Aqueous Lanthanide Shift Reagents. 5. Interaction of the Aquoions with Methoxyacetate. Additional Pathways for Lanthanide-Induced Shifts

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Abstract: Shifts induced by a series of trivalent lanthanides (Pr, Nd, Eu, Tb, Dy, Ho, Er, Tm, Yb) in the proton spectrum of methoxyacetate ($CH_3OCH_2COO^-$) in aqueous solution are reported. A graphical analysis according to a model that assumes isostructurality and constancy of the hyperfine coupling constant along the lanthanide series is presented. The behavior of the methyl shifts indicates negligible contact contribution and isostructurality of the complexes. Additional pathways for lanthanide-induced shifts are suggested as possible sources of the deviations observed for the CH_2 protons of methoxyacetate as well as for nuclei close to the site of complexation in related systems. These pathways include nonbonding overlap between the lanthanide 4f orbitals and ligand orbitals and dipolar shifts from the unpaired spin density distributed over anisotropic ligand orbitals.

Dipolar shifts induced by lanthanide shift reagents are often used in the determination of molecular structure and conformation in solution.[1,2] The chemical shifts in lanthanide complexes arise from a combination of the contact and dipolar interactions. Empirical methods of separating between the two contributions have been suggested.[3-7] The successful application of lanthanide ions as probes in biological systems[2,8] has stimulated the interest in their use as aqueous shift reagents. NMR studies of the interaction of the aquolanthanides with a number of negatively charged substrates have been carried out.[2-5,9-13] Particularly instructive seem to be investigations encompassing a large portion of the lanthanide series. It has been observed in some of these studies that the ratios of lanthanide-induced shifts for diferent nuclei within the same complex deviate from what is believed to be a regular behavior. A structural change of the complexes along the lanthanide series has been suggested as a source of such deviations.[3,11] Levine et al. have proposed, e.g., that complexes of Tm^{3+} may be structurally different from those of other members of the series.[11] It should be emphasized that models of this type, with far reaching chemical implications, are based solely on the behavior of chemical shifts. As a test of structural models based on the behavior of lanthanide-induced shifts, we have investigated the induced shifts in the proton resonances of methoxyacetate, $CH_3OCH_2COO^-$. The methyl protons in this molecule are five bonds away from the site of complexation and the contact contribution to their shift is anticipated to be very small. In addition the formation constants of the lanthanide complexes with methoxyacetate vary very little along the series.[14] Reported in this paper are our results along with a graphical approach to the analysis of lanthanide-induced shifts. Conclusions are reached regarding the isostructurality of the complexes and the pathways for paramagnetic shifts in their ligand nuclei.

Experimental Section

Spectra were recorded with a Varian T-60 spectrometer operating at the ambient probe temperature of 39 ± 1 °C. Solutions, 50 mM in CH_3OCH_2COOLi, were made up in D_2O containing ca. 0.1% v/v *tert*-butyl alcohol which served as an internal reference. A constant pH of 5.5 was maintained using either LiOD or DCl to adjust it. Measurements were carried out in the presence of 1 M $LaCl_3$ in order to avoid the formation of higher than 1:1 complexes and the chemical shifts induced by successive additions of the paramagnetic lanthanide chlorides were determined.

Results and Discussion

The lanthanide-induced shifts interpolated to a 1:1 reagent/substrate ratio are summarized in Table I. It is seen that the ratio of the shifts induced in the CH_2 and CH_3 resonances shows no regularity along the series.

The following pathways for paramagnetic shifts in lanthanide complexes are usually considered.[15] Dipolar shifts are assumed to arise from the antisotropic magnetic susceptibility of the central lanthanide ion. Contact shifts are believed to be due to a spin-polarization mechanism, which assumes electron transfer (configuration interaction) between the ligand molecular orbitals and the lanthanide 6s orbital in a bond with a weak covalent character.[16] Thus the total induced shift for a given nucleus, *i*, in a lanthanide complex can conveniently be expressed as a sum of two terms

$$\delta_i = A_i\langle S_z\rangle + G_iD \qquad (1)$$

where A_i is the hyperfine coupling constant between the nucleus and the unpaired electronic spin, $\langle S_z\rangle$ is the projection of the lanthanide total electron spin magnetization on the direction of the external magnetic field, G_i is the geometrical function $(3\cos^2\theta_i - 1)r_i^{-3}$, and D is a constant for a given lanthanide and temperature. Bleaney[17] has calculated the values of D and has shown that they (except for Eu^{3+} and Sm^{3+}) should exhibit a T^{-2} temperature dependence.[6,13] A second-order perturbation treatment for the calculation of $\langle S_z\rangle$ has been carried out by Golding and Halton. They have shown that A_i for oxygen-17 in the aquolanthanides and for nitrogen-14 in the pyridine adducts of $Ln(dpm)_3$ are constant along the series.[18] If for a given complex the constancy of A_i and G_i along the series can be assumed, the contributions due to the two terms can readily be separated. By rearrangement of eq 1 one obtains

$$\delta_i/\langle S_z\rangle = A_i + G_i(D/\langle S_z\rangle) \qquad (2)$$

Using tabulated values of $\langle S_z\rangle$ and of D (ref 18 and 19, respectively) a plot of $\delta_i/\langle S_z\rangle$ against $D/\langle S_z\rangle$ can be constructed.[20,21] The plot should be linear with a slope of G_i and an intercept on the ordinate of A_i. Any deviations from the model should be clearly revealed in such a plot.[22] Our data for methoxyacetate are plotted in this way in Figure 1. The two proton-containing groups exhibit different behavior. The plot for the CH_3 group is linear implying that G_{CH_3} is constant along the series, i.e., the complexes are isostructural. Also the intercept is virtually zero indicating that the contact contribution is negligible. On the other hand, the great scatter of

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Table I. Lanthanide-Induced Proton Shifts[a] for Methoxyacetate[b]

Ln^{3+} [b]	δ_{CH_2}	δ_{CH_3}	$\delta_{CH_2}/\delta_{CH_3}$
Pr	20	−41	−0.49
Nd	8.5	−28	−0.30
Eu	−8.5	19	−0.45
Tb	7.5	−340	−0.022
Dy	100	−447	−0.22
Ho	22	−170	−0.13
Er	−2	100	−0.02
Tm	10	175	0.057
Yb	0	105	0

[a] In Hz at 60 MHz; downfield shifts given as negative. [b] Concentrations are 50 mM.

points for the CH_2 group or the irregularity of the internal shift ratio (cf. Table I) cannot constitute a basis for conclusions regarding structural variations along the lanthanide series. A similar treatment[23] of literature data for the pyridine-2,6-dicarboxylato complexes[5] and for the $Ln(dpm)_3$-quinoline adducts[24] also shows that nuclei, in particular carbon-13, closer to the site of complexation deviate from linearity and exhibit greater scatter, whereas nuclei farther removed show good linear relationships even when containing relatively large contact contributions. It seems that A_i may vary along the lanthanide series and that its variation may be responsible for deviations from regular behavior. Such variations could be due to additional pathways for lanthanide-induced shifts.

The following possible sources of shifts in paramagnetic complexes have usually been neglected in discussions of lanthanide-induced shifts. Nonbonding overlap between the lanthanide 4f orbitals and ligand molecular orbitals will place unpaired electronic spin on atomic s orbitals. An analogous mechanism is, e.g., the major pathway for proton contact shifts in the aquo complexes of transition-metal ions.[25] The relative importance of such shift contributions along the lanthanide series will depend on the population and symmetry of the 4f orbitals. Dipolar shifts may also arise from the unpaired spin density distributed over the ligand orbitals.[26,27] The anisotropy of the spin is now determined by the electronic g tensor of the corresponding orbital and the shift contribution will have a T^{-1} dependence on the temperature. Thus the shift contributions due to these additional pathways will be indistinguishable in their temperature dependence from the contact shifts arising from spin polarization. Therefore, when the temperature dependence is used to separate between shift contributions, only the lanthanide-centered dipolar shift will be properly evaluated. Fortunately this is the one of interest in structural studies. On the other hand, the "contact" contribution evaluated in this way may have no straightforward structural interpretation. Therefore, serious doubt is cast on recent interpretations of proton contact shifts for the aquolanthanides.[28] In our graphical representation the contributions from the additional pathways are contained in the apparent hyperfine coupling constant and therefore deviations from regular behavior may be regarded as being due to the variations in this apparent A_i along the lanthanide series.

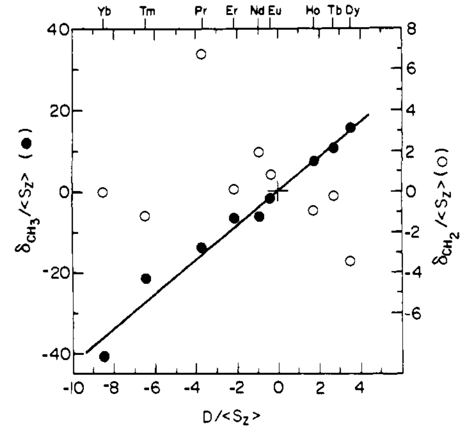

Figure 1. The ratio of the lanthanide-induced shift and $\langle S_z \rangle$ plotted against $D/\langle S_z \rangle$ (see text) for the CH_3 (filled symbols, left scale) and CH_2 protons (open symbols, right scale) of methoxyacetate.

References and Notes

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