formula unit could enter the channels. The introduction of this new atom in the structure did not open any gaps in the total density of states, and the new material should still be metallic.

Acknowledgment. M.J.C. is grateful to the Calouste Gulbenkian Foundation for its support of her stay at Cornell. M.J.C. also thanks Marja Zonnevylle and Jing Li for sharing their expertise and for helpful discussions. Our work was supported by the National Science Foundation, Grant DMR 821722. We thank Jane Jorgensen and Elisabeth Fields for the drawings and Joyce Barrows for the production of the manuscript.

Appendix

All of the calculations were of the extended Hückel type,[9] with the tight-binding approach.[10] The parameters used are collected in Table IV.

The geometry of $Ni_2Ta_9S_6$[1,2] was used as the undistorted structure. In the study of distortion the same unit cell parameters a and $c' = 2c$ were taken, but the general positions of the atoms in $Fe_2Ta_9S_6$ were used.

The k-point sets were chosen according to the size of the unit cell, using the method of Ramirez and Böhm.[19]

Registry No. $Fe_2Ta_9S_6$, 101238-71-5; $Co_2Ta_9S_6$, 101238-67-9; $Ni_2Ta_9S_6$, 101238-83-9; S, 7704-34-9.

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Multinuclear NMR Study of Lanthanide(III) Complexes of Diethylenetriaminepentaacetate

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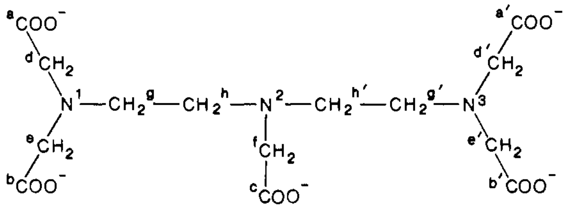
The complexation of lanthanide(III) cations with diethylenetriaminepentaacetate (DTPA) in the presence of lithium as counterion in aqueous solution has been investigated with the use of ^{13}C, ^{17}O, and ^{6}Li NMR shift and relaxation measurements. The data show that the DTPA ligand is bound octadentately via the three nitrogens and the five carboxylates. Conformational interconversions, taking place in the DTPA ligand, give rise to exchange broadening in the ^{13}C and ^{1}H NMR spectra. The first coordination sphere is completed by one water, while two lithium counterions are present in the second coordination sphere. The counterions are probably exchanging between the various carboxylate groups.

Introduction

The paramagnetic lanthanide(III) ions have a pronounced influence on the chemical shifts and relaxation rates of nuclei in their proximity.[1-3] The enhancement of longitudinal and transverse relaxation rates by, particularly, Gd^{III} has been successfully applied to improve contrast in magnetic resonance imaging. In order to reduce its toxicity, the Gd^{III} in contrast agents is bound by a very strong chelator such as diethylenetriaminepentaacetate (DTPA).[4,5]



The X-ray crystal structure determinations of $Na_2Gd(DTPA)\cdot H_2O$[6] and $BaNd(DTPA)\cdot 3H_2O$[7] revealed that in the solid state the Ln^{III} cation is coordinated to the three nitrogens and five carboxylate oxygens of DTPA and to a water. Several studies of the coordination of DTPA by Ln^{III} cations have been reported. Both hepta-[8,9] and octadentate structures[10,11] have been proposed for the DTPA ligand, and it has been shown that in solution one water is coordinated to the Ln^{III} cation.[10,12,13]

This paper reports the results of a multinuclear NMR study on the structure of Ln^{III}–DTPA complexes in aqueous solution. Chemical shifts and Nd^{III}-induced ^{13}C relaxation rate enhancements were used to determine the denticity of the DTPA ligand and to obtain information on its structure, whereas Ln^{III}-induced ^{17}O water shifts were employed to determine the water coordination number. In order to get an impression about the location of the monovalent counterions near the negatively charged Ln^{III}–DTPA complex, ^{6}Li NMR techniques were applied.

Experimental Section

The $LnCl_3\cdot xH_2O$ salts were purchased from Alfa Products. The Ln^{III} content was determined by an EDTA titration using arsenazo I as the indicator. The DTPA used was obtained as the acid ($H_5(DTPA)$) from Fluka A.G. The solutions used in this study were prepared by dissolving $H_5(DTPA)$ in a solution of an equivalent amount of LiOH in D_2O. Then the Ln^{III} salt was added, and the pD was adjusted with DCl or LiOH in D_2O.

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Table I. ^{13}C NMR Shifts[a] of $Ln(DTPA)^{2-}$ Complexes in D_2O[b] at pD 7 and 73 °C[c]

Ln	C(a,a′)	C(b,b′)	C(c)	C(d,d′)	C(e,e′)	C(f)	C(g,g′)	C(h,h′)
La	181.60	182.32	182.12	64.87	64.87	66.57	59.11	57.71
Ce	193.56	186.81	170.16	72.92	80.49	53.17	46.06	36.10
Pr	201.73	185.45	166.25	74.92	89.07	45.99	30.18	13.45
Nd	180.28	180.86	168.97	65.69	68.64	52.88	32.60	24.59
Sm	187.59	187.59	187.79	70.23	69.16	66.69	58.23	56.68
Eu	184.33	183.33	203.84	69.72	70.71	96.07	99.48	114.82
Tb	336	287	18	218	327	~0	~0	-151
Lu	181.86	182.46	181.48	65.01	65.01	65.69	59.61	57.70

[a] In ppm; internal standard *tert*-butyl alcohol (CH_3: 31.20 ppm). [b] Measured from samples obtained upon adding Ln^{III} to a 0.13 M solution of $Li_5(DTPA)$ in D_2O; $\rho = 0.7$. [c] The assignments of the signals are described in the section "Lanthanide-Induced ^{13}C NMR Shifts". Those of the ^{13}C nuclei of the terminal acetate groups might be interchanged. This assignment is leading to the optimum fit between observed and calculated *G* values (see text).

All NMR spectra were recorded with a Nicolet NT-200WB spectrometer using 12-mm sample tubes. The ^{17}O NMR spectra were measured by using 4K data points, 10-kHz spectral width, and a repetition rate of 205 ms. Usually 1000 transients were needed to obtain a good signal-to-noise ratio. The chemical shifts (^{17}O) were determined by fitting the signal with a Lorenzian line function. The ^{17}O chemical shifts were determined with respect to D_2O as external standard, and the ^6Li chemical shifts, with respect to 5 M LiCl in D_2O as external standard. For ^{13}C and ^1H NMR, *tert*-butyl alcohol was used as internal standard (31.2 and 1.20 ppm, respectively). Downfield induced shifts are denoted as positive.

Longitudinal relaxation rates were measured by using a $[(90°_x180°_y90°_x)–\tau–90°–acq]$ inversion recovery pulse sequence. The $1/T_1$ values were calculated by using a three-parameter fit of the experimental data.[14] The transverse relaxation rates were calculated from the line widths at half-height by way of the relation $1/T_2 = \pi\Delta\nu_{1/2}$. These line widths were determined by fitting the NMR signals with a Lorenzian line function.

For the Nd^{III}–DTPA complexes it was established that the ^{13}C NMR spectra were invariant in the range pH 3–9. At pH <3, the exchange between free and Nd^{III}-bound ligand becomes fast on the ^{13}C NMR time scale, probably as the result of proton-catalyzed dissociation–association.[15]

Results and Discussion

Exchange Phenomena in the ^{13}C and ^1H NMR Spectra. The ^{13}C NMR spectra of solutions of a paramagnetic Ln^{III} cation and $Li_5(DTPA)$ in a molar ratio (ρ) of 0.7 at pD 7 and room temperature exhibited broad and featureless signals for the Ln^{III}–DTPA complex, whereas the signals for the free ligand were always sharp. Increasing the temperature to 73 °C resulted in an appreciable sharpening of the signals for most of the Ln^{III}–DTPA complexes. At this temperature, the Ce → Eu complexes showed three carboxylate signals with an integral ratio of 2:2:1 and five methylene signals with an integral ratio of 2:2:2:2:1 (see Table I). The spectra for Ln = Tb → Yb were still rather broad, which precluded an unambiguous determination of the peak positions. Therefore, these spectra were not taken into consideration. For the Gd^{III}–DTPA complex no spectrum could be observed, probably due to severe line broadening. The ^{13}C NMR spectra of the diamagnetic La^{III}– and Lu^{III}–DTPA complexes showed seven sharp resonances (with an integral ratio of 2:2:1:2:4:2:1), which is in agreement with previous observations of Choppin et al.[8]

The broadening of the signals of the paramagnetic complexes cannot be attributed to exchange of DTPA between the complex and the free ligand, since broadening was not observed in the signals of the free ligand. The exchange between the complex and the free ligand is slow with respect to the NMR time scale, as should be expected from the very high stability constants of these complexes ($\log \beta_1 = 18.23–21.15$)[16] and from the results of kinetic studies.[15]

The extreme line broadening of the Gd complex can be ascribed to the large Gd^{III}-induced relaxation rate enhancements due to the relatively long electronic relaxation times of Gd^{III}.[17] The temperature-dependent line broadening in the spectra of the other paramagnetic Ln^{III} complexes, however, can only be explained by exchange phenomena related to the conformational mobility of the DTPA ligand.[18] Apparently, as a consequence of the proximity of the paramagnetic ion, the ^{13}C chemical shift differences of the conformers are increased compared to those in the diamagnetic complexes.

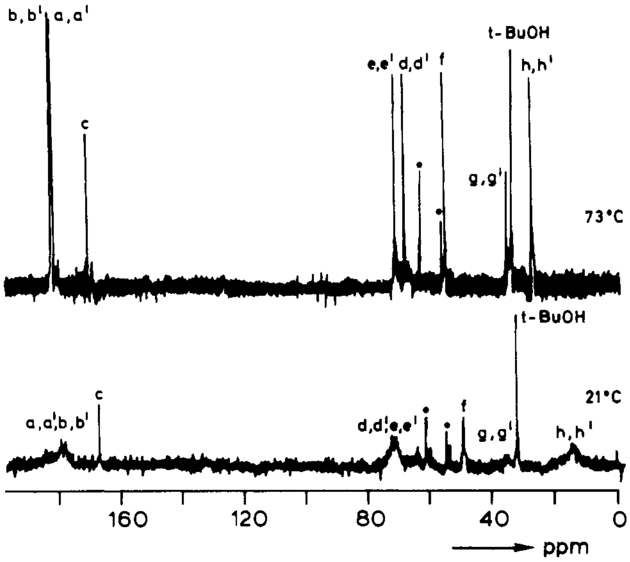

Figure 1. Influence of the temperature on the ^{13}C NMR spectrum of $Li_5(DTPA)$ and Nd^{III} ($\rho = 0.7$) in D_2O at pD 7. The signals of the free ligand are labeled with an asterisk.

An inspection of the X-ray crystal structures[6,7] and of molecular models shows that the possible structures of the $Ln(DTPA)^{2-}$ complex have very low symmetry. For the static situation, therefore, 14 ^{13}C signals should be expected upon increasing the dispersion of the chemical shifts under the influence of a paramagnetic Ln^{III} cation. The number of signals observed (8) and their integral ratios indicate that the exchange phenomena result in an effective mirror plane through the middle nitrogen atom (N(2)), C(f), and C(c) for the averaged situation. The signals of the nuclei in the effective mirror plane were always relatively sharp. A variable-temperature study of the $Nd(DTPA)^{2-}$ complex showed that all ^{13}C signals, except those of C(f) and C(c) broaden extensively upon lowering the temperature (see Figure 1). It

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(18) The line broadening upon decrease of the temperature (Figure 1) cannot be ascribed to the Curie spin relaxation mechanism. This mechanism would lead to a broadening by a factor of 1.4, which is negligible in comparison to the observed line broadening. In addition, it may be noted that the Curie spin relaxation mechanism is important only when T_{1e} is at least 4 orders of magnitude shorter than the rotational correlation time τ_R (see: Vega, A.; Fiat, D. *Mol. Phys.* **1976**, *31*, 347), which is certainly not true for a small molecule like the Ln–DTPA complex. From the longitudinal relaxation rates in the diamagnetic La complex (see below), τ_R can be estimated to be ca. 4×10^{-11} s, whereas for the paramagnetic lanthanides, except for Gd^{III}, T_{1e} is ca. 10^{-13} s.[10]

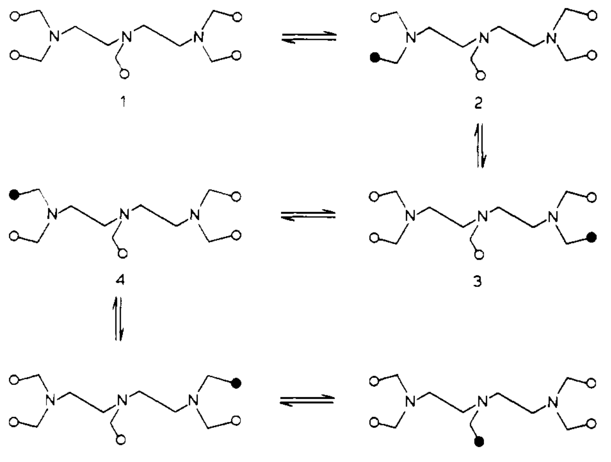

Figure 2. Schematic representation of the modes of coordination of the DTPA ligand in Ln(DTPA)$^{2-}$ complexes. ○ is a carboxylate group that is bound with one of its oxygens to the Ln^{III} cation; ● is an unbound carboxylate group. The nitrogens are always bound to the Ln^{III} cation.

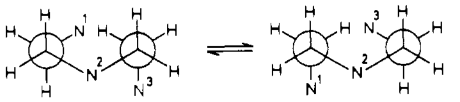

Figure 3. Conformational interconversion in the diethylenetriamine backbone of Ln(DTPA)$^{2-}$ complexes.

should be noted that the exchange broadening in the signals for C(g) and C(h) is relatively large.

The ^{1}H NMR spectra of the diamagnetic La^{III} and Lu^{III} complexes, reported by Choppin et al.,[8] are also in agreement with a "time-averaged" mirror plane through the middle glycine unit; the methylene protons of the terminal acetate groups give rise to two AB systems, whereas for those of the middle acetate a singlet is observed. We have measured the ^{1}H NMR spectra of the paramagnetic Ln(DTPA)$^{2-}$ complexes. Once again, exchange broadening was observed, as already reported by Alsaadi et al.[10] The Ln^{III}-induced ^{1}H shifts were very large with respect to the chemical shifts. Consequently, an unambiguous assignment of the ^{1}H signals is very difficult and probably will require correlation of ^{13}C and ^{1}H shifts, which was not attempted. The number of signals observed was always 9 or less, which again confirms the presence of an effective mirror plane in the time-averaged situation of the ligand.

It may be noted that rather similar exchange phenomena were observed by Desreux and Loncin in the NMR spectra of the lanthanide complexes of the 14-membered macrocycle TETA (1,4,8,11-tetraazacyclotetradecane).[19]

On the basis of the thermodynamic properties,[16] only hepta- and octadentate binding of the DTPA ligand needs to be taken into consideration. The anisochronism of C(a,a′) and C(b,b′) and of C(d,d′) and C(e,e′) indicates that the nitrogen atoms are coordinated to the Ln^{III} cation, which precludes inversion.[20-22] Then, essentially six modes of coordination are possible, which are presented schematically in Figure 2. In the X-ray structure,[6,7] which has coordination mode **1**, two different staggered ethane conformations occur on both sides of the middle nitrogen atom (see Figure 3). It seems likely that a wagging between these two conformations takes place in solution, which makes corresponding nuclei on both sides of the ligand molecule with respect to the pseudomirror plane through N(2), C(f), and C(c) isochronous.[23] Obviously analogous interconversions can occur in **2**–**6**. If, however, there were a rapid equilibrium involving structures **2**–**6**, in which one of the carboxylate groups is not coordinated to the Ln^{III} cation, then each of the carboxylate groups would exchange between sites with large differences in orientation with respect to the Ln^{III} cation. For the paramagnetic ions, the induced shifts for these locations would differ significantly, and accordingly, substantial exchange broadening should be expected for all carboxylate ^{13}C signals. The exchange broadening of these signals, however, appeared to be less than those of the ^{13}C nuclei of the diethylenetriamine backbone. Therefore, on the basis of the exchange phenomena, it is not likely that **2**–**5** play a role. Since the broadening of the signals for the middle acetate group is very small, it is inferred that DTPA is bound in either mode **1** or mode **6**.

Table II. Nd^{III}-Induced ^{13}C Relaxation Rate Enhancements[a] and Nd^{III}–C Distances in Nd(DTPA)$^{2-}$

nucleus	$1/T_1$,[b] s^{-1}	$1/T_2$,[c] s^{-1}	Nd^{III}–C dist from $1/T_1$,[d] Å	Nd^{III}–C dist in X-ray structure,[e] Å
a,a′	5.99	27.27	3.20	3.30
b,b′	6.53	20.20	3.15	3.37
c	6.35	14.60	3.17	3.32
g,g′	5.89	209.47	3.21	3.57
h,h′	3.61	88.22	3.48	3.57

[a] Measured with a sample obtained upon adding Nd^{III} to a 0.13 M solution of Li$_5$(DTPA) in D$_2$O; ρ = 0.9, pD 7.8, temperature 73 °C. [b] Corrected for diamagnetic contributions by subtracting the corresponding relaxation rates of La(DTPA)$^{2-}$ (0.05, 0.05, 0.06, 1.55, 1.61 s^{-1}, respectively). [c] Calculated from line widths at half-height. [d] Calculated from the $1/T_1$ values and eq 3, assuming $T_{1e} = 0.9 \times 10^{-13}$ s. [e] Data from ref 7; averaged values for nuclei indicated.

Nd^{III}-Induced Relaxation Rate Enhancements. Among the Ln^{III} cations, Gd^{III} has the longest electronic relaxation times, and therefore that ion is often the ion of choice in studies of geometries by use of relaxation rate enhancements.[24] This is, however, restricted to cases where the exchange of the ligand nuclei between the free and the bound state is fast with respect to the NMR time scale. When the exchange is slow, as with the DTPA complex, the signals of the Gd complex are not observable, due to the excessive line widths. In the present case, the relaxation rates were measured in the Nd^{III} complex, since Nd^{III} has the longest electronic relaxation times of the lighter Ln^{III} ions (Ce → Eu).[25]

The exchange between free and Nd^{III}-bound DTPA is negligible, whereas at 73 °C the exchange between the various conformers of the Nd(DTPA)$^{2-}$ complex is fast on the NMR time scale. Assuming that there are two conformers A and B, the observed longitudinal ($1/T_{1\text{obs}}$) and transverse ($1/T_{2\text{obs}}$) relaxation rates are then given by[26,27]

$$1/T_{1\text{obs}} = f_A/T_{1A} + f_B/T_{1B} \tag{1}$$

$$1/T_{2\text{obs}} = f_A/T_{2A} + f_B/T_{2B} + f_A f_B \tau_{AB}(\Delta\omega_{AB})^2 \tag{2}$$

where T_{1A}, T_{1B}, T_{2A}, and T_{2B} are intrinsic relaxation times in the absence of exchange, f_A and f_B are the molar fractions of the conformers, τ_{AB} is the rate of equilibration between the conformers, and $\Delta\omega_{AB}$ is the difference in resonance frequency of the nucleus under consideration between the two conformers. For exchange between more than two species, analogous expressions can be derived. For each conformation the relaxation rate is related to the structure via the reduced Solomon–Bloembergen equation:[17,18,28]

$$1/T_1 = {}^4\!/_3(\mu_0/4\pi)^2(\mu^2\gamma^2\beta^2 T_{1e}/r^6) \tag{3}$$

Here $\mu_0/4\pi$ is the magnitude permeability under vacuum, μ is

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(22) The same conclusion has been reached by Choppin et al.[8] on the basis of ^{1}H NMR spectral data for the La(DTPA)$^{2-}$ and Lu(DTPA)$^{2-}$ complexes.

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the magnetic moment, γ is the magnetogyric ratio, β is the Bohr magneton, and T_{1e} is the electron spin relaxation time. The latter is shown to be rather independent of the ligation of the Ln^{III} cation.[10,25,29]

The relaxation rate enhancements were determined for the carboxylate carbons and for the carbons of the diethylenetriamine backbone. The signals of the other nuclei were too close to each other or to signals of the free ligand to allow for accurate relaxation measurements. The relaxation rates obtained are given in Table II. These rates were corrected for any diamagnetic contributions by using the corresponding relaxation rates of the diamagnetic $La(DTPA)^{2-}$ complex. The magnitudes of the various longitudinal relaxation rate enhancements are the same. Therefore, it can be concluded that the distances between the various ^{13}C nuclei and Nd^{III} are about the same, which excludes coordination mode **6** (see Figure 2) and leaves **1** as the most abundant species in solution. By use of the data reported by Alsaadi et al.,[10,25] T_{1e} for Nd^{III} complexes at 73 °C is estimated to be 0.9×10^{-13} s. Then, with the use of the observed relaxation rate enhancements and eq 3, the distances between the various ^{13}C nuclei in DTPA and Nd^{III} can be calculated to be 3.2–3.5 Å (see Table II), which is in good agreement with the distances in the solid-state structure[7] that also has coordination mode **1**.

The transverse relaxation rates ($1/T_2$) (see Table II) of the $Nd(DTPA)^{2-}$ complex are much larger than the longitudinal ones ($1/T_1$), which confirms that the line broadening observed in the ^{13}C spectra must be ascribed to exchange phenomena. It should be noted that the difference is the largest for the nuclei in the diethylenetriamine backbone.

Lanthanide-Induced ^{13}C NMR Shifts. The ^{13}C chemical shifts of the paramagnetic $Ln(DTPA)^{2-}$ complexes, with respect to the diamagnetic analogues $La(DTPA)^{2-}$ and $Lu(DTPA)^{2-}$, Δ, are a combination of contact (Δ_c) and pseudocontact shifts (Δ_p). The contact contribution results from a through-bond transmission of unpaired spin density of the Ln^{III} cation to the nucleus in question, whereas the pseudocontact shift arises from a through-space dipolar interaction between the magnetic moments of the unpaired electrons of the Ln^{III} cations and the nucleus under study. Both Δ_c and Δ_p can be written as the product of a term that is characteristic of the Ln^{III} cation but independent of the ligand ($\langle S_z \rangle$ and k, respectively) and a second term that is characteristic of the ligand nucleus under study but independent of the Ln^{III} cation (F and G, respectively):

$$\Delta = \Delta_c + \Delta_p = \langle S_z \rangle F + kG \qquad (4)$$

Calculated values of $\langle S_z \rangle$ and k have been tabulated in the literature.[30–32] The parameter F describes the relative contact interaction for each ligand nucleus, and G is related to its orientation with respect to the Ln^{III} cation according to eq 5.[30] Here

$$G = C\frac{3\cos^2\theta - 1}{r^3} + C'\frac{\sin^2\theta\cos 2\phi}{r^3} \qquad (5)$$

r, θ, and ϕ are the spherical coordinates of the observed nucleus with respect to Ln^{III} at the origin and with the principal magnetic axis as the z axis. For axially symmetric complexes $C' = 0$. Internal reorientations in the complex may result in effective axial symmetry.[33,34] When the various lanthanide complexes are isostructural, eq 4 can be rearranged into two linear forms:[35–37]

$$\Delta/\langle S_z \rangle = F + kG/\langle S_z \rangle \qquad (6)$$

$$\Delta/k = \langle S_z \rangle F/k + G \qquad (7)$$

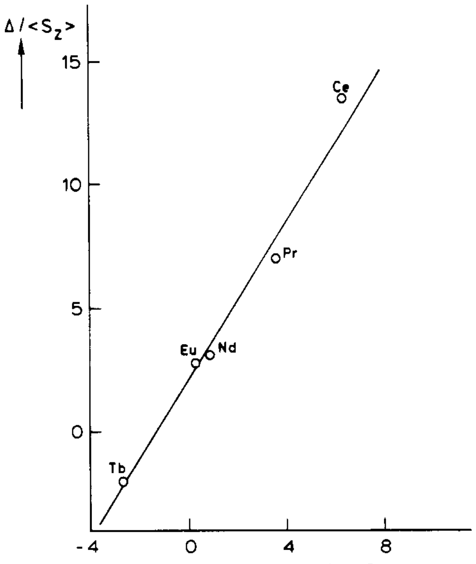

Figure 4. Plot of $\Delta/\langle S_z \rangle$ versus $k/\langle S_z \rangle$ for nucleus C(f) in the Ln–DTPA complex at 73 °C.

Table III. Values of F and G for $Ln(DTPA)^{2-}$ Complexes in D_2O (73 °C)

nucleus	F_{exp}	G_{exp}	G_{calc}[a]
a,a′	1.15	−2.18	−2.88
b,b′	0.37	−0.51	−1.16
c	1.64	1.18	0.76
d,d′	0.96	−1.31	−1.39
e,e′	1.56	−2.75	−2.23
f	2.17	1.42	1.73
g,g′	3.27	1.83	1.20
h,h′	4.35	2.94	2.53

[a] Computed by using the geometry of the X-ray structure of $Nd(DTPA)^{2-}$[7] (see text); angle N(2)–Nd–x axis = 47°, angle C(f)–N–Nd–x axis = 79°; C/C' = 1.9.

Sherry et al. have pointed out that this can be applied for both axial and nonaxial complexes, as long as C, C', and the geometric factors are invariant along the lanthanide series.[38]

The ^{13}C signals of C(c) and C(f) of the $Ln(DTPA)^{2-}$ complexes (Ln = La → Eu) could be assigned unambiguously from their intensities. After subtracting the corresponding chemical shifts of the diamagnetic $La(DTPA)^{2-}$ complex, a plot according to eq 6 or 7, indeed gave straight lines (see Figure 4). Then the other corresponding ^{13}C signals of the various $Ln(DTPA)^{2-}$ complexes could be correlated by plotting their Δ values according to eq 6 and eq 7. These signals could be assigned to carboxylate, acetate methylene, and diethylenetriamine methylene carbons on the basis of their chemical shifts.

In the next step the contact and pseudocontact shifts were separated, by using a procedure described previously,[39] to yield the F and G values given in Table III. The G values obtained were fitted with G values calculated with the use of eq 5 and the X-ray structure of $Nd(DTPA)^{2-}$[7] by varying the orientation of the magnetic axes and the ratio of C/C'. The calculated G values of nuclei, which are symmetry-related with respect to the effective mirror plane, were averaged before the comparison with the experimental ones. This procedure was repeated for the various signal assignments still possible. Only a moderate fit between the calculated and the experimental G values could be attained (see Table III). Interchange of the assignments of a,a′ and b,b′ and of d,d′ and e,e′ had no essential influence on the goodness of the fit. Interchanging the assignments of g,g′ and h,h′, however,

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Table IV. Lanthanide-Induced Water ^{17}O Shifts and ^6Li Shifts (ppm) for Ln^{III}-DTPA-D_2O Complexes with Li^I as Counterion in D_2O at pD 7 and 73 °C

Ln^{III}	$^{17}O^a$	$^6Li^b$	Ln^{III}	$^{17}O^a$	$^6Li^b$
La	152	0.15	Tb	-2144	2.81
Ce	247	0.20	Dy	-1983	2.93
Pr	305	0.51	Ho	-1232	1.90
Nd	452	0.53	Er	-520	-0.51
Sm	99	0.13	Tm	177	-0.91
Eu	-304	-0.03	Yb	155	-0.07
Gd	-1634	0.06	Lu	279	0.03

[a] Shifts extrapolated to a molar ratio of Ln^{III}/water = 1. [b] Shifts extrapolated to a molar ratio of Ln^{III}/Li^I = 0.5.

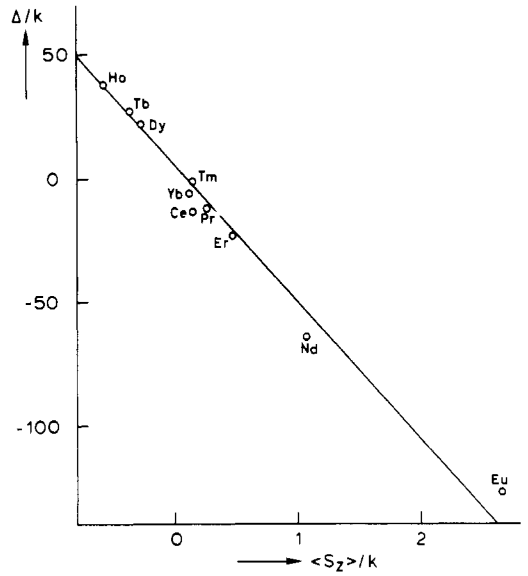

Figure 5. Plot of Δ/k versus $\langle S_z\rangle/k$ for the water ^{17}O signal in the Ln-DTPA complex at 73 °C.

resulted in a dramatic decrease of the goodness of the fit.

In analogous calculations for more rigid ligands, a much better agreement between observed and calculated G values has been obtained.[39-41] Obviously, the crystal structure is not an adequate model for the solution structure. Molecular mechanics might provide better models for calculations of lanthanide-induced shifts, particularly in cases like the present one, where the coordinated ligand is highly mobile.

Ln^{III}-Induced Water ^{17}O Shifts. Previously, we have observed that the values of the F parameter for Ln^{III}-bound oxygens were all in a rather small range of -70 ± 11 at 73 °C, irrespective of the nature of the ligand.[39,42,43] Therefore, Ln^{III}-induced ^{17}O shifts can be utilized to determine the coordinating oxygens of a ligand. Unfortunately, this is only applicable when the exchange between bound and free oxygen nuclei is fast on the NMR time scale, since the ^{17}O signals of Ln^{III}-bound oxygens (in the slow-exchange region) are extremely broad and not observable. Therefore, for the $Ln(DTPA)^{2-}$ complexes, this technique could only be used for the water ^{17}O signal, for which, as should be expected, the exchange between the complex and the bulk was fast on the NMR time scale. The ^{17}O shifts obtained were extrapolated to a Ln^{III}/water ratio of 1 (see Table IV). The values obtained correspond to $n\Delta$, where n is the number of bound waters in the complex and Δ is the bound shift of water. A plot of these shifts according to eq 7 gives a straight line (see Figure 5), which shows that no change in the number of coordinated waters occurs along the lanthanide series.[37] A separation of contact and pseudocontact shifts (see above) afforded $nF = -53$ and $nG = 3.71$. The value of nF indicates that one Ln^{III}-bound water is present in the Ln^{III}-DTPA complexes, which is in agreement with the results of previous investigations.[10,12,13]

Table V. Nd^{III}-Induced Shifts in the $Nd(DTPA)^{2-}$ Complex in Water at pD 7 and 73 °C, at a Molar Ratio of Nd^{III}/DTPA (ρ) = 1.6

nucleus	$\Delta\delta^a$	nucleus	$\Delta\delta^a$
a,a′	-0.94	c	-1.62
b,b′	-0.97		

[a] $\Delta\delta$ is the difference in chemical shifts for ρ = 1.6 and ρ = 1.0.

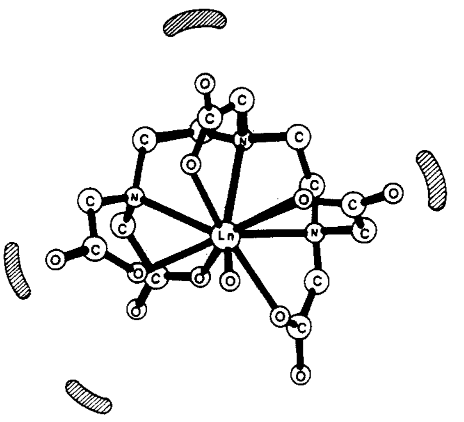

Figure 6. Schematic representation of the $Li_2[Ln(DTPA)(D_2O)]$ complex in aqueous solution. The approximate locations preferred by the counterions are shaded.

The Counterions. The ^6Li nucleus has a very small quadrupolar moment, and consequently its relaxation is very slow. Therefore, ^6Li is a very suitable probe for studying the location of counterions of negatively charged Ln^{III} complexes.[43]

From the observed ^6Li relaxation rate ($1/T_1$) in a solution of Li_5(DTPA) and Nd^{III} at $\rho = 0.94$, the longitudinal relaxation rate in the $Li_2[Nd(DTPA)]$ complex was calculated to be 0.075 s^{-1}. In this calculation it was assumed that all the Nd^{III} is present as the $Li_2[Nd(DTPA)]$ complex and that the relaxation rate of free ^6Li is negligible.[43] Then, with the use of eq 3, a Nd^{III}-Li^I distance of 5.6 Å was calculated. This suggests that two Li^I counterions are in the second coordination sphere of Nd^{III} in the Nd^{III}-DTPA complex. If the number of counterions in the second coordination sphere were lower, the calculation would result in a smaller Nd^{III}-Li^I distance, which seems less likely.

The Ln^{III}-induced ^6Li shifts were very small (see Table IV). It can be assumed that, for the ^6Li counterions, the Ln^{III}-induced shifts are purely of pseudocontact origin. A linear relationship between the induced shifts and the k values reported in the literature[30] was found (correlation coefficient 0.98). Then, with the use of eq 4, G was estimated to be -0.03. This very small G value compared to those of DTPA (see Table III) suggests that the counterion in the Nd^{III}-DTPA complex can occupy a number of locations in which different Nd^{III}-induced shifts are experienced (cf. eq 5). Averaging may then lead to a net shift of about zero. It is likely that the Li^I counterions are coordinated to unbound oxygens of the carboxylate groups of DTPA and that they are exchanging between the five carboxylate groups. This is supported by the induced ^{13}C shifts observed upon addition of Nd^{III} to a solution of the $Nd(DTPA)^{2-}$ complex. In the spectra obtained, fast exchange was observed between nuclei of the $Nd(DTPA)^{2-}$ complex and the binuclear complexes. The induced shifts obtained at a molar ratio of Nd^{III}/DTPA = 1.6 are given in Table V. The counterion- (Nd^{III}-) induced shift of the middle carboxylate carbon (c) is roughly twice those of the signals for the terminal carboxylate carbons (a,a′/b,b′). Since each of the latter signals is resulting from averaging between two ^{13}C nuclei, the bound shifts of all carboxylate ^{13}C nuclei in the $Nd(DTPA)Nd^+$ complex are about

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the same. Assuming that the geometrical approach of Nd^{III} to each of the carboxylates is the same, it can be concluded that in the binuclear $Nd(DTPA)Nd^+$ complex the second Nd^{III} cation is exchanging between the various carboxylate groups without a distinct preference for one of them.

Conclusions

In summary it is concluded that DTPA coordinates with Ln^{III} cations via the three nitrogens and with the five carboxylate groups (in a monodentate fashion). In all Ln–DTPA complexes one water is present in the first coordination sphere (see Figure 6). The exchange between bound and free DTPA is extremely slow, but exchange broadening occurs in the ^{13}C and ^1H NMR spectra as a result of the conformational mobility of the DTPA ligand. The conformational interconversions lead to a pseudomirror plane through the backbone of the middle glycine group. Counterions in the second coordination sphere are probably coordinated to the carboxylate groups and are exchanging almost randomly between them.

This investigation demonstrates that, even in the case of a very asymmetric and mobile complex, a wealth of structural information can be obtained from lanthanide-induced shifts and relaxation rate enhancements. It may be expected that future developments in molecular mechanics will provide us with better geometric models for this type of lanthanide complexes, which will improve the exploitation of the pseudocontact shifts.

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Theory of the Temperature Dependence of the NMR Shift of Intermediate Spin ($S = 1$) Four-Coordinate Ferrous Porphyrins

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The theory of the NMR shift (pseudocontact and contact) for the intermediate spin state ($S = 1$) of four-coordinate ferrous porphyrins is developed for the general case of no axial symmetry. The theory is then fitted to temperature data for the ^1H NMR shifts of Fe(OEP) [(2,3,7,8,12,13,17,18-octaethylporphyrinato)iron(II)], Fe(OEC) [(*trans*-7,8-dihydro-2,3,7,8,12,13,17,18-octaethylporphyrinato)iron(II)], and Fe(TPP) [(5,10,15,20-tetraphenylporphyrinato)iron(II)]. It is also fitted to temperature data for the magnetic susceptibility and magnetic anisotropy of solid Fe(TPP) and Fe(PC) [(phthalocyaninato)iron(II)]. The theory assumes the ground state to be a $^3A_{2g}$ state that is spin–orbit coupled with the ^3E_g state at energy Δ. In low symmetry the ^3E_g state is split by the energy δ. In solution $\Delta = 600$ cm^{-1} for Fe(OEP) and Fe(OEC) and ~ 1000 cm^{-1} for Fe(TPP). Δ is reduced to 400 cm^{-1} in solid Fe(TPP) and is -900 cm^{-1} in solid Fe(PC) (^3E_g ground state). In solution $\delta = -700$ cm^{-1} in Fe(OEC). In Fe(OEP) and Fe(OEC), enough experimental data are available to allow the determination of the geometrical factors for the pseudocontact shift of the methyl resonances from the NMR shifts. The theory is successful in explaining the temperature dependence of the pseudocontact shifts and magnetic susceptibilities but does not fully account for the temperature behavior of the contact shifts.

Introduction

Four-coordinate ferrous porphyrins with an intermediate spin state ($S = 1$) have been studied extensively by using various physical techniques. Assignment of the ground state has proven difficult with three different ground states being proposed as consistent with certain physical properties. The four triplet states considered were $^3A_{2g}$ $[(d_{xy})^2(d_{z^2})^2(d_{xz},d_{yz})^2]$, ^3E_gA $[(d_{xy})^2(d_{z^2})^1(d_{xz},d_{yz})^3]$, ^3E_gB $[(d_{xy})^1(d_{z^2})^2(d_{xz},d_{yz})^3]$, and $^3B_{2g}$ $[(d_{xy})^1(d_{z^2})^1(d_{xz},d_{yz})^4]$. At various times the states $^3A_{2g}$, ^3E_gA, and $^3B_{2g}$ have been proposed as the ground state.

Most theoretical calculations[1–4] have predicted the $^3A_{2g}$ state to be lowest in energy with the ^3E_gA state very close to it. Obara and Kashiwaga[1] have calculated the ^3E_gA state to be only 650 cm^{-1} above the $^3A_{2g}$ state in the Fe(II)–porphine complex. They further calculated the ^3E_g state to be 84% ^3E_gA and 12% ^3E_gB due to configurational interaction. They found this mixing was required to explain the quadrupolar results obtained by Mössbauer measurements. Calculations of Dedieu et al.[2] on Fe(TPP) [(5,10,15,20-tetraphenylporphyrinato)iron(II)] show the $^3A_{2g}$ state to be below the $^3B_{2g}$ state, but their calculations could not give the energy of the ^3E_gA state. Edwards et al.[3] calculated the ^3E_gA state in the Fe(II)–porphine complex to be only 240 cm^{-1} above the $^3A_{2g}$ state but proposed, on the basis of their interpretation of Mössbauer and X-ray data in the literature, that the ^3E_gA state was really the ground state. Sontum et al.[4] did an Xα calculation on the Fe(II)–porphine complex that predicts the $^3A_{2g}$ state to be 1600 cm^{-1} below the ^3E_gA state. Rawlings et al.[5] are the only ones to calculate ^3E_gA as the ground state, which they found to be about 3800 cm^{-1} below $^3A_{2g}$. These calculations, with one exception,[4] do not consider the effect of the spin–orbit interaction, which is about 400 cm^{-1} in magnitude.

The magnetic susceptibility of Fe(PC) [(phthalocyaninato)iron(II)] was measured by Dale et al.,[6] who fitted the data to an $S = 1$ spin Hamiltonian in which the zero-field interaction was 70 cm^{-1}, $g_\parallel = 1.93$, and $g_\perp = 2.86$. They claimed the ground state to be ^3E_gA, but this may be an error because it contradicts their model, which has a nondegenerate ground state. Barraclough et al.[7] have measured both the magnetic susceptibility and anisotropy

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