36.0	72.6	— ^d
2.2.1 (0.265)	NO ₃ (0.197)	—	CDCl ₃	232	7.35	-28.8	-32.1	-35.8	72.6	— ^d
2.2.1 (0.242)	NO ₃ (0.108)	—	CD ₂ Cl ₂	300	7.26	-25.6	— ^d	— ^d	72.7	— ^d
2.2.1 (0.242)	NO ₃ (0.108)	—	CD ₂ Cl ₂	270	7.28	-28.4	-31.1	— ^c	72.6	1.58
2.2.1 (0.042)	NO ₃ (0.108)	—	CD ₂ Cl ₂	230	7.31	-30.2	-32.8	— ^c	— ^c	— ^d

Table continued

Table 1. Continued

Host	¹⁵ NH ₄ X	Addition	Solvent	Temperature/K	δH (ppm)	² ΔH(D) ₁ ^e	² ΔH(D) ₂	² ΔH(D) ₃	¹ J(N, H)/Hz	² J(H, D) ^g /Hz
2.2.1 (0.242)	NO ₃ ⁻ (0.108)	—	CD ₂ Cl ₂	200	7.35	-30.9	-35.2(5)	— ^c	— ^c	— ^d
2.2.1 (0.242)	NO ₃ ⁻ (0.108)	—	CD ₂ Cl ₂	190	7.35	-32.2	-36.9	-41.1	72.4	— ^d
2.2.1 (0.242)	NO ₃ ⁻ (0.108)	—	CD ₂ Cl ₂	180	7.39	-32.6(5)	— ^c	— ^c	— ^c	— ^d
2.2.1 (0.196)	NO ₃ ⁻ (0.192)	TBAI (0.032)	CDCl ₃	270	7.31	-27.2	-30.8	-32.9	72.6	1.53
2.2.1 (0.196)	NO ₃ ⁻ (0.192)	TBAI (0.032)	CDCl ₃	230	7.35	-29.5	-33.2	-36.8	72.6	— ^d
2.2.1 (0.196)	NO ₃ ⁻ (0.192)	TBAI (0.108)	CDCl ₃	270	7.31	-28.4(5)	-31.7	-34.0	72.6	— ^e
2.2.1 (0.196)	NO ₃ ⁻ (0.192)	TBAI (0.108)	CDCl ₃	230	7.34	-30.9	-34.2	-38.4	72.6	— ^d
2.2.1 (0.196)	NO ₃ ⁻ (0.192)	TBAI (0.168)	CDCl ₃	270	7.30	-29.3	-32.7	-34.8	72.6	— ^e
2.2.1 (0.196)	NO ₃ ⁻ (0.192)	TBAI (0.168)	CDCl ₃	230	7.34	-31.1	-34.9(5)	-38.9	72.5	— ^d
2.2.1 (0.159)	I ⁻ (0.160)	—	CDCl ₃	270	7.35	-31.0(5)	-34.4	— ^c	72.6	1.62
2.2.1 (0.159)	I ⁻ (0.160)	—	CDCl ₃	250	7.36	-31.1	-35.0	— ^c	72.6	— ^d
2.2.1 (0.159)	I ⁻ (0.160)	—	CDCl ₃	230	7.37	-32.4	-36.9	-41.3	72.5	— ^d
2.2.1 D (0.066)	I ⁻ (0.066)	—	CDCl ₃	268	7.30	-31.0	-34.5	-37.3	72.5	— ^d
2.2.1 D ^h (0.066)	I ⁻ (0.066)	—	CDCl ₃	268	7.51	-32.0	— ^c	— ^c	72.0(5)	— ^d
2.2.1 D (0.066)	I ⁻ (0.066)	I ₂ (0.033)	CDCl ₃	268	7.27	-38.0	— ^c	— ^c	72.6	— ^d
2.2.1 D ^h (0.066)	I ⁻ (0.066)	I ₂	CDCl ₃	268	7.47	— ^c	— ^c	— ^c	— ^c	— ^d
2.2 DD (0.144)	NO ₃ ⁻ (0.118)	—	CD ₂ Cl ₂	250	7.21	-28.3	-31.0	— ^c	72.5	— ^d
2.2 DD (0.144)	NO ₃ ⁻ (0.118)	—	CD ₂ Cl ₂	240	7.23	-29.3	-32.8	— ^d	— ^d	— ^d
K5 (0.110)	NO ₃ ⁻ (0.108)	—	CD ₂ Cl ₂	270	8.23	-33.8(5)	— ^c	— ^c	72.4	— ^d
K5 (0.110)	NO ₃ ⁻ (0.108)	—	CD ₂ Cl ₂	260	8.27	-34.2	-37.5	— ^c	72.4	— ^d
K5 (0.110)	NO ₃ ⁻ (0.108)	—	CD ₂ Cl ₂	240	8.33	-34.9	-38.6	— ^c	72.4	— ^d
K5 (0.110)	NO ₃ ⁻ (0.108)	—	CD ₂ Cl ₂	225	8.37	-34.7	-40.2	— ^c	72.3	— ^d
K5 (0.112)	I ⁻ (0.115)	—	CD ₂ Cl ₂	270	8.35	-38.3 ⁱ	-40.2	-44.7	— ^j	— ^d
K5 (0.112)	I ⁻ (0.115)	—	CD ₂ Cl ₂	260	8.35	-36.5(5) ⁱ	-41.1	-44.0	— ^j	— ^d
K5 (0.112)	I ⁻ (0.115)	—	CD ₂ Cl ₂	250	8.36	-37.6 ⁱ	-41.2	-44.6	— ^j	— ^d
K5 (0.112)	I ⁻ (0.115)	—	CD ₂ Cl ₂	240	8.37	-37.0	-40.8	-44.4	71.9	— ^d
K5 (0.112)	I ⁻ (0.115)	TBAI (0.047)	CD ₂ Cl ₂	250	8.35	-37.8	-41.2	-44.8	71.9	— ^d
K5 (0.112)	I ⁻ (0.115)	TBAI (0.108)	CD ₂ Cl ₂	250	8.34	-37.1	-41.2	-44.6	72.0	— ^d
18-C-6- (COOH) ₄ (0.132)	NO ₃ ⁻ (0.12)	—	D ₂ O	298	6.65	-10.4	-12.3	-13.6	74.2	1.65
18-C-6- (COOH) ₄ (0.132)	NO ₃ ⁻ (0.12)	TBAI (0.036)	D ₂ O	300	6.63	-10.2(5)	-12.4	-13.6	74.4	1.63
18-C-6- (COOH) ₄ (0.132)	NO ₃ ⁻ (0.12)	TBAI (0.078)	D ₂ O	300	6.64	— ^c	-12.6(5)	-13.5(5)	74.1	1.58
18-C-6- (COOH) ₄ (0.22)	I ⁻ (0.22)	—	D ₂ O	300	6.59	-10.4	-11.9(5)	-13.7	74.2	1.71
—	CF ₃ COO ⁻ (1.18)	CF ₃ COOH (2.3)	D ₂ O	300	6.77	-19.9	-22.3	-24.2	73.1	— ^d
18-C-6 (0.10)	NO ₃ ^{-k} (0.10)	—	CDCl ₃	210	9.20	-18.5	— ^c	— ^c	74.7	— ^c

^aChemical shifts in ppm relative to TMS, if nothing else is given. ²ΔH(D) in ppb. Molar concentrations are given in parentheses.

^bThe data were measured relative to CDCl₃ and converted according to the host added and the temperature. ^cToo low or too high a deuterium content and poor resolution prevented observation. ^dNot observable because of lack of splitting (see text). ^eDefined as δNH₄ - δNH₃D. ^fValues given are for ¹J(N, H₄). The one-bond coupling varies slightly with the degree of deuteration. ^gThe two-bond coupling is measured for the NH₃D species. The coupling varies slightly with the degree of deuteration. ^hMinor species (see text). ⁱOnly the high-field branch could be observed. ^jCould not be determined accurately because of overlap. The values for ¹J(NH₂D₂) are 72.1, 71.9, 71.9 Hz, respectively. ^kAnilinium ion.

Table 2. ^{15}N Chemical shifts^a and $^1\Delta\text{N}(\text{D})$ isotope effects^b of the ammonium ion in complexes.

Compound	Anion	Solvent	Temperature/K	δN	$^1\Delta\text{N}(\text{D})_1$ ^c
18-C-6	NO_3^-	CDCl_3	300	-362.4	0.277
18-C-6	I^-	CDCl_3	300	-354.2	0.350
SC-24	NO_3^-	CDCl_3	300	-362.0	0.308
SC-24	TBAI ^d	CDCl_3	300	-362.0	0.305
[2.2.2]	NO_3^-	CDCl_3	300	-357.2	0.314
[2.2.2]	I^-	CDCl_3	300	-357.2	0.313
[2.2.1]	NO_3^-	CDCl_3	268	-357.3	0.317
[2.2.1]	I^-	CDCl_3	270	-351.8	0.364
[2.2.1]D	I^-	CDCl_3	268	-351.3	0.357
[2.2.1]D	$\text{I}^- + \text{I}_2$	CDCl_3	268	-351.8	0.338
K5	NO_3^-	CDCl_3	300	-359.8(5)	0.305
K5	I^-	CDCl_3	300	-357.8	0.35
18-C-6(COOH) ₄	NO_3^-	D_2O	300	-357.2	0.28
18-C-6(COOH) ₄	I^-	D_2O	300	-357.2	0.284

^aReferenced relative to external CH_3NO_2 . ^bIn ppm. ^cDefined as $\delta\text{N}/\text{H}_4 - \delta\text{N}/\text{H}_3\text{D}$, $\delta\text{N}/\text{H}_3\text{D} - \delta\text{N}/\text{H}_2\text{D}_2$ and $\delta\text{N}/\text{H}_2\text{D}_2 - \delta\text{N}/\text{HD}_3$. ^dTBAI added to NH_4NO_3 solution. For concentrations see Table 1.

is also found for the complexes of SC-24, [2.2.2] and 18-C-6, but the slope is different from that in water (Fig. 6). The data for the complexes of [2.2.1], K5 and 18-C-6(COOH)₄ clearly fall outside. The former two show a parallel behaviour, and both show a more negative $^2\Delta\text{H}(\text{D})$ value for the iodide counterion.

Host. The complex formation of [2.2.2] and [2.2.1] with ammonium ions has been described by Lehn *et al.*^{8,33}

The temperature variations of the ^1H NMR spectrum of the host molecule of the complexes have been investigated for 18-C-6, SC-24,⁷ [2.2.2]⁸ and [2.2.1]. Dramatic changes with temperature take place, mostly because of restriction of the motion of the CH_2 groups.

Comparisons of the ^1H spectra of the hosts (cryptands, podands or crown ethers) and those of the host molecule

of the complex show variations. [2.2.1] shows a distinct change in the host spectrum upon complexation with alkali ions.³³ The ^1H spectrum of the uncomplexed host [2.2.1] in CDCl_3 shows a broad unresolved resonance at 2.7 ppm including all CH_2 groups next to the nitrogen. The CH_2 groups next to oxygen are divided into three groups, a triplet due to the CH_2 protons of the short chain; an AA' system caused by the CH_2 groups of the long chains and an AA'BB' system caused by the O- CH_2CH_2 -O groups. The host spectrum of the complex shows that the NCH_2CH_2 protons of the two long chains have become inequivalent, and the CH_2 groups next to nitrogen have the following chemical shifts and coupling constants: 2.87 ppm (2.84 and 8.50 Hz); 2.56 ppm (1.96 and 4.87 Hz); 2.64 ppm (4.29 Hz) and 3.43 ppm (4.32 Hz). The O- CH_2CH_2 -O groups shows

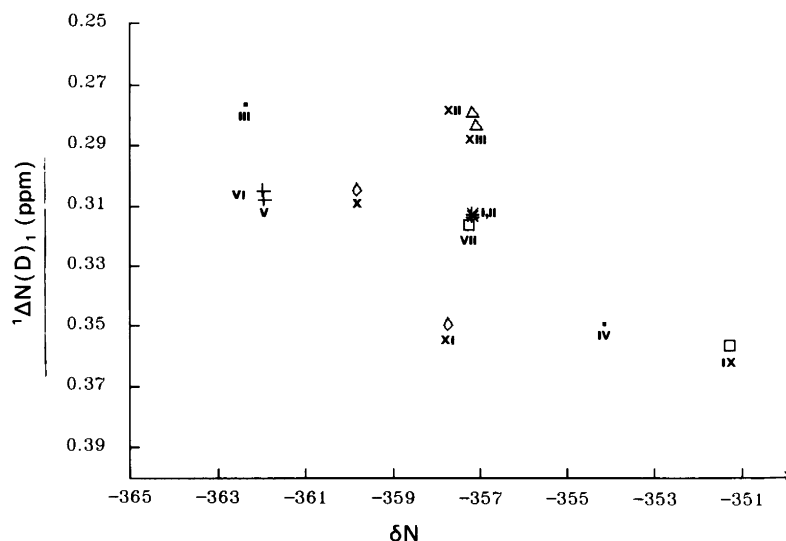


Fig. 3. Plot of $\Delta\text{N}(\text{D})_1$ vs. δN . Complexes of ammonium ions with crown ethers, cryptands and podands: (I, *) [2.2.2]- $^{15}\text{NH}_4\text{NO}_3$, (II, *) [2.2.2]- $^{15}\text{NH}_4\text{I}$, (III, ■) 18-C-6- $^{15}\text{NH}_4\text{NO}_3$, (IV, ■) 18-C-6- $^{15}\text{NH}_4\text{I}$, (V, +) SC-24- $^{15}\text{NH}_4\text{NO}_3$, (VI, +) SC-24- $^{15}\text{NH}_4\text{NO}_3$ + TBAI, (VII, □) [2.2.1]- $^{15}\text{NH}_4\text{NO}_3$, (VIII, □) [2.2.1]- $^{15}\text{NH}_4\text{I}$, (IX, □) [2.2.1]D- $^{15}\text{NH}_4\text{I}$, (X, ◇) K5- $^{15}\text{NH}_4\text{NO}_3$, (XI, ◇) K5- $^{15}\text{NH}_4\text{I}$, (XII, △) 18-C-6(COOH)₄- $^{15}\text{NH}_4\text{NO}_3$, (XIII, △) 18-C-6(COOH)₄- $^{15}\text{NH}_4\text{I}$.

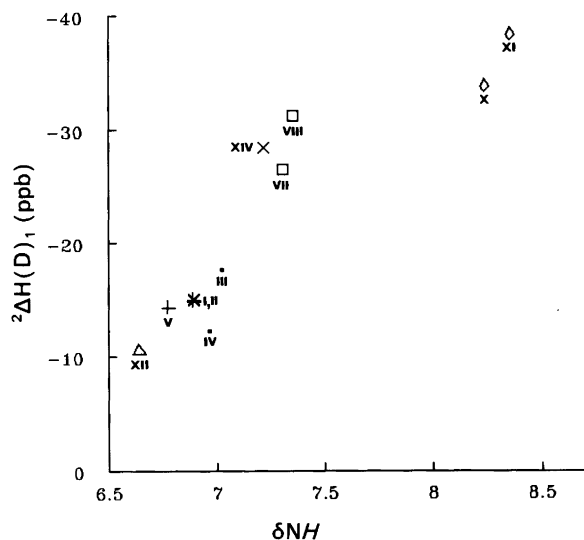


Fig. 4. Plot of ${}^2\Delta H(D)_1$ vs. δNH . Numbering as for Fig. 3, with additionally (XIV, \times) [2.2] DD- ${}^{15}\text{N}_4\text{NO}_3$.

a complicated coupling pattern, with chemical shifts of ~ 3.56 ppm, and two other similar complex spin patterns are observed at 3.71 and 3.81 ppm, respectively.

The solvent influence is seen in some cases. The temperature lowering necessary to observe resonances is different for different complexes. The appearance of the host spectrum of the complex also varies with solvent in the case of [2.2.1].

Deuterium exchange. During the investigation of the NH_4NO_3 complex with [2.2.1] in CDCl_3 it became apparent that the ammonium ion was gradually deuteriated and that at the same time more CHCl_3 appeared in the ${}^1\text{H}$ spectrum. The ammonium ion is completely deuteriated in 10–12 days, depending on the

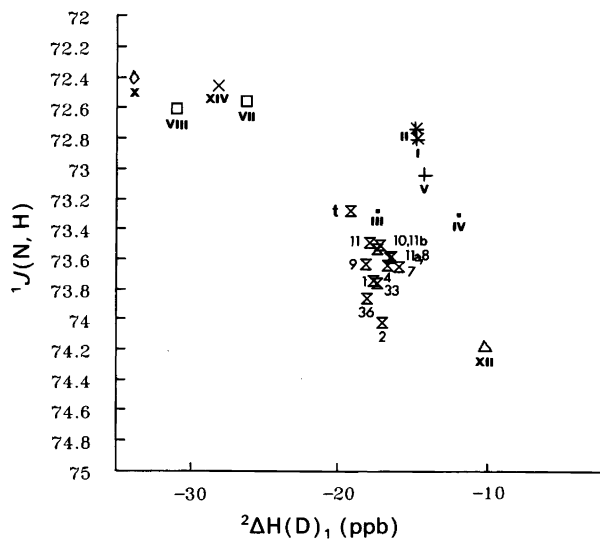


Fig. 5. Plot of ${}^1J(\text{N}, \text{H})$ vs. ${}^2\Delta H(D)_1$. Numbering as for Fig. 3 with additionally (XIV, \times) [2.2] DD- ${}^{15}\text{N}_4\text{NO}_3$; the point \times marks data of ammonium salts in an acidic $\text{H}_2\text{O}-\text{D}_2\text{O}$ mixture taken from Ref. 26; t marks data for trifluoroacetate.

concentration of [2.2.1]. No similar process was observed with any of the other azacrowns or cryptands.

Competition experiments. Addition of [2.2.1] to a [2.2.2]- NH_4NO_3 complex shows that very little [2.2.1] complex is formed. Addition of ammonium nitrate to a mixture of [2.2.2] and [2.2.1] gave the same picture. This can be understood by assuming that [2.2.2] complex formation is fast relative to that of [2.2.1] and that the rate of release of ammonium ions from the [2.2.2] complex is very slow compared to [2.2.1]. This leads to a considerably larger equilibrium constant for the [2.2.2] complex. The ratio is around 70. Addition of less than an

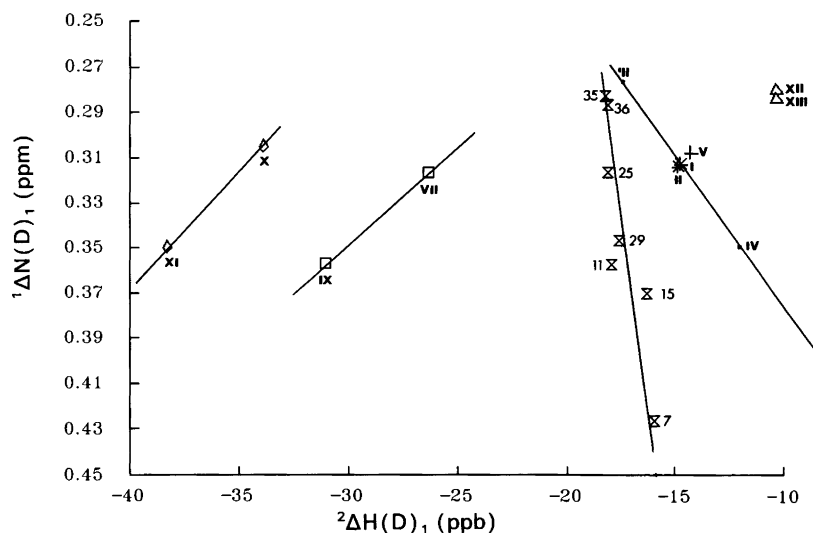


Fig. 6. Plot of ${}^1\Delta N(D)_1$ vs. ${}^2\Delta H(D)_1$. Numbering as for Fig. 3. Italic numbers refer to salts in water solution from the work presented in Ref. 26.

Table 3. Calculated ^{15}N nuclear shieldings,^a $^1\Delta\text{N}(\text{D})$, $^2\Delta\text{H}(\text{D})$ and NH nuclear shieldings of hydrogen-bonded protons.

$R_{\text{N}\cdots\text{N}}$	δN	$^1\Delta\text{N}(\text{D})$	$^1\Delta\text{N}(\text{D})^d$	δNH^c	$^2\Delta\text{H}(\text{D})$	$^2\Delta\text{H}(\text{D})^d$
2.62	231.6	0.31	—	15.1	-0.025	—
2.72	233.4	0.3	0.37	17.1	-0.0183	-0.012
3.02	237.4	0.44	0.48	21.1	-0.010	-0.003
3.2	240.5	0.52(5)	0.56	23.9	0	0.005
4.02	241.4	0.58	0.60	24.5	0.003	0.005
3.02 ^a	237.4	0.7	—	21.1	0.01 ^e	—

^aAbsolute shieldings. $R(\text{N}_1\text{-H}_2) = 1.019 \text{ \AA}$. ^b $R(\text{N}_1\text{-H}_3) = 1.019 \text{ \AA}$. ^cHydrogen part of hydrogen bond (Fig. 7). ^d $\text{NH}_3\text{D}\cdots\text{H}_2\text{O}$ complex. Data from Ref. 26. ^e $^2\text{H}_3(\text{D})$ is given. $^2\Delta\text{H}_2(\text{D}) = 0$.

equivalent amount of [2.2.2] to a [2.2.1]-ammonium nitrate complex leads to the situation seen in Fig. 2B, one well suited for a comparison of the two complexes.

Water solutions. Isotope effects of $\text{CF}_3\text{COO}^{14}\text{NH}_4$ have been investigated in $\text{H}_2\text{O} : \text{D}_2\text{O}$ mixtures in order to add a counterion resembling that of 18-C-6(COOH)₄ to the data set of Ref. 26. The CF_3COO^- counterion is seen to give a $^2\Delta\text{H}(\text{D})$ value similar to that of nitrate.²⁶

Theoretical calculations. Deuterium isotope effects on nuclear shieldings have been calculated *ab initio* using the localized orbital/local origin (LORG) method,^{34,35} as previously described.²⁷ The nuclear shielding and isotope effect calculations were carried out using the RPAC Molecular Properties Package, version 9.0.³⁶ The SCF results required for the LORG calculations were obtained with the GAUSSIAN 90 program system.³⁷ The basis sets used were as previously reported,²⁷ except that the ammonia atoms were assigned the same basis set as in the ammonium molecule. Isotope effects were calculated in the static approximation³⁸ using a shortening of the C-H bond of 0.01 \AA .²⁷ The geometry is shown in Fig. 7.

The calculations show that $^1\Delta\text{N}(\text{D})$ values increase with distance and that $^2\Delta\text{H}(\text{D})$ becomes more negative with shorter N...N distances (Table 3). It is noticeable that the results are qualitatively comparable to those obtained for the ammonium ion surrounded by water molecules.²⁷ However, for a similar distance a slightly smaller $^1\Delta\text{N}(\text{D})$ is calculated in case of ammonia

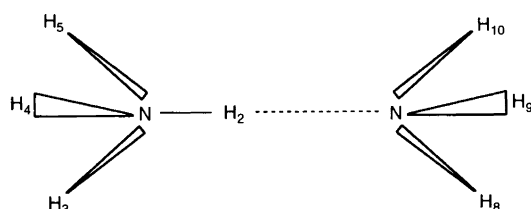


Fig. 7. Structure of the ammonium-ammonia complex. In the standard conformation $R(\text{N-H}_2) = R(\text{N-D}) = 1.019 \text{ \AA}$, $R(\text{N-H}_{3,4,5}) = 1.029 \text{ \AA}$ and the dihedral angle $\text{H}_3\text{-N}_1\text{N}_7\text{-N} = 0^\circ$.

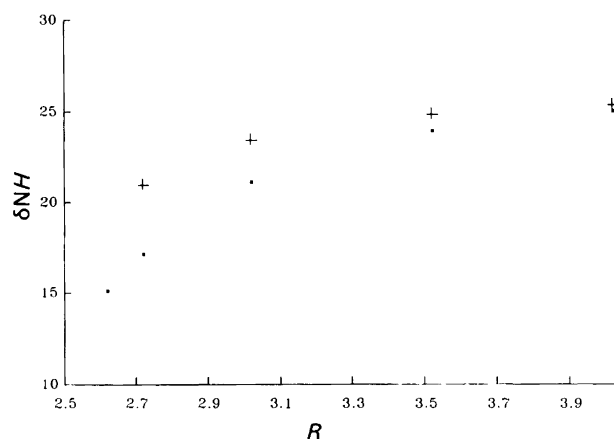


Fig. 8. Calculated ^1H nuclear shieldings for the $\text{NH}_4^+ \cdots \text{H}_2\text{O}$ (+) and $\text{NH}_4^+ \cdots \text{NH}_3$ (■) complexes.

(Table 3), whereas for $^2\Delta\text{H}(\text{D})$ a considerably more negative value is obtained in the ammonia case (Table 3). Deuteriation at a position not in the N-H...N bond (Fig. 7) gives rise to a positive $^2\Delta\text{H}(\text{D})$, confirming that the negative sign is connected to hydrogen bonding of the deuterium. $^1\Delta\text{N}(\text{D})$ is also increased. On the other hand, deuteriation at the ammonia molecule has no effect on the ammonium ion.

The $^1\Delta\text{N}(\text{D})$ isotope effects can be seen to follow a $1/r^2$ dependence, where r is the distance from the nitrogen of ammonia to the midpoint of the N-H bond of the ammonium ion. This relationship is most accurate for N...N distances larger than 3 \AA . A comparison of calculated values of NH nuclear shieldings of water and of the ammonium complexes shows that δH is at lower field in the latter (Fig. 8). Likewise is δN calculated to be at lowest field in the ammonia complex (Fig. 9). These theoretical numbers are obtained for isolated complexes, and both solvent and counterion effects have to be taken into account before one can make direct comparisons to experimental results.

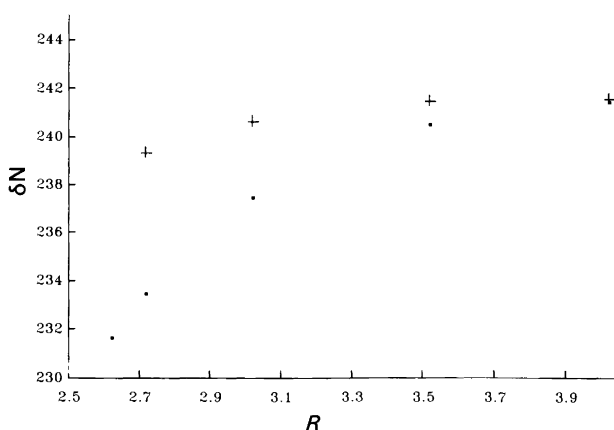


Fig. 9. Calculated ^{15}N nuclear shieldings for the $\text{NH}_4^+ \cdots \text{H}_2\text{O}$ (+) and $\text{NH}_4^+ \cdots \text{NH}_3$ (■) complexes.

Discussion

The experimental investigation of $^1\Delta\text{N}(\text{D})$ and $^2\Delta\text{H}(\text{D})$ of ammonium ions showed strong counterion dependence,²⁶ while theoretical calculations of the ammonium ion–water complex²⁷ and of the ammonium ion–ammonia complexes indicate that the two isotope effects depend on the distance and direction to the acceptor atom of the coordinating molecules. In the following, ^1H and ^{15}N chemical shifts and isotope effects of crown ethers and cryptands complexes are analyzed to separate counterion and coordination effects and to find experimental support for the theoretical predictions.

$^1\Delta\text{N}(\text{D})$ and $^2\Delta\text{H}(\text{D})$ are proportional for water solutions. However, this no longer holds true for the inclusion complexes as a whole, since crown ethers, cryptands and podands fall on separate correlation lines in Fig. 6. The counterion dependence of both $^2\Delta\text{H}(\text{D})$ and $^1\Delta\text{N}(\text{D})$ is clearly seen to be large for 18-C-6, [2.2.1] and K5, whereas the counterion dependence for $^1\Delta\text{N}(\text{D})$ is much larger than for $^2\Delta\text{H}(\text{D})$ for ammonium ions in water, making the slope for the corresponding line in Fig. 6 three times larger than for the crown ethers, cryptands and podands. The direction of the counterion effect on $^1\Delta\text{N}(\text{D})$ is the same for all three compounds, and is in agreement with trends found for water solutions.

On the other hand $^1\Delta\text{N}(\text{D})$ and δN are proportional for crown ethers, cryptands and podands and for ammonium ions in water solutions,²⁶ and they are both strongly dependent on the choice of counterion for all cases except SC-24 and [2.2.2] (Fig. 3 and Ref. 26). The $^1\Delta\text{N}(\text{D})$ of these two inclusion complexes could be said to be dominated by the variation of the ^{15}N chemical shift, as Jameson has suggested that $^1\Delta\text{N}(\text{D})$ is proportional to δN in general.³⁹ A comparison of $^1\Delta\text{N}(\text{D})$ of the SC-24 and [2.2.2] complexes shows isotope effects of comparable magnitude, but larger than found at infinite dilution in water.²⁶ The theoretical calculations show that $^1\Delta\text{N}(\text{D})$ are similar for the ammonium–ammonia complex and the corresponding water complex, but that $^2\Delta\text{H}(\text{D})$ is more negative in the former complex. Coordination to nitrogen is therefore likely to give more negative $^2\Delta\text{H}(\text{D})$ values, whereas $^1\Delta\text{N}(\text{D})$ will be approximately the same for both types of coordination.

$^2\Delta\text{H}(\text{D})_1$ and δNH are roughly proportional, but although the counterion influence is larger for $^2\Delta\text{H}(\text{D})_1$ than for δNH , the influence of counterions is seen to be rather small (Fig. 4). In the case of $^2\Delta\text{H}(\text{D})_1$ the large negative value is not a direct consequence of the low-field NH chemical shift, although a proportionality could be explained in the same way as for $^1\Delta\text{N}(\text{D})$ and δN . That this is not the case is clearly seen from Fig. 4, in which changes in $^2\Delta\text{H}(\text{D})_1$ are found to be of the same magnitude as observed for δNH . Furthermore, the anilinium ion is another interesting case disproving such a suggestion, since the $^2\Delta\text{H}(\text{D})_1$ observed for the anilinium complex with 18-C-6 is similar to that observed

for the ammonium ion, despite the low-field shift of the anilinium proton (9.2 ppm). The counterion influence on $^2\Delta\text{H}(\text{D})$ is small {even zero for SC-24, [2.2.2] and 18-C-6(COOH)₄}. The variation in $^2\Delta\text{H}(\text{D})$ for the three inclusion complexes follows the variation in distance and acceptor type as discussed later.

The variation of $^1J(\text{N}, \text{H})$ in the complexes is much larger than the variation observed in water solution.²⁶ The largest couplings are observed in 18-C-6(COOH)₄ and SC-24, with weak or absent hydrogen bonds, whereas the small values are found for K5, with strong hydrogen bonds. For the water solution the variation is much smaller. The order of $^1J(\text{N}, \text{H})$ couplings indicates that the distance to the hydrogen-bond acceptor thus seems to be the dominant factor for the inclusion compounds. It was previously claimed that no correlations could be found for $^1J(\text{N}, \text{H})$ in water.²⁶ However, as seen from Fig. 5, $^1J(\text{N}, \text{H})$ does depend on $^2\Delta\text{H}(\text{D})_1$, and as the latter is proportional to the counterion concentration, this also holds for the former. The largest change in $^1J(\text{N}, \text{H})$ per mole of counterion is now found for the nitrate ion, and the larger variation observed for nitrates than for the halide ions seems also to hold true for the other two oxygen-containing acids, ClO_4^- and CF_3COO^- . The variation in $^1J(\text{N}, \text{H})$ for ammonium ions in water is hence 1 Hz, whereas the variation in $^2\Delta\text{H}(\text{D})$ is small, -19.9 to -17.5 ppb. This insensitivity of $^2\Delta\text{H}(\text{D})$ could be taken as a sign that NO_3^- and the other hard ions do not interact with the ammonium ion, but the relatively large variation of the one-bond coupling clearly contradicts such a suggestion.

The effects of counterions on $^2\Delta\text{H}(\text{D})$ (Fig. 6) are similar for 18-C-6 in CDCl_3 to that observed in water. One way of accounting for the $^2\Delta\text{H}(\text{D}) = -17.5$ ppb value is to assume that the nitrate ion contributes similarly as a water molecule, i.e. -4.75 ppb/O. This leaves an effect of -4.25 ppb/O for the oxygens of 18-C-6, which is numerically smaller than that for water. This is in line with the fact an experimental solid-state structure for 18-C-6 yields an $\text{N}\cdots\text{O}$ distance of 2.871 \AA ,⁴⁰ which is slightly longer than the $\text{N}\cdots\text{O}$ distance obtained by theoretical calculations of water surrounding ammonium ions (2.729 \AA).²⁷ The $^2\Delta\text{H}(\text{D})_1$ isotope effect found for the SC-24 complex is rather small. This can again be rationalized by reference to the experimental solid-state structure showing four hydrogen bonds, three with $\text{N}\cdots\text{N}$ bond lengths of 3.05 , a fourth with an $\text{N}\cdots\text{N}$ distance of 3.17 \AA , and in addition six non-directional oxygens are positioned further away,⁴¹ since these $\text{N}\cdots\text{N}$ bonds are significantly longer than the optimal distance of 2.7 \AA calculated for ammonium ions surrounded by ammonia.⁴² A rough calculation gives an average effect of 3 ppb per hydrogen bond. The [2.2.2] complex clearly shows an isotope effect less than that of 18-C-6. The experimental $\text{N}\cdots\text{N}$ distance in [2.2.2], 3.026 \AA ,⁸ is similar to that found for SC-24, and assuming the same value for the hydrogen bond to nitrogen, the three hydrogen bonds to oxygen are each contributing -4 ppb.

The smaller value is reasonable, as the N...O distance, 2.931 Å,⁸ is longer than that of 18-C-6.

The much more negative ${}^2\Delta\text{H}(\text{D})_1$ found for [2.2.1] is remarkable. Furthermore, it is also counterion-dependent. The NH chemical shifts are seen to be approximately 0.3 ppm to lower field than that of [2.2.2]. The [2.2.1] complex is less favorable than the [2.2.2] complex, as seen from the competition experiments. However, the cavity of [2.2.1] is narrower, as [2.2.1] shows preference for the smaller ions like Na^+ ($r = 0.94 \text{ \AA}$), whereas [2.2.2] shows preference for K^+ ($r = 1.33 \text{ \AA}$).⁴³ The large negative values for [2.2.1] can, as previously, be divided into a contribution from nitrogen and three identical contributions from oxygen. The counterion dependence shows that the ammonium ion is not fully included. The ${}^2\Delta\text{H}(\text{D})$ and the δNH values suggest a tighter fit than found for [2.2.2], as also suggested above. This fit becomes even tighter at low temperature (see below). The structure of [2.2.1] is clearly more rigid than that of [2.2.2] or SC-24 at the same temperature, as judged from the spectra of the host molecules of the complexes. The rigidity is caused by the formation of a hydrogen bond to the oxygen of the short chain. The $\text{NCH}_2\text{CH}_2\text{O}$ proton chemical shifts of the long chains become diastereotropic in the complex, and the coupling constants show a skew-gauche structure supporting the suggested structure.

The observation of two sets of resonances in case of the [2.2.1]D-ammonium complex is interesting. The major species shows parameters similar to those of the [2.2.1] complex, whereas the NH chemical shift and the ${}^1J(\text{N}, \text{H})$ coupling constants are markedly different (Table 1). This pinpoints the fact that the ammonium ion is too large to fit into the cavity and that the conformational constraint imposed by the long alkyl chain (see previously) leads to a different kind of structure for the minor complex.

The flexible and open-ended structure of K5 permits the formation of a strong complex.^{44,45} An X-ray study of the RbJ complex shows⁴⁶ that the molecule can be folded in a helical way, which enables formation of hydrogen bonds to all four N-H protons (Fig. 10). K5 forms stronger complexes with potassium ions than with sodium ions, again confirming that the size is about right for complex formation with the ammonium ion. The structure shown in Fig. 10 could explain the large numerical value of ${}^2\Delta\text{H}(\text{D})$, if one assumes short N...N distances, as ${}^2\Delta\text{H}(\text{D})$ becomes very negative at short distances

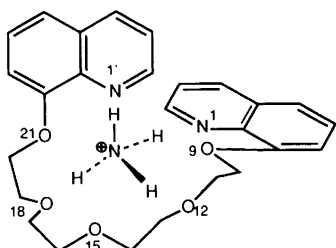


Fig. 10. Suggested structure for the $\text{K5-}^{15}\text{NH}_4^+$ complex based on the X-ray structure of Ref. 46.

according to the theoretical calculations (Table 3). Likewise, the low-field shift of the NH proton is a good indication of a short N...N distance (Fig. 8). For the rubidium complex it was also found that no interaction took place between the cation and the counterion.⁴¹ The weak counterion dependence observed for the ammonium complex could be understood in a similar way. The complex with 18-C-6(COOH)₄ shows the smallest ${}^2\Delta\text{H}(\text{D})_1$ so far. The complex has been suggested to be between two COO^- groups on opposite rings (Fig. 11).⁴⁷ This leaves the other two NH bonds either to point towards the solvent side or towards the interior of the crown. As no counterion dependence is observed, the latter possibility is favoured. Two NH(D) bonds are engaged in bonds to COO^- , and the other two are pointing to the interior with a rather long distance to the nearest oxygens. Such a structure is different from the complex of ethylene diamine or other alkylamines and 18-C-6(COOH)₄.⁴⁸ In those cases, the ammonium ion is pushed far into the crown, leading to short N...O distances. The results from $\text{CF}_3\text{COONH}_4$ show effects of a carboxylate anion of the order of -20 ppb per interaction. To be able to explain the finding of ${}^2\Delta\text{H}(\text{D}) = -10 \text{ ppb}$ for 18-C-6(COOH)₄ we must assume that only two oxygens of the carboxylate groups are effective, and that the effects of the two bonds pointing towards the interior are close to zero.

Temperature effects. Temperature studies show that the ${}^1\text{H}$ spectrum of the host molecule changes dramatically with temperature over a rather narrow temperature range.^{8,33} However, no dramatic changes occur in ${}^2\Delta\text{H}(\text{D})_1$ in this same temperature range. This suggests that the changes are mostly a decrease in the mobility of the side-chains, but not so much in the ability to form hydrogen bonds to the ammonium ions.

${}^2\Delta\text{H}(\text{D})_1$ isotope effects show a gradual change with temperature. For [2.2.2] and 18-C-6 the effect is very small. For [2.2.1] the effect is much larger and to low field, leading to an even larger isotope effect. This change must reflect a tighter fit at low temperature and followingly shorter hydrogen bonds. This is also supported by a low-field shift of the NH proton (Table 1).

Counterion dependence. The finding that the isotope effects of SC-24 and [2.2.2] do not show a counterion dependence is due to the ammonium ion being inside the cage, with no access for the counterion. The effects of counterions on chemical shifts have been ascribed to a direct overlap between the counterion and the nucleus in

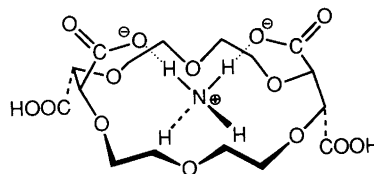


Fig. 11. The $18\text{-C-6(COOH)}_4\text{-}^{15}\text{NH}_4^+$ complex.

question.⁴⁹ This is clearly not possible in for SC-24 and [2.2.2]. However, the charge of the counterions could in itself influence, via an electric field effect, both the chemical shift and the isotope effects.²⁷ From the X-ray data of [2.2.2] and NH_4PF_6 it is seen that the counterion is 7.39 Å away from the nitrogen.⁸ If a similar picture is found in solution, then it is understandable that the influence of the counterion is small. For the cryptand [2.2.1] and the crown ether 18-C-6, the counterion dependence is very strong owing to ion-pairing. This shows that the ammonium ion is not fully buried in [2.2.1], despite the name cryptand.

Quadrupole effects. The appearances of the ^1H spectra and the collapse of N–D couplings are different for the different compounds (Table 1). Collapse of an H–D coupling is supported by large deuterium quadrupole coupling constants, Q_D , and as a consequence, short T_{2D} relaxation times. Q_D is normally reduced by strong hydrogen bonding.⁵⁰ The finding that collapse is seen at a lower temperature in the [2.2.1] complex than in the [2.2.2] complex (Fig. 2) clearly supports the finding that the N...O distances are short in the former complex. The high collapse temperature of the SC-24 complex is likewise in agreement with the rather weak hydrogen bonds of this complex.

Conclusions

A combination of δN , $^1\Delta\text{N(D)}$, δNH , $^2\Delta\text{H(D)}$ and $^1J(\text{N, H})$ and their mutual correlations give the following picture. $^1\Delta\text{N(D)}$ and δN are strongly dependent on counterion concentration in water solution. Such a variation is also strong for inclusion complexes such as [2.2.1] and 18-C-6, but smaller for K5. The strong variation with a change in counterion can be caused by ion-pairing in the organic solvent. For compounds such as SC-24, [2.2.2] and 18-C-6(COOH)₄ no counterion effects are observed, and the changes in ^{15}N chemical shifts and $^1\Delta\text{N(D)}$ isotope effects are now related to differences in distances and the nature of the acceptor atoms, as seen from a comparison of data for SC-24 and [2.2.2]. The variation of $^2\Delta\text{H(D)}$ is roughly proportional to δNH . Counterions only play a small role for these parameters, as seen from Fig. 4. For compounds with known geometries the short hydrogen-bond distances give rise to the low-field shifts and to more negative two-bond isotope effects, $^2\Delta\text{H(D)}$. The ^1H chemical shifts and the $^2\Delta\text{H(D)}$ isotope effects both depend on the N...X distance, X = O or N. The theoretical calculations give, for both $^1\Delta\text{N(D)}$ and $^2\Delta\text{H(D)}$, a $1/r^2$ distance dependence. Furthermore, for an N–D bond taking part in a hydrogen bond, $^1\Delta\text{N(D)}$ is decreased and $^2\Delta\text{H(D)}$ becomes negative, whereas for an N–D bond not taking part in a hydrogen bond the opposite effect is found. Qualitatively similar trends are calculated for the $\text{NH}_3\text{D}\cdots\text{NH}_3$ and the $\text{NH}_3\text{D}\cdots\text{H}_2\text{O}$ complexes.

The one-bond couplings, $^1J(\text{N, H})$, of the complexes

with cryptands and crown ethers correlate well with δH . The one-bond coupling can thus, although relatively invariable, in general be expected to be a useful parameter for detection of hydrogen bonding, provided that it can be measured accurately. In a different context, one-bond couplings of proteins are an interesting case. The $^2\Delta\text{H(D)}$ and $^1J(\text{N, H})$ parameters are very good qualitative ways of describing hydrogen bonding. Too few distance data are available to establish a quantitative correlation, although the existing data look promising. $^1\Delta\text{N(D)}$ and δN are both very useful in gauging the degree of interaction between the ammonium ion and the counterion. They are therefore a good tool to distinguish between an ion buried in a complex and ion-pairing.

Experimental

Compounds. 18-C-6, [2.2.2], [2.2.1], [2.2.1]D, [2.2]DD, K5 and 18-C-6(COOH)₄ were purchased from Merck, Darmstadt, Germany. Trifluoroacetate ammonium salt was from Aldrich, Weinheim, Germany. $^{15}\text{NH}_4\text{NO}_3$ was from Stohler Isotopes, Waltham, MA, USA.

The pH of the $^{15}\text{NH}_4\text{NO}_3$ –18-C-6(COOH)₄ solution was 1.12, and was 1.34 with iodide instead of nitrate. $^{15}\text{NH}_4\text{I}$ was prepared by Kjeldahl treatment of the nitrate and collection of the ammonia in HI. The water was then evaporated under reduced pressure until the remaining salt was white.

The ammonium compounds were deuteriated by dissolving the compounds in mixtures of H_2O and D_2O and evaporation, or complexes were occasionally deuteriated by treatment with CH_3OD and subsequent evaporation. The SC-24 complex could not be redeuteriated this way.

NMR spectroscopy. The NMR spectra were recorded on a Bruker AC 250 instrument. The ^1H NMR spectra were measured at 250 MHz in 5 mm tubes with TMS as internal reference. The spectral width was 5000 Hz and the digital resolution was 0.3 Hz/point; solvents were CDCl_3 or CD_2Cl_2 . The ^{15}N spectra were recorded at 25.35 MHz in 10 mm tubes with nitromethane as external reference. The spectra were recorded using the INEPT technique,³² with a delay of 0.003 42 s and a digital resolution of 0.49 Hz/point.

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