Separation of Contact and Pseudocontact Contributions to ^{13}C Lanthanide Induced Shifts in Non-Axially-Symmetric Lanthanide Ethylenediaminetetraacetate Chelates

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Abstract: Lanthanide-induced shifts in the carboxyl carbon resonance of 12 paramagnetic lanthanide [1-^{13}C]ethylenediaminetetraacetate chelates have been measured from 298 to 358 K. Separate carbon resonances are observed for bound and excess free chelate carbons over this range and the bound peak sharpens considerably at higher temperatures. Attempts were made to separate the contact and pseudocontact contributions to the paramagnetic shifts by fitting the data to several temperature-dependent approximations but none yielded consistent results. The shifts at 318 K were successfully separated into their contact and pseudocontact components by using the method of Reilley.[17] The analysis indicates that a structural change occurs between the terbium and dysprosium chelates which results in a larger pseudocontact component for the heavier lanthanide chelates but with no corresponding change in the scalar hyperfine coupling constant. These results show that the Reilley method of separation is preferred even in slowly exchanging, nonaxial lanthanide chelate systems and the temperature-dependent separation is unacceptable.

Introduction

Lanthanide-induced shifts (LIS) in nuclear resonances have been used to simplify complex NMR spectra,[1] determine the enantiomeric purity,[2] and probe the dynamic solution conformations of molecules.[3] The first two applications are qualitative and require little theoretical justification while the latter use demands a careful analysis of the shift origin based upon current theoretical models. The observed shifts may arise from a delocalization of metal unpaired spin density to the substrate nuclei (contact shift) or from a dipolar through-space interaction between each individual nucleus and the metal ion center (pseudocontact shift). It is this latter contribution which provides the necessary geometric information for conformational studies and it must therefore be purified of any contact shift contribution.

An excellent review[4] has appeared which details the methods used for probing the conformations of water-soluble molecules ranging in size from amino acids to polynucleotides and proteins. Although the technique is quite straightforward, there are several questions which should be addressed before proceeding to calculate solution structures of molecules. First, how important are contact shift contributions to a measured LIS? Although it is recognized that ^{13}C and ^{31}P shifts may be dominated by contact interactions,[4] ^{1}H shifts are generally assumed free of such effects. Recent results with L-alanine[5] show that these proton LIS contain a significant contact contribution and furthermore these shifts do not necessarily decrease in magnitude for nuclei which are progressively further away from the lanthanide ion. What is the best method for separating contact shifts from pseudocontact shifts? Reilley[6] has outlined and compared methods which rely upon proportionating the measured LIS for a series of lanthanide cations with the contact and pseudocontact shifts predicted by theory and those which rely upon differences in the temperature dependency of the contact and pseudocontact terms. The former methods require that shifts be measured for several lanthanide cations and rely strictly on forming isostructural lanthanide–substrate complexes and having metal ion independent scalar hyperfine coupling constants while the latter method may be accomplished with a single lanthanide cation. Is it valid to assume that all lanthanide cations form isostructural complexes with a given substrate? This assumption may not be poor for the homologous tris(β-diketonate) lanthanide shift reagents or for rigid chelates like $Ln(DPA)_3^{3-}$ but is certainly tenuous for sustrate complexes with the aquo cations. Changes in structure across the lanthanide series have been detected in shift studies of L-alanine,[5] 3-indoleacetic acid,[7] a variety of carboxylic acids,[8] and water.[6] In principle then, a separation based upon temperature variations should be the simplest, yet there is disagreement as to whether the pseudocontact shift should very as T^{-1} or T^{-2}. The elegant theoretical treatment of pseudocontact shifts presented by Bleaney[9] predicts that these shifts should vary as T^{-2}. Elgavish and Reuben[10] showed experimentally that the proton LIS of acetone complexed with $Yb(fod)_3$ varied linearly with T^{-2} and suggested that contact shifts may be separated from pseudocontact shifts from temperature-dependent data. Desreux and Reilley[11] have reported that the proton LIS in the exchange-inert complex $Yb(DPA)_3^{3-}$ follow a T^{-2} dependence and use this method to successfully separate the contact and pseudocontact contributions to the carbon LIS of this same complex. Horrocks and Wong,[12] however, reported a T^{-1} dependency for the proton shifts in an exchange inert ytterbium porphyrin complex while Cheng and Gutowsky[13] find that the proton LIS in *N,N*-dimethylacetamide may be fit equally well by either a T^{-1} or T^{-2} dependence. McGarvey[14] has shown that several temperature-dependent terms may make significant contributions to the pseudocontact shift and therefore extraction of contact shifts from data over a temperature range normally accessible to lanthanide chelates is impractical.

We have measured the temperature dependence of the LIS in the carboxyl resonance of 12 lanthanide–EDTA chelates. The

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contact and pseudocontact contributions to the observed shifts were separated by using three independent methods with particular attention given to a change in structure of the Ln(EDTA) chelates near the center of the cation series.

Experimental Section

Lanthanide chloride salts were prepared from lanthanide oxides (gift from the Molybdenum Corp.) and standardized against EDTA by using xylenol orange as the indicator. [^{13}C]EDTA was synthesized from ethylenediamine and 90 atom % [1-^{13}C]bromoacetic acid by Vernon Kerr and Donald Ott of the Los Alamos Scientific Laboratory. The Ln(EDTA) solutions were prepared by dissolving the [^{13}C]EDTA into D_2O, adjusting the pH to approximately 6, adding an appropriate amount of $LnCL_3$, and readjusting the pH to the desired value. Dioxane (5%) was added as an internal chemical shift standard (67.86 ppm downfield of Me_4Si). pH measurements were made on a Sargent-Welch NX meter equipped with a glass combination electrode. The values are actual meter readings and have not been corrected for the deuterium isotope effect.

Proton-decoupled ^{13}C NMR spectra were recorded on a Bruker WP-60 spectrometer operating at a carbon frequency of 15.1 MHz. All chemical shifts were measured from an internal dioxane signal. The reported LIS represent the chemical shift differences between the paramagnetic Ln(EDTA) and diamagnetic La(EDTA) and Lu(EDTA) chelates. The probe temperature was calibrated with a VSI Model 42C telethermometer and maintained at ±0.5 °C with a Bruker BST 100/700 control unit. The Gd(EDTA) spectra were recorded at 50.3 MHz on a Bruker WP-200 instrument.

Theory

A pseudocontact shift arises from a dipolar interaction between the magnetic moment of the unpaired electrons on a metal center and the nucleus under examination. Bleaney[9] and Golding and Pyykkö[15] have evaluated the relative pseudocontact shifts expected for the lanthanide ion series and predicted that the shifts should vary as T^{-2}. Stout and Gutowsky[16] and McGarvey[14] have expanded Bleaney's theory to include higher order terms which have a T^{-3} dependence but conclude that these cannot contribute more than 10–20% to an observed pseudocontact shift in most lanthanide complexes. The expanded form of Bleaney's equation includes magnetic constants J and g

$$\mathrm{LIS}_{\mathrm{pc}} = -C_j^{\mathrm{D}}\left[\frac{\beta^2\langle r^2\rangle 2A_2^{\,0}(3\cos^2\theta - 1) + \beta^2\langle r^2\rangle 2A_2^{\,2}\sin^2\theta\cos 2\phi}{60(kT)^2r^3}\right] \tag{1}$$

where

$$C_j^{\mathrm{D}} = g^2J(J + 1)(2J - 1)(2J + 3)\langle J\|\alpha\|J\rangle$$

characteristic of each lanthanide ion, a numerical coefficient $\langle J\|\alpha\|J\rangle$ which determines the overall sign of the pseudocontact shift, two crystal field coefficients, $\langle r^2\rangle 2A_2^{\,0}$ and $\langle r^2\rangle 2A_2^{\,2}$, and two geometric terms which relate the distance and spherical coordinates of the nucleus under observation with respect to a lanthanide at the origin of this coordinate system. A series of isostructural lanthanide complexes (i.e., constant r, θ, and ϕ) having common crystal field coefficients would show pseudocontact shifts proportional to the C_j^{D} values in eq 1. Excellent agreement between these values and observed pseudocontact shifts have been reported.[6,7,11,17–19] It should be noted that an observed linearity between measured $\mathrm{LIS}_{\mathrm{pc}}$ and Bleaney's theoretical C_j^{D} values is not a test for axial symmetry. Deviations from linearity, however, may reflect a structural change or a change in crystal field coefficients along the lanthanide series.[5] A second shift contribution could arise from unpaired electrons occupying orbitals centered at the nucleus under observation.[20] This would add a term which varies as T^{-1}.

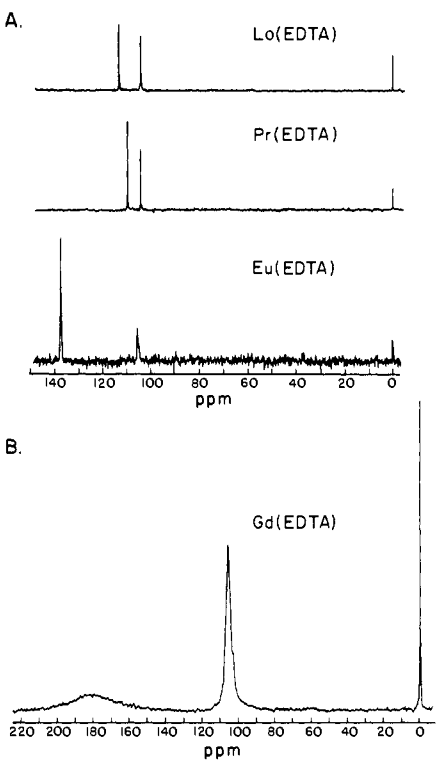

Figure 1. (A) The 15.1-MHz ^{13}C spectra of D_2O solutions containing 0.05 M 90% [1-^{13}C]ethylenediaminetetraacetic acid plus 0.025 M $LaCl_3$, $PrCl_3$, or $EuCl_3$ at 318 K, pH 4.5. Dioxane (5%) was added as an internal chemical shift standard. (b) The 50.3-MHz ^{13}C spectrum of a D_2O solution containing 0.05 M 90% [1-^{13}C]ethylenediaminetetraacetic acid and 0.025 M $GdCl_3$ at 318 K, pH 4.5.

A Fermi contact contribution resulting from a through-bond delocalization of lanthanide electron spin density onto the nucleus may be described by[4]

$$\mathrm{LIS}_{\mathrm{c}} = -\frac{2\pi\beta A}{3kT\gamma_{\mathrm{N}}}\langle S_z\rangle_j \tag{2}$$

where A is the scalar hyperfine coupling constant, γ_{N} is the gyromagnetic ratio of the nucleus under observation and $\langle S_z\rangle_j$ is the spin expectation value characteristic of each lanthanide ion, j. The relative theoretical $\langle S_z\rangle_j$ values for each lanthanide have been tabulated[21] and these have been found proportional to observed LIS in systems where contact shifts were expected to predominate.[6,17,22–24]

Results and Discussion

Measurement of the Lanthanide-Induced Shifts. The high-resolution carbon nuclear magnetic resonance spectra of EDTA containing a 90% enrichment of the ^{13}C isotope in the four carboxyl carbons shows a single resonance 104.2 ppm downfield from internal dioxane at pH 4.5 that shifts to 113.4 ppm downfield from dioxane upon complete deprotonation at pH 12. Solutions containing a 2:1 excess of [^{13}C]EDTA over a diamagnetic lanthanide cation, La^{3+} or Lu^{3+}, show two resonances at pH 4.5, one at 104.2 ppm and a second at 113.4 ppm (Figure 1). When the concentration of the diamagnetic cation is increased, the upfield peak gradually disappears and the downfield resonance increases in

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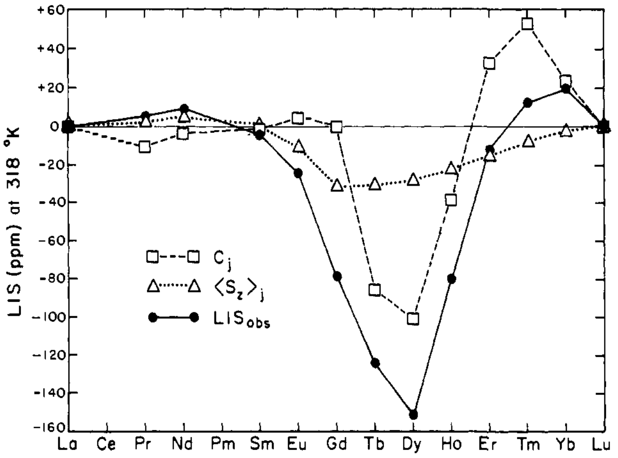

Figure 2. A comparison of the measured paramagnetic lanthanide-induced shifts (LIS) in the carboxyl resonance of 90% [1-^{13}C]ethylenediaminetetraacetic acid at 318 K, pH 4.5, with the relative values expected for "pure" contact ($\langle S_z \rangle_j$)[21] and pseudocontact (C_j^D)[9] shifts for each lanthanide ion.

intensity. This verifies that the 113.4-ppm resonance represents the chelated La(EDTA) or Lu(EDTA) species. An examination of the pH dependency of these two signals shows that the unchelated EDTA resonance follows the same downfield shift pattern between pH 4.5 and 8 as a solution containing free EDTA while the chelated EDTA resonance remains unshifted (113.4 ± 0.1 ppm) over this same pH interval. Between pH 8 and 10, both chelated and unchelated EDTA signals broaden, collapse into a single peak, and then sharpen and continue the downfield shift behavior. Above pH 11, the single resonance appears sharp and has the same chemical shift as a solution containing only the free unprotonated ligand. These results indicate that exchange between unchelated EDTA and La^{3+} or Lu^{3+} chelated EDTA occurs only slowly ($\tau_M \geq 10^{-3}$ s) at pH 4.5 while rapid exchange persists under alkaline conditions. This is in agreement with ^{1}H NMR results reported earlier by Ryhl[25] and Baisden et al.[26]

The shift induced by a paramagnetic lanthanide cation (LIS) in the chelated EDTA carboxyl resonance was easily determined at pH 4.5 without any of the complications normally associated with rapid chemical exchange. Four sample spectra are shown in Figure 1 for solutions containing a twofold molar excess of EDTA over the lanthanide cation. As observed, Pr^{3+} shifts the chelated EDTA peak upfield from that found in La(EDTA), whereas Eu^{3+} and Gd^{3+} both induce downfield paramagnetic shifts in the chelated EDTA carboxyl resonance. The resonance characteristic of unchelated EDTA never shifts more than ±1 ppm in the paramagnetic chelate solutions compared to its position in La(EDTA). The exact magnitude and direction of this shift depend upon the identity of the added paramagnetic cation. The LIS induced in the chelated EDTA carboxyl resonance at 318 K for 13 lanthanide cations are presented in Figure 2 along with the relative theoretical shifts expected for pure contact ($\langle S_z \rangle_j$)[21] and pseudocontact (C_j)[9] shifts. The observed pattern across the series is not characteristic of shifts dominated by either contact *or* pseudocontact origins but rather a mixture of the two. The shifts induced by the lighter lanthanides (Pr^{3+} → Eu^{3+}) seem dominated by contact while those induced by the heavier ions (Tm^{3+} and Yb^{3+}) seem dominated by pseudocontact interactions. The chelated EDTA carboxyl resonance in Gd(EDTA) is extremely broad ($\nu_{1/2} \sim 27$ ppm) because of the long electron–spin relaxation time characteristic of the isotropic Gd^{3+} ion and is contact shifted downfield 79 ± 1 ppm at 318 K. Thus, assuming that the remaining Ln(EDTA) chelates display a scalar hyperfine coupling constant of the same sign as Gd(EDTA), it is clear that the shifts induced by Tb^{3+} and Dy^{3+} are even further downfield than that induced by Gd^{3+} and this difference must result from a downfield pseudocontact shift.

Table I. Measured Lanthanide-Induced Shifts in the Carboxyl Resonance of Ln(EDTA) and the T^{-1} and T^{-2} Components to These Shifts at 318 K as Determined by Equation 3

ion	LIS_{obsd}, ppm[a]	T^{-1}, ppm component[b]	$\langle S_z \rangle_j$	T^{-2}, ppm, component[b]	C_j^D
Pr^{3+}	+3.92	+13.0	+3.0	−9.1	−11
Nd^{3+}	+9.68	+27.2	+4.5	−17.5	−4.2
Gd^{3+}	−79 ± 1	*c*	−31.5	*c*	0
Tb^{3+}	−124.86 ± 1	−188.6	−31.8	+63.9	−86
Dy^{3+}	−151.14 ± 1	−217.7	−28.5	+66.7	−100
Ho^{3+}	−80.10 ± 0.5	−95.0	−22.6	+15.1	−39
Er^{3+}	−12.90	+38.1	−15.4	−51.0	+33
Tm^{3+}	+13.04	+100.9	−8.2	−88.0	+53
Yb^{3+}	+19.92	+45.9	−2.6	−26.1	+22

[a] ±0.1 ppm unless otherwise indicated. Downfield LIS are negative. Eu^{3+} and Sm^{3+} are not included in this separation procedure because of low-lying excited states which complicate the temperature-dependent shifts of these two ions.[9] [b] The error was never greater than ±0.08 ppm. [c] Not determined because of excessive line broadening.

Temperature Dependence of the LIS. A separation of the individual contact and pseudocontact contributions to each of these shifts was first attempted by measuring the temperature dependence of each LIS between 298 and 358 K at 10 K intervals. The chemical shifts of the chelated carboxyl groups in the diamagnetic La(EDTA) and Lu(EDTA) complexes were temperature independent while the shifts induced by the paramagnetic ions were quite temperature sensitive over this temperature range. The LIS increased with increasing temperature for the ions Pr^{3+}, Nd^{3+}, Sm^{3+}, Eu^{3+}, Tm^{3+}, and Yb^{3+} and decreased with increasing temperature for Tb^{3+} → Er^{3+}. Since a "pure" contact or pseudocontact shift must vary inversely with temperature (eq 1 and 2), the opposite behavior observed for the former six chelates is only consistent with opposing contact and pseudocontact shifts in these chelates with each contribution displaying different temperature dependencies. The temperature-dependent data for the latter five chelates do not require additive contact and pseudocontact contributions for these ions but are most consistent with this hypothesis. In each of the paramagnetic complexes, the line width of the chelated EDTA signal sharpened considerably at the higher temperatures while the line width of the unchelated ligand did not change significantly. These line-width changes therefore do not reflect alterations in the ligand exchange rate between the two environments at pH 4.5 but rather must reflect an intramolecular averaging process for the carboxyl groups of the complexed EDTA which relaxes the LIS nonequivalency at higher temperatures.

As noted above, pseudocontact shifts are expected to follow a T^{-2} dependency (with perhaps a minor contribution from a T^{-3} term[14,16]) and contact shifts a T^{-1} dependency. Thus, in principle, a separation of these individual contributions could be achieved by plotting LIS·T vs. T^{-1} and extrapolating the data to infinitely high temperatures.[10,11,13,27]

$$\mathrm{LIS}\cdot T = A + B/T \tag{3}$$

The intercept, A, would yield the contact contribution and the slope, B, the pseudocontact contribution to the observed LIS at any given temperature. The results of a linear regression of the data are found in Table I. Although the statistical fit of the temperature data to eq 1 was excellent ($R^2 \geq 0.98$ for eight of the lanthanides), the T^{-1} and T^{-2} dependent shift contributions tabulated for T = 318 K do not correlate well with the signs or relative magnitudes of $\langle S_z \rangle_j$[21] and C_j^D[9] values for each lanthanide, respectively. Furthermore, as noted above, the Tb^{3+} and Dy^{3+} pseudocontact shifts must be downfield and the temperature-dependent separation procedure predicts upfield shifts for both chelates. These results led us to examine the fit of our data to

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Table II. Linear and Nonlinear Regressions of the Tb(EDTA) Temperature-Dependent Lanthanide-Induced Shift Data to Four Mathematical Functions

function[a]	W	A[b]	B[b]	C[b]	R^2	$\mathrm{LIS_{calcd}}$
$\mathrm{LIS} = \frac{A}{T} + W$	−60.0	-2.05×10^4			0.984	−124.4
$\mathrm{LIS} = \frac{B}{T^2} + W$	−90.2		-3.47×10^6		0.989	−124.5
$\mathrm{LIS} = \frac{A}{T} + \frac{B}{T^2}$		-5.89×10^4 (−185.2)	$+6.09 \times 10^6$ (+60.2)		0.985	−125.0
$\mathrm{LIS} = \frac{A}{T} + \frac{B}{T^2} + \frac{C}{T^3}$		-8.53×10^4 (−268.2)	$+2.32 \times 10^7$ (+229.5)	-2.75×10^9 (−85.6)	0.999	−124.3

[a] The data consisted of seven LIS measured between 298 and 358 K at 10 K intervals. [b] The values in parentheses are calculated shift contributions to each temperature-dependent term for $T = 318$ K.

other possible temperature-dependent functions.

The results of four such fits of the Tb(EDTA) temperature data are illustrated in Table II. All four functions correctly predict the measured Tb(EDTA) shift at 318 K to within the error limits of the experimental measurement (−124.9 ± 1 ppm). The large intercepts observed for the LIS vs. T^{-1} and T^{-2} functions indicate quite clearly that the LIS data contain multiple T^{-n} component terms. A nonlinear regression of the data to the multiple T^{-n} functions also yields excellent fits but there is little agreement between the calculated T^{-1}-dependent shifts for functions 3 and 4 nor between the calculated T^{-2}-dependent shifts for these same functions. In fact, for several of the lanthanides these two functions predict opposite signs for the T^{-1}-dependent and/or T^{-2}-dependent terms. Our analyses show quite clearly that separation of LIS into their unique contact and pseudocontact components by any temperature-dependent separation method is improbable, especially using temperature data collected over a limited range as required for aqueous solutions.

Temperature-Independent Separation Methods. The pseudocontact and contact contributions to the observed LIS were also separated by the method of Reilley.[17] The requirements for successful use of this method include an isostructural approximation for the Ln(EDTA) chelates across the series or within subgroups along the series and constant scalar hyperfine coupling constants, A, within each group or subgroup. An assumption of axial or "effective" axial symmetry for the chelates is not necessary. Substituting the measured shifts along with the pseudocontact (C_j^{D}) and contact ($\langle S_z \rangle_j$) proportionality constants tabulated by Bleaney[9] and Golding and Halton,[21] respectively, into a nonlinear least-squares fitting procedure yields the best values of G_i and F_i for the entire data set.

$$\mathrm{LIS_{obsd}} = G_i C_j^{\mathrm{D}} + F_i \langle S_z \rangle_j \tag{4}$$

In this case, G_i is a geometric factor which describes the pseudocontact shift in the complexed carboxyl carbon (see eq 1) and F_i includes several constants including the scalar hyperfine constant which best describes the contact shift contribution to this same nucleus (see eq 2). A rather poor fit is achieved when all ten lanthanide shifts (excluding $\mathrm{Gd^{3+}}$) are included; the calculated $\mathrm{Dy^{3+}}$ shift is too low by 12 ppm and the signs of two other shifts are incorrectly calculated. Previous data from our laboratory[28] and others[29-31] indicated that a structural change occurs near the middle of the Ln(EDTA) series, perhaps due to an exclusion of one water molecule from the primary coordination sphere of the heavier lanthanide chelates. Dividing these into two subgroups, $\mathrm{Pr^{3+}} \rightarrow \mathrm{Tb^{3+}}$ and $\mathrm{Dy^{3+}} \rightarrow \mathrm{Yb^{3+}}$, improved the fit dramatically. This does not result from a statistical bias due to a reduction in variable parameters from ten to five because a random selection of any five shifts does not mimic the improvement. The "best fit" calculated pseudocontact, contact, and total shifts are compared with the measured LIS in Table III. The largest deviation between observed and calculated shifts occurs in the Tm(EDTA) and Yb(EDTA) chelates, perhaps indicating that these chelates display a slightly different structure from the other chelates in this subgroup.

Table III. Pseudocontact and Contact Contributions to the Lanthanide-Induced Shifts in the Carboxyl Resonance of Ln(EDTA)

	Lanthanide Induced Shifts (ppm)			
ion	$\mathrm{LIS_{obsd}}$[a]	$\mathrm{LIS_{calcd}}$	$\mathrm{LIS_{pc}}$[b]	$\mathrm{LIS_{c}}$[b]
$\mathrm{Pr^{3+}}$	+3.92	+2.0	−5.6	+7.6
$\mathrm{Nd^{3+}}$	+9.68	+9.3	−2.1	+11.4
$\mathrm{Sm^{3+}}$	−4.12	−0.6[c]	−0.4[c]	−0.3[c]
$\mathrm{Eu^{3+}}$	−23.87	−25.1	+2.0	−27.2
$\mathrm{Gd^{3+}}$	−79 ± 1	*d*	*d*	*d*
$\mathrm{Tb^{3+}}$	−124.86 ± 1	−124.7	−43.9	−80.8
$\mathrm{Dy^{3+}}$	−151.14 ± 1	−147.3	−76.3	−71.1
$\mathrm{Ho^{3+}}$	−80.10 ± 0.5	−86.1	−29.8	−56.3
$\mathrm{Er^{3+}}$	−12.90	−13.2	+25.2	−38.4
$\mathrm{Tm^{3+}}$	+13.04	+20.0	+40.4	−20.4
$\mathrm{Yb^{3+}}$	+19.92	+10.3	+16.8	−6.5

[a] The shifts were measured at 318 K and have an error limit of ±0.1 ppm unless otherwise indicated. Downfield LIS are negative. [b] Separated by the method of Reilley (ref 17). [c] Large uncertainties in the $\langle S_z \rangle$[21] and C_j^{D}[9] values for $\mathrm{Sm^{3+}}$ make the errors on these values correspondingly large. [d] Data not included in the least-squares separation procedure.

The least-squares fit yields the parameters $G_i = 0.51 \pm 0.02$, $F_i = 2.53 \pm 0.03$ and $G_i = 0.76 \pm 0.03$, $F_i = 2.49 \pm 0.03$ for the light and heavy lanthanide subgroups, respectively. These values suggest that the two subgroups arise from a geometrical change in structure which alters the pseudocontact term without changing the contact term. Therefore, in this case, an equally good estimate of the contact contribution to each shift could have been made by calculating the scalar hyperfine coupling constant (A in eq 2) from the measured Gd(EDTA) shift at 318 K. Although the Gd(EDTA) data were not used in the fitting procedure, the contact shift calculated for Gd(EDTA) by using $F_i = 2.53$ and the appropriate value of $\langle S_z \rangle_j$ is −79.7 ppm, a value in excellent agreement with the experimentally determined shift.

Conclusions

The lanthanide–EDTA chelates provide excellent systems for examining the temperature dependency of paramagnetic lanthanide-induced shifts. Below pH 8, the chelated EDTA exchanges only slowly between the lanthanide ion coordination sphere and the bulk solution, thereby eliminating any extrapolation procedures to obtain the LIS and avoiding complications arising from a temperature-dependent Ln(EDTA) stability constant. Several of the paramagnetic induced shifts actually increase in magnitude with temperature between 298 and 358 K and this observation proved to parallel those ions which induce opposing contact and pseudocontact shifts. Each chelated Ln(EDTA) carboxyl resonance sharpens with increasing temperatures, indicating some internal averaging of the bound EDTA with respect to the lanthanide ion coordination sphere. The small shifts in the unchelated EDTA resonances correspond to a rapid exchange of

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these nonchelated ligands with the remaining water molecules in the primary coordination sphere of the chelated lanthanide ion.[29,31]

As outlined above, a separation of the contact and pseudocontact components of each LIS by using the temperature-dependent data did not prove successful. The reasons for the failure in these systems vs. the excellent success in the exchange-inert Yb(DPA)$_3$ system[11] are not clear. Perhaps the line-width changes we observe in the chelated Ln(EDTA) resonances reflect a rather dramatic temperature-dependent structural change in this more flexible chelate. Such a structural change would clearly doom the temperature-dependent separation procedure to failure.

The temperature-independent Reilley method[17] not only proved useful for the separation of contact and pseudocontact shift components to the Ln(EDTA) but also provided indirect evidence for a Ln(EDTA) structural change near the center of the lanthanide series. Although the numerical values of G_i and F_i for the two Ln(EDTA) structural subgroups provide no specific structural information, we suspect that the change in G_i values near the center of the series parallels a decrease in coordination number perhaps due to the expulsion of one water molecule from the lanthanide coordination sphere. The minor changes in Ln–O and Ln–N bond lengths within each subgroup necessitated by decreasing cation size apparently do not preclude successful use of this separation method. Clearly, even the chelates within each subgroup are not "isostructural" but their dynamic solution structures are similar enough to allow evaluation of unique G_i and F_i values for the entire subgroup. The identical values of F_i for the two subgroups indicate that the structural change which increases G_i by nearly 50% does not alter the hyperfine coupling constant, A. Perhaps this is only fortuitous but we could argue that a structural alteration such as removal of one water molecule from the lanthanide coordination sphere would not necessarily change the lanthanide ion electron spin density reaching the carboxyl nucleus. Regardless, the constancy of A along the entire Ln(EDTA) series would have allowed a rapid estimation of the contact component to each shift by proportioning the shift observed for Gd(EDTA) to the relative $\langle S_z \rangle$ values for each lanthanide. This method of determining the contact component should, however, in general, be avoided for aqueous lanthanide species unless other evidence is available to indicate that A is relatively constant along the entire cation series.[5]

The positive electron spin density found at the carboxyl carbon nuclei in EDTA is similar to that measured in L-alanine at pH 3.[5] A comparison of the carboxyl contact shifts observed here with those of the exchange-inert trisdipicolinate chelates[11] shows that the latter are approximately 50% smaller than the EDTA shifts and the electron spin density at the carboxyl nuclei of dipicolinate is of opposite sign. This suggests that the unpaired spin density may be delocalized onto the carboxyl nuclei via a different mechanism in the aromatic chelate systems. Further chelate studies will be necessary to delineate such differences in electron delocalization mechanisms.

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Supplementary Material Available: Paramagnetic lanthanide-induced shifts in the carboxyl resonance of EDTA as a function of temperature (Table IV) (1 page). Ordering information is given on any current masterhead page.

Electronic Structure of the Alkyllithium Clusters, $(CH_3Li)_n$, n = 1–6, and $(C_2H_5Li)_n$, n = 1–2

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Abstract: Optimized geometries and wave functions for the oligomers of CH_3Li, $(CH_3Li)_n$, for n = 1–6, and for the monomer and dimer of C_2H_5Li have been obtained by using the approximate molecular orbital method, PRDDO. Wave functions for $(CH_3Li)_n$, n = 1–3, have also been obtained from double-ζ basis sets. The properties of these oligomers have been examined by using both the canonical and localized molecular orbitals. Binding energies show that there exist stable planar arrangements of Li and C atoms for each oligomer n = 2–6 and that a condensed tetramer and condensed hexamer are also stable. The ionization potentials derived from Koopmans' theorem have been used to reinterpret experimental mass spectral studies. Bonding is discussed in terms of localized molecular orbitals obtained by using the Boys criteria. The bonding in these clusters is found to be multicentered involving closed three-center Li–C–Li and closed four-centered Li_3C bonds. The ethyllithium compounds are found to be very similar to their methyl counterparts.

Introduction

Currently there is wide interest in molecules containing lithium and organic fragments.[2a–d] This interest is due to their use as synthetic reagents[2e] and to their novel bonding and spin properties.[3] These molecules are also useful as models for simple electron-deficient metal clusters, an added advantage being that they have been partially characterized experimentally. Since they are electron deficient, these compounds can oligomerize and should form multicentered bonds that are analogous to bonding patterns found in the boron hydrides and carbonanes.[4] Oligomers of the

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