the opioid peptides with the N-terminal tyrosyl residue, the bonding with the receptor could involve the stacking interaction between the phenol group of Tyr and the aromatic side chain of the receptor, possibly the imidazole ring which has been reported to be located at the binding site.[15] In line with this, the receptor has been found to interact with a dopamine analogue containing a diphenol moiety.[39] In low molecular weight complexes, stacking has been concluded to occur between the Cu(II)-coordinated histidine imidazole ring and the aromatic side chain of Tyr, Trp, or Phe.[10,11] The present NMR study offers convincing evidence for the stacking interaction between an aromatic amine and the side chain of a peptide both firmly coordinated. Metal ions may assist the interaction in two ways: they put the interacting groups close to each other in the coordination sphere and/or enhance the charge transfer between the stacked rings by reducing the electron density of coordinated aromatic amines. Model studies aimed at demonstrating the latter point are in progress in our laboratory.

Regulation of stacking by introducing a charged or a hydrophilic group into the stacked ring is clearly seen from the log K values obtained for Pd(TyrO$^-$-X)(DA) (X = Gly or Glu and DA = bpy or bphen) and Pd(Ptyr)(bphen). This confirms the earlier observation on the Cu(II) complexes and may suggest regulation of biological reactions by tyrosine phosphorylation or sulfation;[40,41] while dissociation of the phenol OH group requires a strong base, its phosphorylation takes place in vivo by kinases and may break up possible stacked structures. In this connection, it is worth mentioning that phosphorylation of Tyr residues is regarded as the key step in the growth of cancer cells[40] and that sulfation of the Tyr residue of enkephalin[42] and phosphorylation of the opiate receptor site[43] inhibit the physiological reactions.

Acknowledgment. We thank Dr. Yoshitaka Itatani of Kanazawa University for measurements of the NMR spectra. This work was supported by a Grant-in-Aid for Scientific Research (No. 59470033) from the Ministry of Education, Science, and Culture, Japan, to which our thanks are due.

Registry No. Pd(Trp-Glu)(en), 99546-63-1; Pd(Trp-Blu)(bpy), 99546-64-2; Pd(Tyr-Glu)(en), 99546-65-3; Pd(Tyr-Glu)(bpy), 99546-66-4; Pd(Tyr-Glu)(bphen), 99546-67-5; Pd(TyrO$^-$Glu)(en), 99546-68-6; Pd(TyrO$^-$-Glu)(bpy), 99546-69-7; Pd(TyrO$^-$-Glu)(bphen), 99546-70-0; Pd(Phe-Glu)(en), 99546-71-1; Pd(Phe-Glu)(bpy), 99546-72-2; Pd(Trp-Gly)(en), 99546-73-3; Pd(Tyr-Gly)(en), 99546-74-4; Pd(Tyr-Gly)(bpy), 99546-75-5; Pd(TyrO$^-$-Gly)(en), 99546-76-6; Pd(TyrO$^-$-Gly)(bpy), 99546-77-7; Pd(Phe-Gly)(en), 99546-78-8; Pd(Phe-Gly)(bpy), 99546-79-9; Pd(Ptyr)(en), 99546-80-2; Pd(Trp-Glu)(bphen), 99546-81-3; Pd-(Phe-Glu)(bphen), 99546-82-4; Pd(Trp-Gly)(bphen), 99546-83-5; Pd-(Tyr-Gly)(bphen), 99546-84-6; Pd(TyrO$^-$-Gly)(bphen), 99546-85-7; Pd(Phe-Gly)(bphen), 99559-67-8; Pd(Ptyr)(bphen), 99546-86-8; Pd-(Gly-Gly), 99546-87-9; Pd(Gly-Gly)$_2$, 99546-88-0; Pd(Gly-Gly)(en), 62424-35-5; Pd(Gly-Gly)(bpy), 99546-89-1; Pd(Gly-Gly)(bphen), 99546-90-5; Pd(Tyr-Gly), 99546-91-5; Pd(en)$_2^{2+}$, 22573-08-6; Pd(Ala-Gly)(bpy), 99546-92-6.

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NMR Investigation of the Lanthanide Complexes with a 14-Membered Polyaza Polyacetic Macrocycle, TETA. Another Rare Example of Nonlabile Lanthanide Compounds

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The 14-membered macrocycle TETA (1,4,8,11-tetraazacyclotetradecane-N,N',N'',N'''-tetraacetic acid) forms unusually rigid lanthanide complexes whose solution properties have been investigated by ^{1}H and ^{13}C NMR spectroscopy after deuterium labeling of the ligand. The conformational analysis was based on the previously published crystallographic structure of TbTETA. A quantitative agreement is obtained between the dodecahedral geometry found in the solid and the spectra of paramagnetic YbTETA, provided the complete form of the dipolar equation is used in the calculations. The temperature dependence of the ^{1}H spectra of YbTETA and of the ^{13}C spectra of diamagnetic LuTETA is interpreted as arising from an exchange between two equivalent dodecahedral geometries. The kinetic parameters of this process were obtained by band-shape analysis in the case of LuTETA. The free energy of activation ($\Delta G^{\ddagger}_{25\,°\mathrm{C}}$ = 63.7 kJ mol^{-1}) is remarkably high for a lanthanide complex, a special feature ascribed to the steric requirements of the macrocyclic ring. The dynamic behavior of the TETA complexes depends on the ionic radius of the metals: EuTETA behaves like the heavier lanthanide complexes, while PrTETA assumes a highly asymmetric geometry that is rigid only at −55 °C.

Introduction

Structural inferences made with lanthanide shift reagents[1] must be accepted with reservation for a number of reasons. Foremost among them are the unknown origin of the induced NMR shifts, the low symmetry of the lanthanide complexes, and the high lability of these compounds.[2] Separating the various contributions to the NMR shifts can be achieved by published procedures[1,3] provided a number of conditions are fulfilled or, better, can be avoided by selecting the ion Yb(III) as paramagnetic center since this ion induces shifts that are essentially dipolar in origin. However, the lack of symmetry of the lanthanide complexes remains one of the key questions in the analysis of the NMR spectra of these compounds. Indeed, the vast majority of the lanthanide complexes exhibit at best a C_2 axis and the complete form of the

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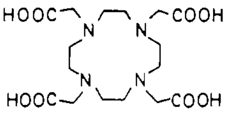
dipolar equation should thus be used to account for the induced paramagnetic shifts

$$\Delta\nu = D_1\left\langle\frac{3\cos^2\theta - 1}{r^3}\right\rangle + D_2\left\langle\frac{\sin^2\theta\cos 2\phi}{r^3}\right\rangle \qquad (1)$$

where r, θ, and ϕ are the polar coordinates of the nucleus under study relative to the magnetic susceptibility axes. D_1 and D_2 are coefficients that depend on the anisotropy of the magnetic susceptibility of each lanthanide complex. These coefficients can be measured, although painstakingly,[2] and are most often taken as unknowns in a best-fit treatment that also includes the orientation of the axes that do not coincide with a symmetry axis, if any is present. Such an approach is further complicated by the high lability of the lanthanide complexes that can adopt a large number of conformations of comparable energies in solution. All the geometric isomers are in fast exchange on the NMR time scale, and none of them are likely to be axially symmetric.[1,2] The paramagnetic shifts are then the result of an average over all the possible structures of a complex, a situation that could not be handled unambiguously by a best-fit computer program.

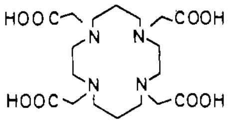
The advent of more powerful magnets and the problems we just mentioned above have led many spectroscopists to forsake the use of lanthanide shift reagents. However, the study of the NMR spectra of paramagnetic complexes affords an interesting insight into the coordination properties of the lanthanides provided the compounds under investigation are sufficiently rigid and stable. Rigidity can be achieved at very low temperatures if the lanthanide complexes are highly crowded, for instance because of the bulky substituents of the ligands.[4] Another approach consists in selecting ligands that exhibit a strong preference for one conformation only. This approach is particularly well illustrated by investigations of axially symmetric lanthanide complexes with small macrocycles substituted by carboxylic pendant arms such as DOTA[5,6] (I) or DOTMA.[7] The steric requirements of these polyaza polyacetic ligands were shown[5] to be those of all 12-membered macrocycles. Indeed, cyclododecane and its derivatives, such as 12-crown-4, adopt preferentially a very stable quadrangular (3333) conformation[8] of C_4 symmetry, which is also exhibited by the lanthanide DOTA complexes in solution and in the solid. Moreover, the quantitative analysis of the NMR spectra of YbDOTA is straightforward[6,9] since, in the case of axially symmetry complexes, the dipolar shifts are a simple function of only one geometric factor:

$$\Delta\nu = D_1\left\langle\frac{3\cos^2\theta - 1}{r^3}\right\rangle \qquad (2)$$



I

Finally, the conformational process that takes place within the macrocyclic ring of DOTA is readily observed in the NMR spectra at or above room temperature[5] and the DOTA complexes are the most rigid lanthanide compounds known thus far. These most unusual features in lanthanide chemistry prompted us to carry out a detailed analysis of the properties of the lanthanide complexes with TETA (II) (1,4,8,11-tetraazacyclotetradecane-*N,N′,N″,N‴*-tetraacetic acid). Our study is directed toward addressing the dependence of the geometry and of the conformational behavior of the lanthanide polyaza polyacetates upon the cavity size and the steric requirements of the ligands. Also an important question probed herein is the effect of a low symmetry on the NMR spectra. Our results indicate that the small structural differences between DOTA and TETA bring about drastic changes in the dynamic behavior of the complexes but do not notably alter their rigidity.



II

Experimental Section

The preparation of 1,4,8,11-tetraazacyclotetradecane-*N,N′,N″,N‴*-tetraacetic acid, TETA, followed a previously reported procedure.[5] This synthesis involves a template condensation described by Barefield et al.,[10] and the same method was used for the synthesis of the TETA ligand partially deuterated at the ethylenic positions (1,4,8,11-tetraazacyclotetradecane-2,2,3,3-d_4-*N,N′,N″,N‴*-tetraacetic acid). Using 1,2-dibromoethane-d_4 for obtaining the key starting material 1,5,8,12-tetraazadodecane-6,6,7,7-d_4 yielded the sought compound. The ligand TETA fully deuterated at the acetate positions (1,4,8,11-tetraazacyclotetradecane-*N,N′,N″,N‴*-tetraacetic-α,α'-d_8 acid) was prepared by condensation of the tetraaza macrocycle with chloracetic-d_2 acid.[5] Deuterium labeling at the central carbon atom of one of the propylenic groups of TETA was accomplished by synthesizing 1,4,8,11-tetraazacyclotetradecane-6,6-d_2-*N,N′,N″,N‴*-tetraacetic acid. The tetraaza cycle was obtained according to the method of Richman and Atkins[11] by reacting the disodium salt of the tetrakis(*p*-tolylsulfonyl) derivative of 1,4,8,11-tetraazaundecane with ditosylated 1,3-propanediol-2,2-d_2 in anhydrous dimethylformamide. The deuterated diol was obtained by reduction of dimethyl malonate-d_2 as described by Lambert,[12] and 1,4,8,11-tetraazaundecane was synthesized according to Barefield et al.[10] The cyclization reaction follows previously outlined procedures[11] and will therefore not be discussed in detail except for the cleavage of the *p*-toluenesulfonate groups that was accomplished by a modification of a published method.[11] The tetratosylated tetraaza cycle (13.5 g, 16.5 mmol) was added to 40 mL of concentrated H_2SO_4, and the mixture was stirred for 48 h at 100 °C under dry nitrogen. The dark brown solution was then chilled in an ice bath, and 80 mL of cold water was added dropwise. The pH was adjusted to 11 by the slow addition of 160 mL of a 6 M NaOH solution and the sodium sulfate that precipitated immediately was filtered off and washed twice with 25 mL of $CHCl_3$. The aqueous filtrate was extracted three times with 100-mL portions of $CHCl_3$. All the organic extracts were collected and stirred for a few hours with 6 mL of concentrated HCl. The precipitated 1,4,8,11-tetraazacyclotetradecane-6,6-d_2 tetrahydrochloride was filtered, washed with ethanol, and dried in vacuo, giving a yield of 5.5 g (95%).

The purity of all the deuterated derivatives of TETA was checked by proton NMR. Each ligand was deuterated to the extent of 95% or better at the sought positions, and the lanthanide complexes with all ligands exhibited identical paramagnetic shifts.

All solutions for NMR studies were prepared by complete dissolution of a lanthanide oxide by a stoichimetric amount of TETA in water at 80 °C or as reported elsewhere.[5] The NMR measurements were carried out as described previously.[5] No special precautions were taken to record NMR spectra at temperatures close to 100 °C other than loosening the cap of each NMR tube so as to avoid any overpressure. Positive ^1H NMR shifts are referenced downfield to the corresponding resonances of the diamagnetic complexes of LaTETA or LuTETA.

Results and Discussion

The dynamic processes taking place in the lanthanide TETA complexes depend on the size of the encapsulated ion. The NMR spectra of the complexes of the heavy and light lanthanides will thus be dealt with separately.

Structure and Stereochemical Nonrigidity of YbTETA and LuTETA. The ^1H NMR spectra of YbTETA at 5 and 98 °C are reproduced in Figure 1. The complete assignment of the peaks

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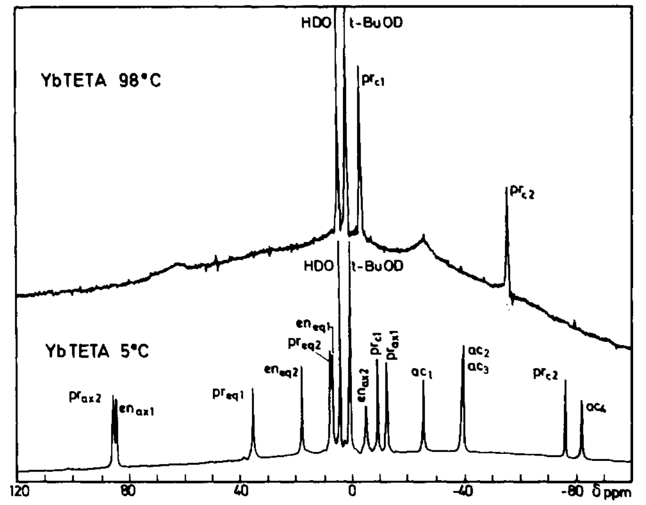

Figure 1. 90-MHz ^1H NMR spectra of YbTETA in D_2O at 5 °C and at 98 °C. Assignments of the resonances: ac, acetate; en, ethylenic; pr, propylenic; ax, axial; eq, equatorial; c, central group of a propylenic moiety.

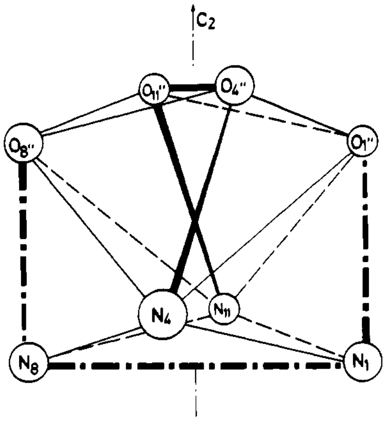

Figure 2. Schematic presentation of the dodecahedral structure of the TbTETA complex in the solid state.[9] The coordination sphere of the Tb(III) ion is divided into two groups of atoms that are distinguished by connecting them with solid and dash-dotted lines for the "high" and "low" groups, respectively.

follows from a comparison with the spectra of YbDOTA and from deuterium labeling experiments. Two features of particular interest should be noted in these spectra. First, a large number of peaks occur at both high and low fields; YbTETA is thus stereochemically rigid at low temperatures. Second, a structural rearrangement appears to take place when the temperature is increased since all NMR peaks broaden except the two resonances assigned to the protons pr_{c1} and pr_{c2} that are attached to the central carbon atoms of the propylenic chains. A temperature dependence of the NMR spectra was also observed in the case of YbDOTA,[5] but in contrast to the results presented in Figure 1, it was found that all the signals exhibited by this complex undergo exchange broadening.

The complexity of the NMR spectra of YbTETA is such that even simply accounting for the number of peaks appeared difficult. It was thus deemed preferable to investigate first the crystallographic structure of a TETA complex.[9] The coordination sphere of the metal ion in the compound $Na^+(TbTETA)^-6H_2O\cdot{}^1/_2NaCl$ is a dodecahedron that despite pronounced distortions displays a C_2 symmetry axis. Moreover, the macrocyclic ring adopts the only conformation that is suited for complexation among the various conformations of similar energy that are assumed by the 14-membered macrocycles. The dodecahedral geometry of TbTETA is presented schematically in Figure 2, which shows that this complex contains two different groups of atoms. At the center of Figure 2 is a group of atoms consisting of two nitrogen and two oxygen atoms that are higher than the mean N_4 or O_4 planes. The other group of atoms is made of nitrogen and oxygen atoms that are lower than their respective mean planes. The two N_2O_2 moieties will be referred to as the "low" and "high" groups.

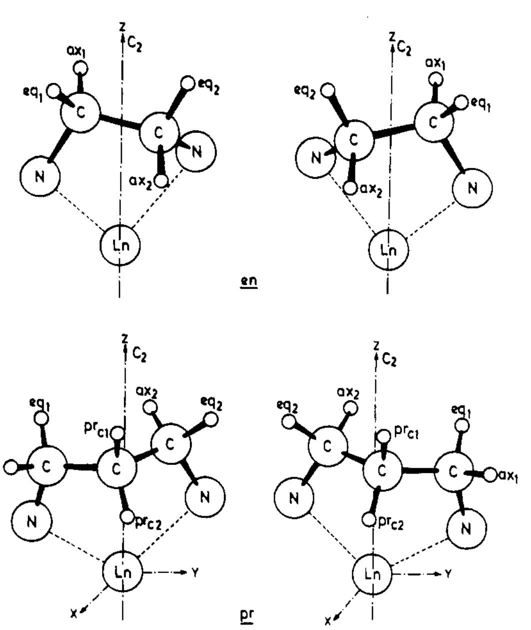

Figure 3. The two conformations that ethylenic and propylenic groups can assume in a dodecahedral geometry.[9] The best agreement between the solid-state and the solution structures is obtained when the X axis is perpendicular to the plane of the figure.

Each acetate arm of TETA links nitrogen and oxygen atoms belonging to a "low" or to a "high" group; they are thus located in two different magnetic environments. By comparison with the DOTA complexes, one may further assume that, in each magnetic environment, the acetate groups are oriented in such a way as to make their two protons inequivalent. Hence, the four acetate resonances (ac_1 to ac_4) that are displayed in the spectra of YbTETA appear to be consistent with a dodecahedral geometry. A square-antiprismatic structure can be ruled out because it would lead to only two acetate NMR peaks; indeed, all four acetate arms would be equivalent as in the case of the DOTA complexes. Moreover, the quantitative analysis of the paramagnetic shifts reported below is consistent only with a dodecahedral geometry.

In the solid,[9] each propylenic or ethylenic group spans "low" and "high" nitrogen atoms. This situation is illustrated in Figure 3, in which the ethylenic and propylenic groups are depicted in the two conformations they assume in crystallized TbTETA. Since their polar coordinates are different, the four ethylenic protons do not have the same geometric factors G and G' and hence resonate at different frequencies. Likewise, the propylenic groups contain six distinct types of hydrogen nuclei. The geometry of YbTETA in the solid thus accounts for the number of peaks observed in Figure 1. It also accounts quantitatively for the relative position of these peaks. The values of the geometric factors G and G' are readily calculated from the crystallographic structure of TbTETA for any orientation of the magnetic axes. In the present case, the Z axis was postulated to be collinear with the C_2 symmetry axis and the geometric factors were computed after each modification of the position of the X and Y axes. The agreement between the solution and the solid-state structures was assessed by calculating the statistical factor R:[13]

$$R = \left[\frac{\sum(\Delta\nu^{\text{exptl}} - \Delta\nu^{\text{calcd}})^2}{\sum(\Delta\nu^{\text{exptl}})^2} \right]^{1/2} \qquad (3)$$

As indicated in Table I, an agreement factor R = 8.9% was

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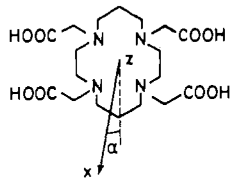
Table I. Calculated and Experimental NMR Shifts of YbTETA at 5 °C

proton	$(3\cos^2\theta - 1)/r^3$, 10^2 Å^{-3}	$\sin^2\theta\cos 2\phi/r^3$, 10^2 Å^{-3}	$\Delta\nu^{\text{exptl}\,a}$	$\Delta\nu^{\text{calcd}\,b}$
pr_{AX1}	−0.406	0.145	−16.2	−16.6
pr_{EQ1}	1.130	−0.025	35.7	37.4
pr_{c1}	−0.035	0.564	−12.3	−15.3
pr_{c2}	−1.538	1.894	−85.3	−97.6
pr_{EQ2}	0.472	0.367	5.5	5.9
pr_{AX2}	2.950	0.341	90.2	86.9
en_{EQ1}	−0.531	−0.872	5.5	4.9
en_{AX1}	2.231	−0.568	89.5	86.5
en_{AX2}	−2.295	−2.380	−6.1	−14.2
en_{EQ2}	0.069	−0.563	17.2	16.3
ac_1	−1.286	−0.476	−30.8	−29.3
ac_2	−1.891	−0.800	−44.3	−41.4
ac_3	−0.966	0.399	−46.2	−41.6
ac_4	−2.005	0.906	−93.2	−87.4

[a] Induced paramagnetic shifts relative to the NMR spectrum of LuTETA. [b] Computed with $D_1 = 3237 \pm 520$, $D_2 = -2526 \pm 73$, and $\alpha = 9°$; $R = 8.9\%$.

obtained if the X (or Y axis) makes an angle α of 9 ± 0.5° with the line joining the two central propylenic carbon atoms:



This orientation of the axes appears reasonable although there is no true element of symmetry that bisects the TETA ligand. We thus are led to conclude that YbTETA is another rare example of a nonlabile lanthanide complex that exhibits exactly the same conformation in the solid and in solution. It is worth mentioning here that the axial form of the dipolar equation (eq 2) as used to interpret the spectra of YbDOTA cannot be relied upon in the case of YbTETA; for the latter, high values of the agreement factor R were obtained for all orientations of the susceptibility axes. The small structural differences between the compounds DOTA and TETA thus have a drastic effect on the NMR spectra. They also profoundly modify the dynamic properties of the lanthanide complexes.

The alterations that take place in the spectra of YbTETA on increasing the temperature can be accounted for after a close examination of the crystallographic structure of TbTETA. If the group of atoms labeled "high" in Figure 2 is moved down while the opposite translation is performed with the "low" group, one finally obtains a new dodecahedral configuration that is identical with the original geometry but has been rotated by 90° along the C_2 axis. In this process, the dipolar geometric factors G and G' of all protons are modified except those of the central CH_2 group of each propylenic chain. For the latter, the polar coordinates are identical in absolute value in the two conformations depicted in Figure 3. Consequently, and as observed, all NMR peaks should undergo exchange broadening and eventually coalesce at high temperatures with the exception of two peaks, which should remain well-resolved in all experimental conditions. The NMR spectra of YbTETA are thus consistent with a dynamic process in which the "high" and "low" groups of atoms are continuously moving up and down like two blades in a chopping machine. It is noteworthy that the dynamic behaviors of the TETA and DOTA complexes are totally different: the inversion of the conformation of the tetraaza ring of YbDOTA proceeds without substantial motions of the ligating atoms[5] while the donor groups in the coordination sphere of YbTETA are exchanging between two different locations, thus leading to a complete rearrangement of the complex.

The kinetic parameters for the structural interconversion of YbTETA cannot be deduced from the NMR spectra of this compound since no peaks have yet coalesced at 100 °C. Interesting information is however obtained from an investigation of the spectra of the diamagnetic LuTETA complex. At 0 °C, the "low" and "high" acetate CH_2 protons of LuTETA are each resolved into an AB form but these peaks are not amenable to band-shape analysis because of partial overlapping of one of the peaks with ethylenic and propylenic resonances in a large temperature range. The dynamic behavior of LuTETA is reflected in a much simpler way in its ^{13}C spectra. Because there are two distinct groups of atoms in the dodecahedral geometry of the TETA complexes, all ^{13}C peaks should appear as doublets at low temperatures except for the resonance assigned to the central propylenic carbon atoms. All other nuclei can indeed be located in a "high" or a "low" position as illustrated in Figures 2 and 3. A representative spectrum is set out in Figure 4, which also shows the assignment of the resonances made after deuterium labeling. Most ^{13}C shifts are very sensitive to temperature, and the resulting spectral overlappings do not allow accurate line-shape simulations. The carbonyl doublet that arises at around 150 ppm downfield from *tert*-butyl alcohol is the only peak for which a complete band-shape analysis can be carried out although the workable temperature

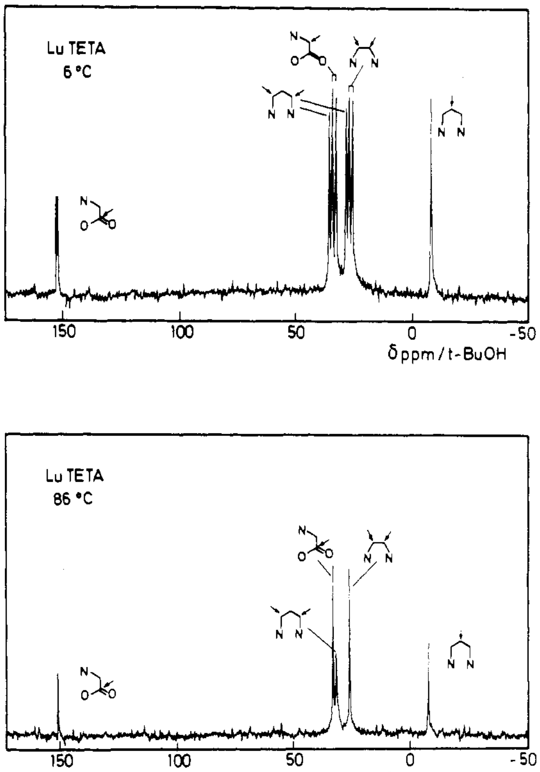


Figure 4. 22.6-MHz ^{13}C spectra of an aqueous solution of LuTETA at 6 and 86 °C (reference: internal *tert*-butyl alcohol).

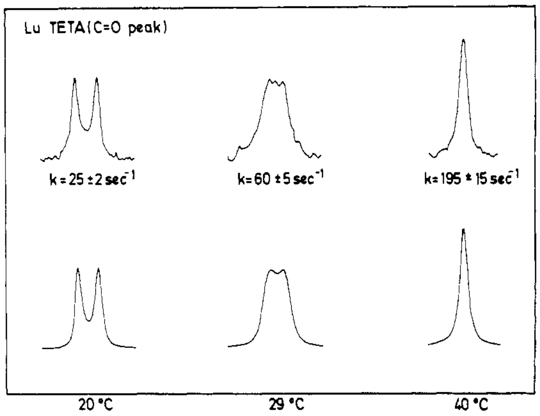


Figure 5. Band-shape simulation of the C=O ^{13}C peaks of LuTETA at 75.7 MHz.

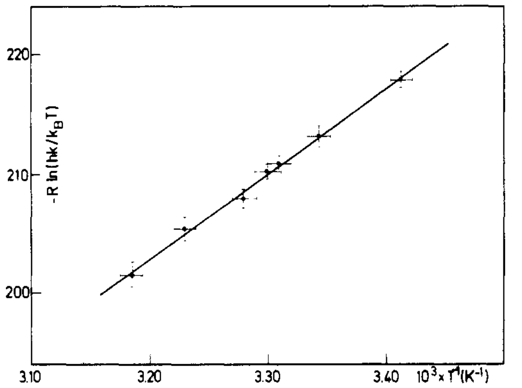


Figure 6. Eyring plot for the intramolecular rearrangement of LuTETA in D_2O.

Table II. Kinetic Parameters for the Rearrangement of Diamagnetic LuTETA[a]

$\Delta G^{\ddagger}$, kJ mol^{-1} [b]	63.7 ± 7.5	log A	14.6 ± 0.8
$\Delta H^{\ddagger}$, kJ mol^{-1}	71.7 ± 5.3	$k_{5^\circ C}$, s^{-1}	7
$\Delta S^{\ddagger}$, J K^{-1} mol^{-1}	27 ± 8	$k_{80^\circ C}$, s^{-1}	2.3 × 10^3
E_A, kJ mol^{-1}	74.4 ± 5.0		

[a] 0.1 M solution in D_2O at pH 8. All errors are random errors estimated at the 95% level. [b] At 25 °C.

range does not exceed 20 °C at 75.5 MHz. The rate constants were obtained from a total line-shape analysis for a two-site exchange.[14] A few representative spectra are shown in Figure 5 together with the corresponding calculated band shapes. The kinetic parameters were deduced from the Eyring plot reproduced in Figure 6 and are listed in Table II. LuTETA appears to be as rigid as the DOTA complexes and is thus considerably less labile than all other known lanthanide compounds.

NMR Spectra of the Lighter Lanthanide TETA Complexes. The NMR spectra of EuTETA at 3 °C (slow-exchange limit) and 98 °C (fast-exchange limit) are shown in Figure 7. As expected, the spectra are well-resolved because of the short electron relaxation time of the ion Eu^{3+}.[1] Around 0 °C, the spectra consist of the expected number of peaks, which were readily assigned after the synthesis of deuterium-labeled compounds. However, the spectra do not exhibit the same peak ordering as that of YbTETA and do not lend themselves to quantitative analyses based on the crystal structure of TbTETA. The systematically high values of the agreement factor R are in keeping with results obtained earlier[5] in the case of EuDOTA and point to the probable presence of large contact shifts. However, the solution structure of EuTETA is probably very close to the conformation of the corresponding complexes with heavier lanthanides since all these compounds exhibit the same dynamic properties. Indeed, when the temperature is increased, most NMR peaks displayed by EuTETA start to broaden and to shift. This leads to numerous spectral overlappings, but a careful analysis of the NMR spectra indicates that the two peaks attributed to the central propylenic groups pr_c are not involved in the dynamic process. At 98 °C, full coalescence is reached for all peaks except for two propylenic resonances, which are probably still too broad to be observed. In contrast, the acetate peaks have become so well resolved that coupling patterns are now visible. The barrier to the conformational rearrangement of EuTETA can be deduced approximately from the temperature of coalescence of protons ac_1 and ac_4 and of protons en_{AX1} and en_{EQ2}. The values $\Delta G^{\ddagger}_{317}$ = 59.6 kJ mol^{-1} and $\Delta G^{\ddagger}_{315}$ = 60.1 kJ mol^{-1} are in good agreement with the more accurate ^{13}C measurements reported in Table II.

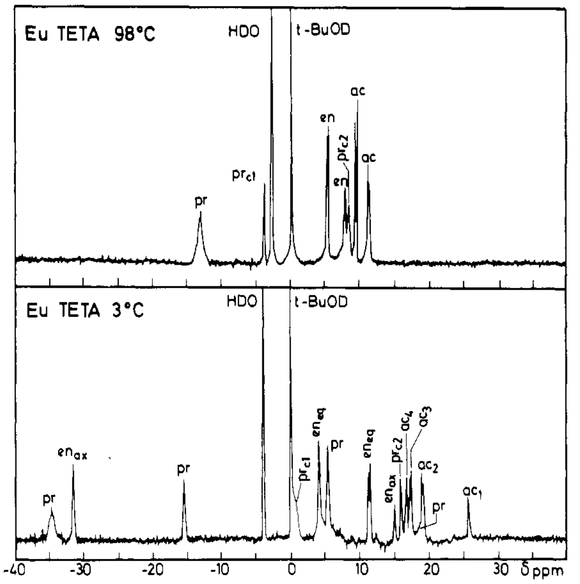


Figure 7. 90-MHz ^1H NMR spectra of EuTETA at 3 and 98 °C. Assignments of the peaks as in Figure 1.

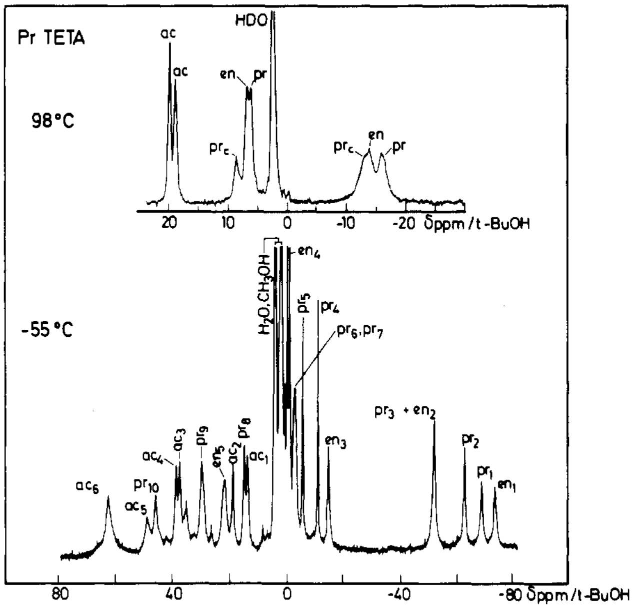


Figure 8. ^1H NMR spectra of PrTETA at -55 °C in a 30% D_2O–70% CD_3OD mixture (at 250 MHz) and at 98 °C in D_2O (at 60 MHz).

All TETA complexes with the heavier lanthanides Eu(III) to Lu(III) thus seem to be subjected to the same intramolecular rearrangement mechanism, and their rigidity appears independent of the ionic radius of the metals. However, dramatic alterations of the properties of the TETA complexes take place if the ionic size of the lanthanides is sufficiently large. It has been reported[15] that Pr(III) is 0.06 Å larger than Eu(III) if the coordination number is equal to 8. This small difference suffices to modify completely the NMR spectra. At 30 °C, all the peaks displayed by PrTETA are broad and the spectrum is totally featureless. However, lowering the temperature to -55 °C allows us to obtain a well-resolved spectrum in a 30% D_2O–70% CD_3OD mixture (see Figure 8). In addition to the resonances overlapping with the solvent peaks, the complex shows at least 6 acetate, 10 propylenic, and 5 ethylenic resonances. PrTETA probably assumes a highly asymmetric structure in which all protons are inequivalent. At high temperatures in D_2O, all NMR peaks have coalesced into the expected number of resonances as indicated in Figure 8. However, the molecular rearrangement that takes place is not comparable to the interconversion of structures illustrated in Figure 2 since the statistical factor R calculated for the agreement between the high-temperature spectrum of PrTETA and the crystal

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structure of TbTETA assuming fast conformational exchange is at best equal to 47.9% for a rotation angle of the X axis $\alpha = 39°$. The exact nature of the dynamic behavior of PrTETA is unknown at this stage.

Conclusion

The present investigation provides yet another example of the successful application of NMR spectroscopy to structural studies of lanthanide compounds in solution. Despite the low symmetry of the TETA complexes, a quantitative conformational analysis remains feasible provided Yb(III) is the paramagnetic center and provided the complete form of the dipolar equation is used in the calculations.

Only a handful of investigations have permitted complete characterization of the solution behavior of lanthanide complexes. Previous reports deal with the solution structure of lanthanide shift reagents at low temperatures or at room temperature after taking averaging processes into account.[4] Detailed studies have also been carried out on organometallic derivatives at −50 °C,[16] on an unusually rigid tris(pyrazolyl) Yb(III) complex,[17] and on the highly symmetric lanthanide tris(pyridine-2,6-dicarboxylates).[18] A variety of complexes can thus be studied by NMR provided the ligands are properly selected to ensure rigidity. In this respect, the polyaza polyacetic macrocycles appear particularly interesting since they form lanthanide complexes that are as rigid as many transition-metal compounds and since they exhibit dynamic behaviors that are readily observed at or above room temperature.

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Absorption and EPR Spectral Characterization of Tetrasulfur-Bridged Mixed-Valence Dimers of Molybdenum(III/IV). EPR Evidence for Tight Ion Pair Formation in Anionic Systems

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The electronic properties have been characterized for a series of mixed-valence tetrasulfur-bridged Mo(III)/Mo(IV) dimers of the general formula $[(CpMo)_2(S)_x(SR)_{4-x}]^n$ (Cp = C_5H_5, n = +1, 0, −1). An absorption in the near-infrared region of the spectrum has been observed for each of the mixed-valence dimers. The relatively narrow peak widths of the absorption bands and the independence of the absorption maxima from solvent dielectric properties have led to the classification of the mixed-valence complexes as completely delocalized (class III) systems. EPR spectra, which show hyperfine coupling to two equivalent molybdenum ions, suggest delocalization on a time scale of 10^7 s^{-1}. The sodium salts of the anionic dimers are proposed to be tight ion pairs in THF on the basis of the observed EPR spectra, which show hyperfine coupling with the counterions. The spectral results are discussed in terms of an extended Hückel molecular orbital description of the dimers.

Introduction

The bridging sulfido ligands of Mo(IV) dimers $[CpMo(\mu\text{-}S)(\mu\text{-}SH)]_2$ and $[CpMo(\mu\text{-}S)]_2S_2CH_2$ display an extensive reaction chemistry with hydrogen and unsaturated molecules.[2,3] Although no evidence for coordination of the reactants to the metal ions has been observed, the molybdenum ions are important in regulating the electron density within the Mo_2S_4 core. The addition or dissociation of an unsaturated molecule to or from the sulfur ligands results in a formal two-electron reduction or oxidation, respectively, of the molybdenum centers. The tetrasulfur-bridged molybdenum dimers also display reversible cyclic voltammograms that are characteristic of metal ion oxidation state.[4] The Mo(IV) dimers undergo one or two reversible one-electron reductions, and the Mo(III) complexes undergo two reversible one-electron oxidations. The ability of the metal ions in these dimeric complexes to reversibly cycle between the +4 and +3 oxidation states is believed to be fundamental to the interaction of sulfido ligands with hydrogen and/or substrate that occurs during the catalysis of hydrogenation[3] and hydrogenolysis[5,6] reactions by these dimers.

Strong electronic interactions between the molybdenum sites of these complexes may be partly responsible for the observed reaction chemistry and reversible redox processes. Application of the effective atomic number formalism to the tetrasulfur-bridged dimers leads to the postulate of a single bond between Mo(III) ions and a double bond between Mo(IV) ions. The Mo–Mo distances in structurally characterized tetrasulfur-bridged Mo(III), Mo(IV), and mixed valence Mo(III)/Mo(IV) dimers have been found to be essentially invariant to metal ion oxidation state and have values of ~2.60 Å.[7,8] Although the distances are compatible with a M–M bonding interaction, the steric constraints of the bridging sulfur ligands preclude using the Mo–Mo distances as reliable indications of direct metal–metal bonding interactions or as indices of bond order.

As part of an effort to understand the general underlying electronic basis for the chemical reactivity and electroactivity of these complexes, and the role of Mo–Mo interactions in particular, we have undertaken a spectroscopic study of the mixed-valence Mo(III)/Mo(IV) dimers shown in Table I. The complexes share

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