J. Am. Chem. Soc. **1983**, *105*, 7549–7553

first-order relativistic correction to the kinetic energy. The mass–velocity term will, as explained in ref 11, reduce the electronic kinetic energy to an increasing extent as the two W atoms approach each other. The net effect is a lowering in the total electronic energy and a shortening of the metal–metal bond. Relativistic calculations were not carried out for the Cr_2L_6 and Mo_2L_6 systems. We expect from previous experience[11] the influence to be neglibible for Cr_2L_6, and amount to an increase of ΔE_{MM} by a few kJ mol^{-1} in the case of Mo_2L_6.

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Registry No. CrH_3, 87698-70-2; $Cr(CH_3)_3$, 3047-87-8; $Cr(NH_2)_3$, 20253-28-5; $CrCl_3$, 10025-73-7; $Cr(OH)_3$, 1308-14-1; MoH_3, 87698-71-3; $Mo(CH_3)_3$, 87698-72-4; $Mo(NH_2)_3$, 87698-73-5; $MoCl_3$, 13478-18-7; $Mo(OH)_3$, 60414-57-5; Cr_2H_6, 87698-74-6; $Cr_2(CH_3)_6$, 87698-75-7; Cr_2Cl_6, 87698-76-8; $Cr_2(NH_2)_6$, 87698-77-9; $Cr_2(OH)_6$, 87698-78-0; Mo_2H_6, 83636-49-1; $Mo_2(CH_3)_6$, 73581-14-3; Mo_2Cl_6, 87698-79-1; $Mo_2(NH_2)_6$, 87711-09-9; $Mo_2(OH)_6$, 64438-94-4; W_2H_6, 87698-80-4.

Anion Coordination Chemistry. ^{35}Cl NMR Studies of Chloride Anion Cryptates

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Abstract: The chlorine NMR signals of the chloride inclusion complexes $[Cl^- \subset L{-}H_n^{n+}]$, L = **1–5**, formed by the protonated species of cryptands have been measured. In combination with proton and carbon-13 NMR data, they provide information about chloride chemical shifts, mono- and bimolecular exchange processes, and quadrupolar coupling constants χ of the chloride cryptates. Very large chemical shifts are induced by cryptate formation. The high χ values calculated indicate that appreciable field gradients are generated by the ligands at the nucleus of the bound spherical anion, due to deformation of the coordination shell from ideal symmetry. The results obtained emphasize the contribution of NMR studies of anion cryptates to the field of anion coordination chemistry.

Whereas macrocyclic complexes of cations have been the subject of intense investigation over the past decade, anion coordination chemistry, the binding of anions by organic ligands, in particular of the macrocyclic type, has only recently been recognized and developed as a new area of coordination chemistry.[3,4]

Thus, macrocyclic, macrobicyclic, and macrotricyclic polyammonium and polyguanidinium receptor molecules have been shown to complex a variety of inorganic and biological anions.[3–13] As in the case of cation complexes, physicochemical investigations should provide insight into the structure of such anion complexes and the properties of the bound anion. In this respect, direct observation of the bound species as well as of the ligand by heteronuclear NMR is a particularly powerful tool, as witnessed by numerous studies of macrocyclic cation complexes, such as alkali cryptates.[14,15]

The present work represents the first such investigation of well-defined anion complexes, the chloride cryptates of the spherical macrotricycles SC-24 (**1**), SC-25 (**2**), and SC-26 (**3**),[16] the bis(tren)macrobicycle (**4**), and the macrobicyclic diamine (**5**)[5], using ^{1}H, ^{13}C, ^{35}Cl, and ^{37}Cl NMR. The tetraprotonated forms of **1–3**, the hexaprotonated form of **4**, and the diprotonated form of **5** have been shown to bind various anions[4,5,17] in particular chloride, yielding chloride cryptates in which the substrate is located inside the intramolecular cavity and held by an array of zwitterionic hydrogen bonds, as represented schematically by structures **6** and **7** and confirmed by the crystal structures of these ($Cl^- \subset$ **1**-$4H^+$)[18] and ($Cl^- \subset$ **4**-$6H^+$)[19] cryptates. In the katapinates of macrobicyclic diammonium ions the anion is bound by

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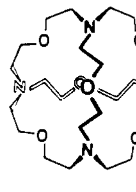

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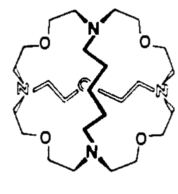

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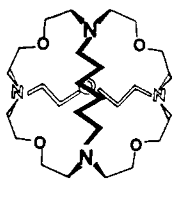

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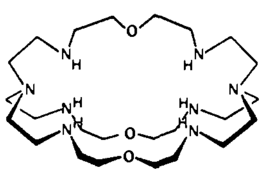

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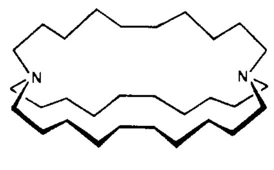

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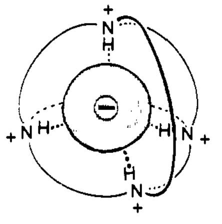
two hydrogen bonds.[5] The stability constants of the chloride cryptates have been determined by several techniques and the respective log K_s values are 4.2,[4,20,21] 4.7,[4,20,21] 2.0,[20] and 2.3[22] in aqueous solution and 2.1[20] (in methanol/water 9/1) for **1**-4H$^+$, **2**-4H$^+$, **3**-4H$^+$, **4**-6H$^+$, and **5**-2H$^+$, respectively. We report here a study of the heteronuclear NMR spectra, the chloride exchange rates, and the chloride quadrupolar coupling constants of these complexes.



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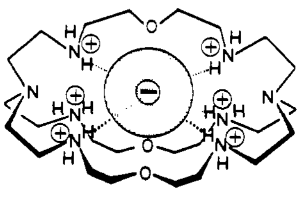
[Cl$^-$ ⊂ 1-4H$^+$]



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[Cl$^-$ ⊂ 4-6H$^+$]

Experimental Section

The synthesis of ligands **1**–**4** has been described elsewhere.[16,17] Aqueous solutions of chloride complexes of ligands **1**–**3** and **5** were obtained by dissolving the desired quantities of free ligands in 2 mL of D_2O/H_2O (1/4), adding 1 equiv of sodium chloride, and adjusting the pH with nitric acid. Solutions of [Cl$^-$ ⊂ **4**-6H$^+$] were obtained by dissolving crystalline **4**-6HCl in water. Solutions in CD_3OD/D_2O mixtures were obtained by evaporating the previously described solutions to dryness and redissolving the solid in 2 mL of the solvent mixture.

Proton NMR spectra were obtained at a frequency of 180 MHz with a Bruker WH-180 spectrometer operating in the FT mode with use of 5-mm tubes. The solutions were 3.3×10^{-3} M. For ^{13}C and ^{35}Cl nuclei, the measurements were made at 50.13 and 19.6 MHz, respectively, on a Bruker WP-200 SY spectrometer in the FT mode, in 10-mm tubes. The concentration range used was $2\text{–}5 \times 10^{-2}$ M.

Some ^{35}Cl and ^{37}Cl measurements have been done at 39.2 and 32.6 MHz on a Bruker WH 400 spectrometer. In the case of chlorine NMR at 19.6 or 16.3 MHz a long delay time was necessary (~1 ms) between the end of the pulse and the beginning of the acquisitions in order to avoid base-line deformations. At 39.2 and 32.6 MHz a special pulse sequence was used for eliminating acoustic ringing.[23] Relaxation times of ^{13}C were measured by inversion-recovery.[24] In order to avoid heating the solutions by broad-band decoupling, a two-level decoupling sequence was used. A three-parameter fit (program KINFIT[25]) of the experimental data (10 to 14 points) to the equation $M(t) = A + B \exp(-t/T_1)$ yields the ^{13}C spin–lattice relaxation time. The chlorine spin–spin relaxation time T_2 was computed from the line width at half-height W according to $T_2 = 1/\pi W$.

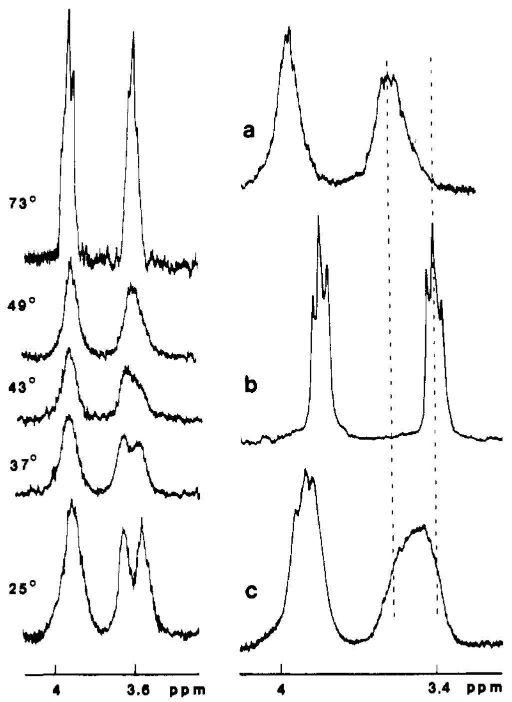

Figure 1. Proton NMR spectra (at 180 MHz) of **1**-4D$^+$ and of its chloride cryptate. (Left) Temperature dependence of the spectrum of **1**-4D$^+$, 3.3 mM in D_2O at pD 0.6. (Right) Spectra of (a) **1**-4D$^+$, (b) the complex [Cl$^-$ ⊂ **1**-4D$^+$], and (c) a 1/1 mixture of **1**-4D$^+$ and [Cl$^-$ ⊂ **1**-4D$^+$]. Concentrations 3.3 mM; pD 0.6; temperature +49 °C. Chemical shifts are given in ppm with respect to TMPS.

Results

Prototropy of 1-4D$^+$. The proton NMR spectrum of **1**-4D$^+$ at 25 °C and pD 0.6 consists of a band corresponding to the OCH_2 protons at δ 3.95 and two bands of equal intensity at 3.6 separated by 19.5 Hz corresponding to N$^+$CH_2. The two bands broaden upon heating, coalesce at 46 ± 3 °C, and form a triplet at 73 °C (Figure 1).

Completely protonated forms of **1**-4H$^+$ can exist in five different configurations, i_4, i_3o, i_2o_2, io_3, and o_4, depending on the proton positions inside or outside the cavity. The spectrum at ambient temperature suggests that the predominant form is i_2o_2.[26] Upon heating, protonation–deprotonation processes accelerate, which results in exchange of *in–out* sites and leads to the symmetrization of i_2o_2 and of other species. The free energy of activation calculated from the observed coalescence is $\Delta G^{\ddagger}_{319} = 16.3$ kcal mol^{-1} corresponding to an overall rate constant of 4 s^{-1} at 20 °C.

Rate of Chloride Exchange in 1-4D$^+$ and Contributions to the Line Width of the Cl$^-$ NMR Signals. The proton NMR spectrum of [Cl$^-$ ⊂ **1**-4D$^+$] at 25 °C and pD 0.6 consists of two triplets at δ 3.40 and 3.85 corresponding to the OCH_2 and NCH_2 protons respectively (Figure 1). The ^{1}H spectrum of a solution of **1**-4D$^+$ containing $^1/_2$ equiv of Cl$^-$ is a superposition of the spectrum of **1**-4D$^+$ and of [Cl$^-$ ⊂ **1**-4D$^+$], indicating a slow exchange according to the equilibrium

$$[\mathrm{Cl}^- \subset \mathbf{1}\text{-}4\mathrm{D}^+] + \mathbf{1}\text{-}4\mathrm{D}^+ \rightleftharpoons \mathbf{1}\text{-}4\mathrm{D}^+ + [\mathrm{Cl}^- \subset \mathbf{1}\text{-}4\mathrm{D}^+] \quad (1)$$

where, by analogy with cation cryptates, the rate-determining step

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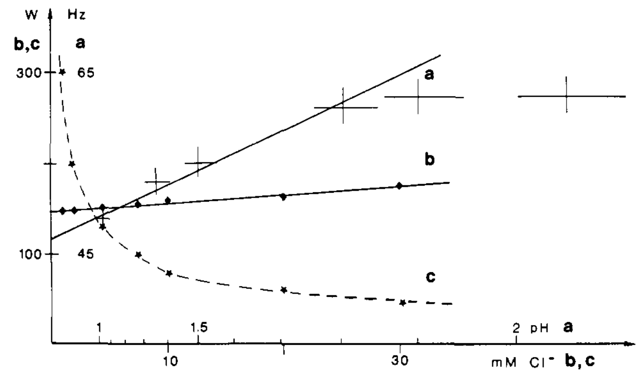

Figure 2. Line width of the ^{35}Cl NMR signals of the chloride ions in the following conditions (aqueous solutions): (curve a) signal of uncomplexed Cl$^-$ (40 mM) in the presence 0.5 equiv of [Cl$^-$ $\subset$ **1**-4H$^+$] as a function of pH, at 19.6 MHz and 20 °C; (curves b and c) signals of complexed (b) (20 mM) and uncomplexed (c) chloride as a function of uncomplexed Cl$^-$ concentration, at 39.2 MHz, pH 1.5, and 20 °C. The line widths of curves b and c have been obtained from the spectra shown in Figure 3 with use of the line width fitting subroutine of the Bruker DISNMRP software.

is probably slow monomolecular dissociation of the chloride cryptate. Upon heating, prototropy accelerates and at 49 °C a unique coalesced signal is observed for the NCH_2 protons of both species (Figure 1).

The coalescence at 49 ± 2 °C corresponds to an activation energy $\Delta G^{\ddagger}_{322} = 16.2$ kcal mol^{-1} and to a dissociation rate constant of 5 s^{-1} at 20 °C. The near equality of the rate constants for deprotonation of **1**-4D$^+$ (4 s^{-1}) and for dissociation of [Cl$^-$ $\subset$ **1**-4D$^+$] (5 s^{-1}) suggests that complex dissociation is preceeded by deprotonation. One may indeed expect that chloride exchange is markedly faster for the triprotonated cryptate [Cl$^-$ $\subset$ **1**-3H$^+$] than for the tetraprotonated one. The pH dependence of the chloride exchange rate was measured by ^{35}Cl NMR at 19.6 MHz for a 1/2 solution of [Cl$^-$ $\subset$ **1**-4H$^+$] and Cl$^-$ in H$_2$O/D$_2$O (4/1) between pH 1.05 and 2.05 by following the line width of the "free" chloride anion. In the slow exchange limit, chloride exchange between "free" and cryptated chloride sites at a rate k produces a broadening $W^e = k/\pi$. The line width W of the non-cryptated chloride is then related to the hydroxyl ion concentration in the solution through

$$W = W^0 + k_2[\mathrm{OH}^-]/\pi \tag{2}$$

where W^0 is the line width in the absence of exchange and k_2 is the second-order rate constant for base-catalyzed chloride exchange. Figure 2 shows that the line width W increases with the pH up to a value of 1.8. Since the pK_4 of **1** is equal to 2.2,[20] for pH values above 1.8 formation of substantial amounts of the triprotonated species **1**-3H$^+$ increases the amount of free chloride. From the linear portion of the curve, one calculates that at pH 0.6 the free chloride is broadened by 1 Hz corresponding to a dissociation rate of 6 s^{-1} for [Cl$^-$ $\subset$ **1**-4H$^+$]. At pH 1.5, the base-catalyzed contribution accounts for only 8 Hz for a measured width of 55 Hz.

Line-width measurements of the ^{35}Cl$^-$ and ^{37}Cl$^-$ NMR signals allow for separation of the slow exchange line width contribution W^e (W^e is the same for ^{35}Cl and ^{37}Cl) from the quadrupolar contribution $^{35}W^Q$ and $^{37}W^Q$ (the ratio $^{37}W^Q/^{35}W^Q$ is equal to the ratio of the squares of the quadrupolar moments $(e^{37}Q/e^{35}Q)^2 = 0.62$) according to eq 3 For a solution containing [Cl$^-$ $\subset$ **1**-4H$^+$]

$$^{35}W = W^e + {}^{35}W^Q \qquad {}^{37}W = W^e + {}^{37}W^Q$$
$$^{37}W/^{35}W = 0.62 \tag{3}$$

($c = 2 \times 10^{-2}$ M) and Cl$^-$ in a ratio 4/3 at pH 1.5 in H$_2$O/D$_2$O the line widths measured for ^{35}Cl$^-$ and ^{37}Cl$^-$ at 39.2 and 32.6 MHz, respectively, in the complexes (W_c) and free sites (W_f) are $^{35}W_c = 157$, $^{35}W_f = 99$; $^{37}W_c = 110$, and $^{37}W_f = 79$ Hz. Putting these values into eq 3 gives $^{35}W_c^Q = 124$ Hz, $^{35}W_f^Q = 53$ Hz, $W_c^e = 38$ Hz, and $W_f^e = 46$ Hz. The exchange contributions W_c^e and W_f^e are as expected in a 3/4 ratio, but are larger than the base-catalyzed contribution expected at this pH. This may be indicative of a bimolecular exchange process such as

$$[\mathrm{Cl}^- \subset \mathbf{1}\text{-}4\mathrm{H}^+] + \mathrm{Cl}^- \rightleftharpoons [\mathrm{Cl}^- \subset \mathbf{1}\text{-}4\mathrm{H}^+] + \mathrm{Cl}^- \tag{4}$$

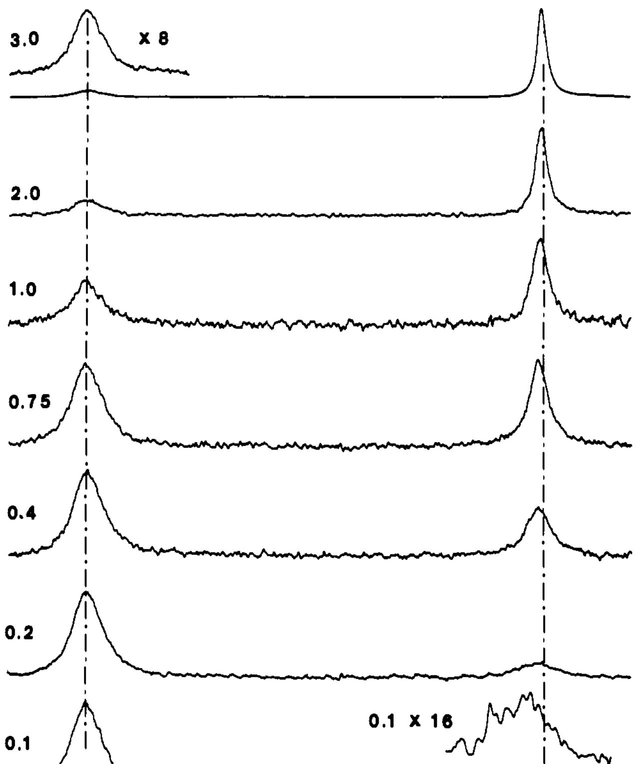

Figure 3. ^{35}Cl NMR spectra (at 39.2 MHz) of aqueous solutions of [Cl$^-$ $\subset$ **1**-4H$^+$] (20 mM) and uncomplexed Cl$^-$ as a function of the ratio of free Cl$^-$/[Cl$^-$ $\subset$ **1**-4H$^+$]; the chemical shifts are given in ppm with respect to external aqueous NaCl (0.1 M); pH 1.5, and 20 °C.

Starting from a solution of [Cl$^-$ $\subset$ **1**-4H$^+$] ($c = 2 \times 10^{-2}$ M, pH 1.5) where the cryptated chloride has a line width of 144 Hz, progressive addition of NaCl up to a ratio of free Cl$^-$/cryptated Cl$^-$ = 3 produces a broadening that is proportional to the concentration of free chloride (Figure 2b). At the point where [Cl$^-$] = [Cl$^-$ $\subset$ **1**-4H$^+$], the broadening is equal to 16 Hz, corresponding to a rate of dissociation of 50 s^{-1} for [Cl$^-$ $\subset$ ^{1}-4H$^+$] and, since [Cl$^-$] = 2 × 10^{-2} M, to a second-order rate constant of 2500 mol L^{-1} s^{-1} for bimolecular eq 4. The 160-Hz line width of ^{35}Cl in [Cl$^-$ $\subset$ **1**-4H$^+$] in the presence of 1 equiv of free chloride might then be divided into 124 Hz for the true quadrupolar line width, 16 Hz for the bimolecular chloride exchange process (eq 4)8 and 20 Hz for the base-catalyzed exchange process. Figures 2c and 3 also show the line-width variation of free chloride as the ratio of free/crypt goes from 0.1 to 3; the line width decreases from about 300 Hz to 44 Hz. At a low concentration of free Cl$^-$, the exchange contribution is dominant, and at equal concentration of [Cl$^-$ $\subset$ **1**-4H$^+$] and [Cl$^-$] the contributions to the observed line width of 80 Hz are 36 Hz for exchange broadening and 44 Hz for quadrupolar broadening. This free chloride line width is about 32 Hz larger than the width of a more concentrated 1 M NaCl solution. This extra broadening probably arises from a loose outside binding of Cl$^-$ to the cation [Cl$^-$ $\subset$ **1**-4H$^+$]$^{3+}$ or from hydrophobic interactions, since it is known that ammonium cations broaden halide resonances, at least in a concentrated solution of ammonium halides.[27,28]

Table I. ^{35}Cl NMR Parameters for Chloride Inclusion Complexes of the Protonated Forms of Ligands 1–5[a]

ligand (solvent)[b]	δ	W	T_1	χ
1-4H$^+$				
WW	52 ± 0.5	125 ± 10[c]	0.4	1.3
M/W	48.1	200 ± 10	0.33	1.5
2-4H$^+$				
W	52 ± 2	340 ± 30	0.45	2.3
M/W	51 ± 2	400 ± 40	0.32	2.1
3-4H$^+$				
M/W	25 ± 3	580	0.33	2.6
4-6H$^+$				
W	66 ± 6	2600 ± 300	0.2	4.4
5-2H$^+$				
M/W	35 ± 5	2500 ± 250[d]	0.6[d]	7.2

[a] δ = chemical shift in ppm with respect to 0.1 M aqueous NaCl as external reference; $W_{1/2}$ = chloride ion ^{35}Cl line width at half-height in Hz; T_1 = carbon-13 relaxation time of CH$_2$ groups, in seconds, measured by the inversion-recovery technique, accuracy ±5%; χ = ^{35}Cl quadrupolar coupling constant of the chloride ion in MHz, calculated by eq 7, accuracy better than ±10%. Ligand concentrations: 1-4H$^+$ (20 mM), 2-4H (50 mM), 3-4H$^+$ (50 mM), 4-6H$^+$ (25 mM), 5-2H$^+$ (25 mM). pH 1.5 for 1-4H$^+$ and 2-4H$^+$ and 3.6 for 4-6H$^+$ in aqueous solution. [b] Solvent: W = H$_2$O/D$_2$O 4/1; M/W = CD$_3$OD/D$_2$O 9/1. [c] Corrected for exchange broadening (see text). [d] Measured at 30 °C.

Rate of Chloride Ion Exchange in 4-6H$^+$. Chlorine-35 NMR of a 2.5 × 10^{-2} M aqueous solution of **4**-6HCl, at pH 3.6 and 18 °C, shows one resonance line at δ 11 ± 1 with the line width W = 460 Hz. In view of its pK_a values,[7] **4** exists as the hexaprotonated form at this pH.

Between 18 and 80 °C the line width decreases linearly as a function of $1/T$, indicating that the chloride exchange is rapid and that there is no exchange contribution to the line width. The stability constant of [Cl$^-$ $\subset$ ^{4}-6H$^+$] is sufficiently high so that **4**-6H$^+$ is completely complexed and 5/6 of the total chloride ions are free. The line width of ^{35}Cl at the *complexed* site may therefore be estimated to be about 2600 Hz.[29]

Determination of the Quadrupolar Coupling Constant of Chlorine. Since the quadrupolar relaxation mechanism is expected to be dominant for the nuclei of chloride ions, the line width at half-height is related to the quadrupolar coupling constant χ by

$$W = \frac{2\pi}{5}\chi^2\tau_q \tag{5}$$

where τ_q is the correlation time describing the fluctuation of the electrical field gradient. Thus, χ may be calculated if τ_q can be determined independently. This is possible by employing the double nuclear spin probe method[15,30,31] which asumes that in first approximation, the quadrupolar correlation time τ_q may be approximated by the correlstion time τ_c calculated from the relaxation time of a dipolar nucleus belonging to the same molecule or complex, in the absence of fast internal motions.

Since the Cl$^-$ ion is confined in the cryptand cavity, τ_q for Cl$^-$ may be equated with the average correlation time τ_c obtained from the ^{13}C relaxation times T_1 of the ligand by using the relationship[15]

$$1/T_1 = (4.4 \times 10^{10})\tau_c \tag{6}$$

where T_1 is the relaxation time of the CH$_2$ carbon-13 nuclei, and the bond length is taken to be 1.085 Å.

The combination of eq 5 and 6 gives

$$\chi = ((3.5 \times 10^{10})T_1W)^{1/2} \tag{7}$$

The W values for the complexed Cl$^-$ ion, the T_1 values, as well as the values of χ for the different environment of Cl$^-$ calculated from these data are listed in Table I.

Discussion

Chloride Chemical Shifts of Chloride Cryptates. The chloride chemical shifts in aqueous solution of alkali or ammonium chloride salts are well documented.[27] The ammonium cation produces a deshielding,[32] and the greatest reported shift is a deshielding of 32 ppm for a 8 M solution of CsCl.[33] This limit is considerably extended by the present data (Table I), up to a shift of 66 ppm for the chloride ion in the [Cl$^-$ $\subset$ **4-6H**$^+$] cryptate. As for other chloride resonances, the chemical shift is dependent on the proton to deuterium ratio;[32,34] an isotopic shift of −4 ppm is measured for [Cl$^-$ $\subset$ **1-4X**$^+$] (X = H or D) between a 4/1 H$_2$O/D$_2$O solution and a pure D$_2$O solution.

The chloride ion held in a tetrahedral arrangement of $^+$N–H···Cl$^-$ hydrogen bonds of 3.09-Å length[18] in the cavity of **1-4H**$^+$ is deshielded by 52 ppm. For the complex [Cl$^-$ $\subset$ **4-6H**$^+$] with six $^+$N–H···Cl$^-$ hydrogen bonds of 3.29 Å,[19] the deshielding is 66 ppm. The binding pattern of the other cryptates is not known, but for **2-4H**$^+$ it should be nearly the same as for **1-4H**$^+$, and as expected, the same chemical shift is measured. These results suggest that the chemical shifts are dependent upon the number and the length of the hydrogen bonds formed, but considering the δ values for the cryptates [Cl$^-$ $\subset$ **3-4H**$^+$] and [Cl$^-$ $\subset$ **5-2H**$^+$] it confirms that the relation is not simple.

Whereas chloride shifts are solvent dependent for electrolyte solutions,[35] the chemical shifts measured for cryptated chloride are the same in water or in methanol/water 9/1. This reflects the shielding of the anion from the environment which results from the inclusive nature of the complexes and represents an aspect of the "cryptate effect" already well documented for cation cryptates (see ref 36 and references therein).

Chloride Quadrupolar Coupling Constants (QCC) in Chloride Cryptates. The quadrupolar coupling constants χ of the chloride ion (Table I) have values ranging from 1.4 MHz for [Cl$^-$ $\subset$ **1-4H**$^+$] to 7.2 MHz for [Cl$^-$ $\subset$ **5-2H**$^+$]. For chloride bound to proteins, the measured values of χ are in the range 0.6 to 15.6 MHz.[37]

A strictly tetrahedral arrangement of the $^+$N–H bonds together with an octahedral arrangement of the O atoms of ligand **1-4H**$^+$ around the chloride ion cannot result in a permanent field gradient. The value of 1.4 MHz found in this work for [Cl$^-$ $\subset$ **1-4H**$^+$] in water and in methanol can only result from the deformation of the cavity from a regular tetrahedron of hydrogen bonds just as in the case of the NH$_4$$^+$ ion enclosed in **1**.[38] Taking into account the present values of the nuclear quadrupolar moments of ^{35}Cl and ^{14}N one calculates that the field gradient experienced by the ^{35}Cl nucleus of chloride in the cavity of **1-4H**$^+$ is 280 times greater than that of the ^{14}N nucleus of $^+$NH$_4$ in the cavity of **1**.[38] After correction of this ratio through the respective ratio o the Sternheimer factor of chloride (γ_∞ = −60)[39] and ammonium (γ_∞ =

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–4),[40] it appears that the field gradient created at the center of the cavity of **1**-4H$^+$ is about 19 times greater than that at the center of the cavity of **1**. For the cryptates **2** and **3** where a tetrahedral arrangement of $^+$N–H$\cdots$Cl$^-$ is also formed, the χ value increases slightly as the symmetry of the ligand is reduced.

For the cryptated chloride in **4**-6H$^+$, the environment is an octahedral arrangement of the $^+$N–H bonds and a trigonal bipyramid of three oxygens and two nitrogen atoms.[19] The χ value increases to 4.4 MHz. Finally for **5**-2H$^+$ where the bonding pattern, by analogy with the X-ray structure of an other katapinate,[5] is reduced to two $^+$N–H$\cdots$Cl bonds, a χ value of 7.2 MHz is reached. From this series of χ values it appears that the QCC of cryptated chloride is controlled by the symmetry of the environment and that small differences in the $^+$N–H$\cdots$Cl$^-$ bond length suffice to create appreciable field gradients. The classical electrostatic model of quadrupolar interaction[41] predicts a $1/r^5$ relation between the values of the field gradient and the distance between the nucleus and the fluctuating dipole, that is a doubling of χ when two dipole–nucleus distances differ by about 15%. This model predicts quite nicely the behavior of aquo halide ions[42] where the distances are equal to or greater than the sum of van der Waals radii, but it fails here where some of the $^+$N–H$\cdots$Cl$^-$ distances as in [Cl$^-$ $\subset$ **1**-4H$^+$][18] and [Cl$^-$ $\subset$ **4**-6H$^+$][19] are smaller than the sum of the ionic radii of Cl$^-$ (1.81 Å)[43] and $^+$NH$_4$ (1.48 Å).[43]

A theory of chemical shifts of spherical ions predicts a linear relation between δ and χ values.[44] Such a relation has been found experimentally for ^{23}Na NMR on sodium cryptates[45] and also for other sodium complexes.[46] No correlation is found here between the deshielding of ^{35}Cl and the increasing value of χ. A possible explanation for this discrepancy might be that ^{23}Na parameters are much less sensitive than ^{35}Cl parameters to the modification of the coordination sphere.

Conclusion

Cryptate complexes allow physicochemical studies to be performed on substrates bound in a well-defined, "frozen" coordination shell. Various earlier studies have taken advantage of this feature for cationic substrates. The present results give insight into the properties of bound chloride anions and emphasize the contributions which the well-defined anion cryptates may bring to the study of the general phenomenon of anion coordination to receptor molecules of either chemical or biological nature.

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Registry No. **1**-4H$^+$Cl$^-$, 61136-83-2; **2**-4H$^+$Cl$^-$, 61136-87-6; **3**-4H$^+$Cl$^-$, 87585-87-3; **4**-6H$^+$Cl, 87585-88-4; **5**-2H$^+$Cl$^-$, 61136-91-2.

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Origin of Asymmetry in Nitrogen Hyperfine Interactions in Metmyoglobin

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Abstract: The aim of this study was to investigate possible sources that could explain the experimentally observed differences in the electron–nuclear hyperfine interactions from diagonally opposite nitrogens of heme in metmyoglobin. The Self-Consistent-Charge-Extended Hückel (SCCEH) technique was used to investigate the perturbation on heme nitrogen electron spin densities from two possible sources: First, the direct electronic orbital influence of the side chains attached to pyrrole rings was found to provide a difference in ^{14}N hyperfine couplings substantially smaller than that found by experiment. This conclusion is unchanged even when one changes the orientation of the vinyl group or the charge on the propionic acid side chains. Second, the effect on nitrogen hyperfine couplings from small distortions in the position of diagonally opposite nitrogens was investigated. The relative hyperfine couplings of diagonally opposite nitrogens were found to be strongly influenced by differences in pyrrole Fe–N bond distances. A difference of 0.018 Å between Fe–N bond distances corresponding to diagonally opposite nitrogens was sufficient to explain the difference in hyperfine couplings. Such a distortion in geometry appears to involve only a small energy of the order of 100 cal/mol and could arise out of small differences in heme–protein interactions associated with diagonally opposite pyrrole rings. Thus, while one cannot rule out other possible causes, a difference in Fe–N bond distances does appear to be a plausible source for the origin of the observed difference in ^{14}N hyperfine interactions in metmyoglobin.

Recent ENDOR experiments[1]on aquometmyoglobin single crystals have shown that the hyperfine couplings of diagonally opposite pyrrole nitrogens are significantly different from each other. Earlier theoretical investigations[2-5] of high-spin heme systems have provided overall explanations of both the absolute values and trends in experimentally observed hyperfine couplings[6-8] at ^{57}Fe, ^{14}N, and ^{1}H nuclei among different heme derivatives, such as between different halogen-substituted five-liganded heme

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