Analysis of Multinuclear Lanthanide-induced Shifts. Part 2.[1] The Geometry of Ketone Binding to Lanthanides

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Multinuclear lanthanide-induced shifts for a variety of Ln(fod)$_3$ shift reagents have been combined with Gd(fod)$_3$-induced longitudinal relaxation-rate enhancements in geometry calculations for lanthanide adducts of adamantanone. The experimental results are most consistent with an Ln–O–C angle of about 180° and an Ln–O distance of approximately 2.5 Å. The fit between calculated and experimental data is very soft, and simulated data indicate that this is characteristic of the linear Ln–O–C array. When induced shifts and relaxation rate enhancements are simulated for nonlinear co-ordination geometries, the results are inconsistent with the experimental data.

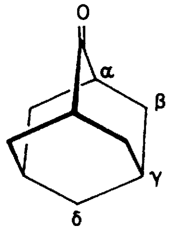
The induced effects of lanthanide reagents on the chemical shifts and relaxation rates of the nuclei of organic ligands bound to them are valuable qualitative aids for the simplification and interpretation of n.m.r. spectra.[2–5] An even more powerful application of lanthanides in structural analysis employs the mathematical relationships between the induced phenomena and the geometry of the complex. In particular, the relaxation-rate enhancements and the pseudocontact portion of the lanthanide-induced shifts (LIS) contain important information about the structure of the substrate ligand.

The pseudocontact contribution frequently dominates the observed LIS, but for nuclei close to the co-ordination site and for non-hydrogen nuclei, substantial contact and diamagnetic shifts are commonly observed as well. Although the latter two are again related to the structure of the complex, simple mathematical relationships that would allow prediction of these components are not available. Consequently, the use of LIS for rigorous analysis of molecular structure requires a separation of the various contributions to the experimentally observed shifts. In a previous paper we have reported improved procedures for obtaining the required separation.[1] Assuming that the lanthanide complex has axial symmetry or effective axial symmetry as result of internal reorientations,[6,7] the pseudocontact shift can be related to the structure of the complex by the McConnell–Robertson equation (1):[8]

$$\Delta = k\cdot G = k(3\cos^2\theta - 1)/r^3 \qquad (1)$$

Here Δ is the pseudocontact shift for a given nucleus in the 1:1 lanthanide–substrate complex. It is equal to the product of the geometry factor, G, and the constant k, a measure of the induced magnetic dipole, which is characteristic of the particular lanthanide. The geometry factor is defined in terms of r, the distance between the Ln^{III} centre and the nucleus in question, and θ, the angle made by the vector r with the Ln-donor site bond.

Generally, gadolinium reagents are the most suitable for relaxation-rate enhancement studies. Gd has a relatively long electron relaxation time, and this gives rise to large lanthanide-induced relaxation (LIR) effects in the ligand nuclei. The large magnitudes of the enhancements allow measurements at low molar ratios of Gd reagent: substrate ($<10^{-2}$). Assuming that the mean residence time of the substrate ligand in a Gd complex is short with respect to the longitudinal relaxation time of the ligand nuclei in this complex, the measured relaxation rate can be related to the molecular structure *via* equation (2).[9–11]



Adamantanone

$$\text{LIR} = 1/T_1 - 1/T_1{}^0 = k'/r^6 + 1/T_1{}^{\text{int}} \qquad (2)$$

Here $1/T_1$ denotes the measured relaxation rate of a nucleus in the complex, $1/T_1{}^0$ is the relaxation rate in the absence of Gd, and $1/T_1{}^{\text{int}}$ is the contribution from nonspecific intermolecular interactions. Previously, we have shown that a good estimate of the intermolecular contribution is essential for structural analysis based on relaxation-rate enhancements.[12]

In this paper we present the results of structural analysis of the Ln(fod)$_3$–adamantanone adducts (Ln = La, Pr, Eu, Gd, Dy, Yb, where fod = 6,6,7,7,8,8,8-heptafluoro-2,2-dimethyl-3,5-octanedionate) based on LIS for ^{17}O, ^{13}C, and ^{1}H combined with LIR for ^{13}C and ^{1}H.

The lanthanide-induced shifts of ketones have generally been interpreted in terms of a two-site model in which the observed LIS are time-averages resulting from two discrete, rapidly interconverting complexes, or in terms of a one-site model in which there is a single complex.[13] The co-ordination geometry of the 2-site model has generally been assumed to be that of an sp^2 carbonyl oxygen with a C–O–Ln bond angle of about 120°, whereas an approximately linear co-ordination geometry is anticipated for the one-site model.[13] Abraham has suggested that the two-site model for a lanthanide adduct of adamantanone would produce unfavourable steric interactions.[14] These interactions correspond to H–C–O–Ln eclipsing and could be alleviated by small distortions of the lanthanide out of the plane of the carbonyl group. This is chemically a reasonable modification of the two-site model, but the better fit between calculated and observed LIS for the resulting four-site model[14,15] might only be the result of increasing the number of variable

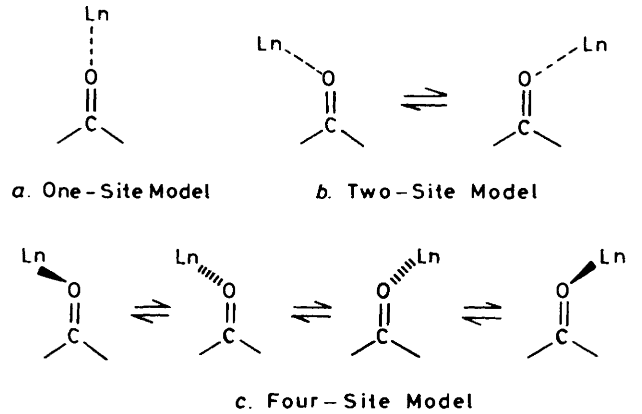


Figure 1. Co-ordination geometry of the carbonyl group according to different models for interaction with lanthanide shift reagents.

parameters in the fitting procedure. Hofer has demonstrated with simulated shift data that, at least in certain situations, it is difficult statistically to distinguish between the one- and two-site models on the basis of LIS data alone.[16] These different models are illustrated in Figure 1.

A previous study of the Eu(fod)$_3$-induced ^{1}H shifts of adamantanone and its substituted derivatives afforded results for which a satisfactory interpretation could be obtained only by employing the one-site model.[13] Moreover, *ab initio* molecular orbital calculations of the geometries and energies for complexes between formaldehyde and first- and second-row cations suggest that the one-site model may be a proper description of the actual complex between a ketone and a lanthanide shift reagent.[17]

For different ketones, the one-site, two-site, and four-site models have all been found to give reasonable agreement between experiment and prediction.[2,13–16] Consequently, the correct co-ordination geometry for lanthanide shift reagents with carbonyl compounds has not yet been established. In view of the potential value of using both lanthanide-induced shifts and lanthanide-induced relaxation enhancements for rigorous structural analysis, a satisfactory resolution of this question takes on considerable significance. Therefore, we undertook a careful and extensive study of both LIS and LIR for all nuclei (^{13}C, ^{17}O, and ^{1}H) of adamantanone using a variety of different lanthanides as shift reagents. A thorough analysis of the LIS and LIR was carried out in order to determine which, if any, of the models most accurately and reliably predicts the experimental data.

Experimental

All n.m.r. experiments were performed on a Nicolet 200 WB spectrometer at 25 °C. The measurement of the lanthanide-induced shifts and the data handling have been described previously.[1,18]

The longitudinal ^{13}C relaxation rates were measured with a sample containing 0.721 mol l^{-1} of adamantanone in CDCl$_3$. In order to estimate the intermolecular contribution to the relaxation-rate enhancement, adamantane (0.220 mol l^{-1}) was added to this solution. A 12 mm sample tube containing 6.28 ml of this solution was used for the measurements. No degassing was employed. The gadolinium reagent was added as a 0.165M solution in CDCl$_3$ *via* a calibrated micro-syringe. Five measurements at ρ-values (Ln/adamantanone molar ratios) varying between 0 and 2.7 × 10^{-3} were carried out. The relaxation rates were obtained with the inversion recovery method: (180°—τ—90°) pulse sequence. The ^{1}H relaxation-rate measurements were performed with a 5 mm sample tube containing a CDCl$_3$ solution of adamantanone (0.220 mol l^{-1}), adamantane (0.050 mol l^{-1}), and tris(fod)europium(III) (0.041 mol l^{-1}). The ρ-values were varied between 0 and 4.24 × 10^{-4}. Here a (180°—τ—12°) pulse sequence was employed.[19] The magnetization recovery curve was always single exponential.

All solvents used were dried over zeolite KA. Since commercial tris(fod)lanthanide(III) reagents are often contaminated with impurities,[20] all of our lanthanide reagents were synthesized according to the procedure described by Sievers *et al.*[21] Purification was achieved by recrystallization from dichloromethane at −30 °C. Subsequent storage and handling in a glove box flushed with dry nitrogen prevented any hydration of the Ln(fod)$_3$ reagents.

Results and Discussion

Lanthanide-induced Shifts.—We have previously measured the bound shifts for the 1:1 adducts of adamantanone and several Ln(fod)$_3$ reagents (where Ln = La, Pr, Eu, Gd, Dy, Yb).[1] The diamagnetic, contact, and pseudocontact contributions to the observed LIS were separated using a procedure which was not subject to any constraints on the structure of the complexes other than the approximation that the complexes are isostructural.[1] This means that the relative pseudocontact shifts do not vary for the different lanthanides. Although only relative values of *k* and *G* were obtained by that procedure, their product affords the absolute magnitudes of the pseudocontact contribution to the LIS. The relative pseudocontact shifts determined in that study[1] have now been used to evaluate the one-site and two-site models for co-ordination of adamantanone to the Ln(fod)$_3$ reagents. The relative bound pseudocontact shifts for the ^{1}H, ^{13}C, and ^{17}O nuclei were compared statistically with those predicted by equation (3) for a variety of different co-ordination geometries corresponding to the two-site model.

$$\Delta_{rel} = k_{rel}(3\cos^2\theta - 1)/r^3 \qquad (3)$$

The adamantanone structure, as determined by a molecular mechanics (MM2)[22] calculation, was held constant in these computations. Since the previously determined pseudocontact shifts were relative rather than absolute,[1] the only parameter requiring optimization was a single scaling factor, k_{rel} in equation (3), which was optimized for each co-ordination geometry. We employed the agreement factor[23,24]*,† as the criterion for statistically evaluating the fit between calculated and experimental pseudocontact shifts. Data for each adamantanone nucleus were weighted as the inverse of the square of the relative bound pseudocontact shift in an effort to minimize the effect of experimental errors.[1] Co-ordination geometries were varied in both Ln–O distance (0.02 Å increments) and in the C–O–Ln bond angle (2.0° increments). Identical bond lengths and angles were used for each of the two geometries of the two-site model as demanded by the C_{2v} symmetry of adamantanone.

The resulting matrix of agreement factors indicated a very soft fit between observed and predicted LIS as a function of the bond length. Nevertheless, a minimum agreement factor (AF =

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* The agreement factor is defined as: AF = $[\Sigma w(\text{obs.} - \text{calc.})^2/\Sigma w(\text{obs.})^2]^{0.5}$, where obs. is an experimental Ln-induced shift or relaxation enhancement, calc. the corresponding calculated value, and *w* is the weighting factor for a particular observation.

† The usefulness of Hamilton's *R*-ratio test using the agreement factor AF has been questioned.[24] However, we have only employed the agreement factor qualitatively, and have not attempted to select a single, 'correct' structure on the basis of the *R*-ratio.

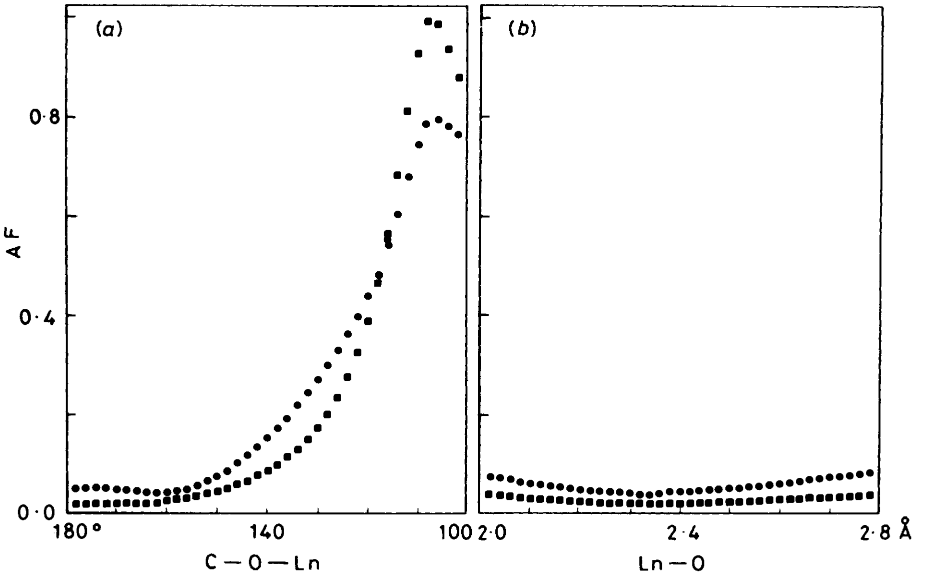

Figure 2. Plots of the agreement factor for experimental LIS (■) and LIS/LIR (●) as a function of the co-ordination geometry assumed for the two-site model. (*a*) Variation of the C–O–Ln bond angle, and (*b*) variation of the Ln–O bond length. Each of the curves represents a cross-section through the minimum on the agreement factor surfaces (C–O–Ln = 180° and Ln–O = 2.34 Å).

Table 1. Experimental and predicted relative pseudocontact LIS for adamantanone

Nucleus	Exp.[a]	Calc. (2.34)[b]	Calc. (2.50)[c]
C=*O*	23.03	19.09	19.12
C=O	4.90	5.84	5.85
C_α	2.64	2.52	2.53
C_β	1.44	1.36	1.36
C_γ	1.07	1.05	1.05
C_δ	0.80	0.80	0.82
H_α	2.51	2.20	2.20
H_β*syn*	1.26	1.27	1.27
H_β*anti*	0.82	0.82	0.82
H_γ	0.65	0.67	0.67
H_δ	0.58	0.59	0.59

[a] Optimized (relative) values of *G* from Table 3 of ref. 5; [b] Calculated for the optimum geometry in Figure 1; scaled to give the best agreement with the experimental values; [c] Calculated for the geometry of the Eu complex suggested in ref. 13; scaled to give the best agreement with the experimental values.

Table 2. Experimental and predicted LIR for adamantanone[a]

Nucleus	Exp.[b]	Calc. (opt)	Calc. (2.50)[e]
C=O	7.20	7.11[c]	6.50
C_α	1.55	1.56[c]	1.52
C_β	0.45	0.48[c]	0.48
C_γ	0.24	0.23[c]	0.24
C_δ	0.14	0.12[c]	0.12
H_α	22.32	17.22[d]	17.18
H_β*syn*	5.12	5.11[d]	5.19
H_β*anti*	1.64	1.64[d]	1.63
H_γ	0.87	0.88[d]	0.87
H_δ	0.54	0.54[d]	0.53

[a] Values of $1/T_1$ (10^3 s^{-1}) from extrapolation to $\rho = 1$; [b] After subtraction of $1/T_1^{int}$; for ^{13}C, $1/T_1^{int} = 0.088 \times 10^3$ s^{-1}; for ^1H, $1/T_1^{int} = 0.624 \times 10^3$ s^{-1}; [c] Calculated for the optimum geometry (Ln–O = 2.64 Å) for ^{13}C LIR; $k' = 1.42 \times 10^{-5}$; [d] Calculated for the optimum geometry (Ln–O = 2.34 Å) for ^1H LIR; $k' = 1.45 \times 10^{-5}$; [e] Calculated for the optimum geometry for LIS/LIR of all nuclei (excluding the carbonyl group and H_α); this is also the geometry suggested in ref. 13; $k' = 1.69 \times 10^{-5}$ for ^{13}C; $k' = 1.31 \times 10^{-5}$ for ^1H.

0.021) was found for an Ln–O bond length of 2.34 Å and a C–O–Ln bond angle of 180°. Note that the bond angle of 180° corresponds to a *single structure*, *i.e.*, it supports the *one-site* model. Table 1 summarizes the experimental data and that for the structure with the lowest agreement factor. Also shown are the data for the geometry suggested previously for the adamantanone–Eu(fod)$_3$ complex.[13] Figure 2 depicts cross-sections through the minimum in the agreement factor surface. Although the agreement factor is essentially invariant over the range of 160—180° in Figure 2*a*, the fit for a bond angle in the region of 120° (the bond angle expected for sp^2-hybridized oxygen) is clearly unacceptable. The extremely shallow curve in Figure 2*b* supports our previous arguments that bond lengths to lanthanide shift reagents cannot be determined solely on the basis of LIS.[25,26] Over the entire range of bond lengths shown in Figure 2*b* the agreement factor remains below the level of 5%, a value that we have suggested as typical experimental error for multinuclear LIS studies.[1] The results obtained here for our multinuclear study are thus in full accord with a previous study using only ^1H LIS with Eu(fod)$_3$.[13]

^{13}C *Relaxation Rates.*—The Gd(fod)$_3$-induced ^{13}C relaxation rates were measured at five different Gd:adamantanone molar ratios (ranging up to 2.7×10^{-3}). The inert hydrocarbon adamantane, which has about the same molecular dimensions as adamantanone, was used as a probe for the nonspecific intermolecular contribution to T_1 upon addition of Gd(fod)$_3$. Linear relationships (correlation coefficients >0.998) were observed for the relaxation rates of the various nuclei as a function of ρ. Since the ρ-values used were very low, the slope of these lines gave directly the values of the relaxation enhancements in the 1:2 complex of Gd(fod)$_3$ with the ketone.[12] Once these intermolecular contributions had been determined, the relaxation enhancements were fitted to the molecular

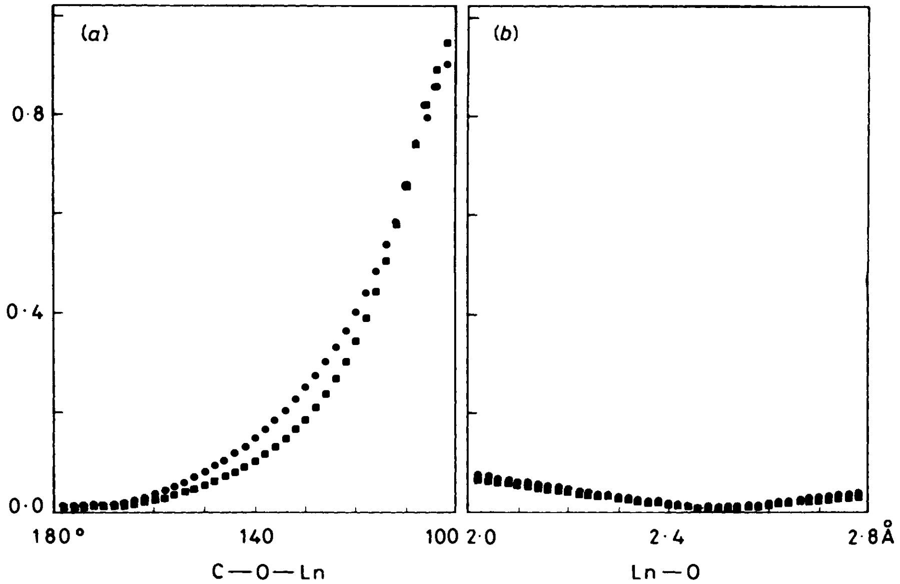

Figure 3. Plots of the agreement factor for simulated 'experimental' LIS (■) and LIS/LIR (●) as a function of the co-ordination geometry assumed for the two-site model: (*a*) Variation of the C–O–Ln bond angle, and (*b*) variation of the Ln–O bond length. Each of the curves represents a cross section through the minimum on the agreement factor surface (C–O–Ln = 180° and Ln–O = 2.50 Å). 'Experimental' values were simulated for a 1-site model with a C–O–Ln bond angle of 180° and a Ln–O bond length of 2.50 Å.

structure *via* equation (2) using the same co-ordination geometries as described above for the LIS studies. Of necessity, k' was treated as a variable parameter in the fitting procedure, but as discussed above for LIS calculations, all geometric parameters were fixed for each computation.

As in the case of the LIS, the fit of the agreement factor as a function of Ln–O bond length and C–O–Ln bond angle was again very soft. The overall minimum (AF = 0.049) was again found at a bond length of 2.34 Å and a bond angle of 180°, but comparable agreement factors were observed over a wide range of bond lengths and for bond angles in the region of 160—180°. Table 2 summarizes the experimental LIR (for both ^{13}C and ^{1}H). Also shown are the calculated values for the geometry corresponding to that reported previously for the Eu(fod)$_3$ adduct of adamantanone.[13]

^{1}H *Relaxation Rates.*—In the unperturbed spectrum of adamantanone the ^{1}H peaks overlap substantially. In order to permit measurement of the individual signals, just enough Eu(fod)$_3$ was added to the sample ($\rho = 0.22$) to produce full separation of the peaks. Adamantane was again added as a probe for the intermolecular contributions. The relaxation rates were measured at five different Gd(fod)$_3$: adamantanone ratios (to a maximum molar ratio of 4.3×10^{-3}). Straight lines were again obtained for plots of the relaxation rates *vs.* ρ (correlation coefficients >0.997). However, statistical comparison of observed ^{1}H LIR with those predicted by equation (2) produced no minimum in the agreement factor at Gd–O bond lengths below 4 Å. It appears that our estimates of the intermolecular contributions to the ^{1}H LIR are inadequate, although the same procedures have previously afforded consistent results for both ^{13}C and ^{1}H data.[12,27] We suspect that the inconsistent results for the present ^{1}H LIR data result from the complexity of the system: a number of assumptions must be made in deriving the equations used for estimating the intermolecular contribution to the longitudinal relaxation-rate enhancement.[28] For example, the various species involved in the intermolecular relaxation mechanism are treated as spherical, and this approximation is less valid for the hydrogens on the periphery than for the carbon atoms in the interior.

As seen in Table 2, the relaxation-rate enhancement of H_α appears to be too large. Therefore we carried out an additional set of computations in which that nucleus was excluded. We used the total LIR as defined in equation (2), and both k' and T_1^{int} were optimized. A shallow minimum with an agreement factor of 0.005 was then obtained for a bond length of 2.64 Å and a C–O–Gd bond angle of 170°. This procedure resulted in an optimized value of $T_1^{int} = 0.624 \times 10^{-3}$, which is quite different from the value of 0.233×10^{-3} that had been estimated from the ^{1}H LIR data for adamantane.

Combination of All Data (*LIS/LIR*).—A simultaneous fit of the induced shift and relaxation data to the molecular structure gave a minimum agreement factor of 0.042 for a lanthanide–oxygen bond length of 2.34 Å and a C–O–Ln bond angle of 172°. Cross sections through this minimum are presented in Figure 2. As in the case of LIS data alone, the agreement factor surface is very flat. When the calculation was repeated, however, with exclusion of the data for the carbonyl oxygen and carbon and for H_α (the nuclei for which the pseudocontact shifts may be less reliable),[1] a lower agreement factor (0.029) resulted, together with a more reasonable co-ordination geometry[13] (Ln–O = 2.50 Å, C–O–Ln = 180°). As can be seen from inspection of Figure 2, however, the fit remains soft. Nevertheless, the agreement factors for structures corresponding to a two-site model with C–O–Ln = 120° remain totally unacceptable.

The poor agreement between experimental and predicted LIS and LIR for the nuclei close to the Ln^{III} cation may have several causes: (i) the separation of the several contributions to the LIS may not be sufficient for those nuclei; (ii) the observations for those nuclei are relatively inaccurate due to line broadening; and (iii) the geometry around the carbonyl function may differ somewhat in the bound and the free state: MO calculations on cation complexes of formaldehyde show that there such deformations indeed occur.[17]

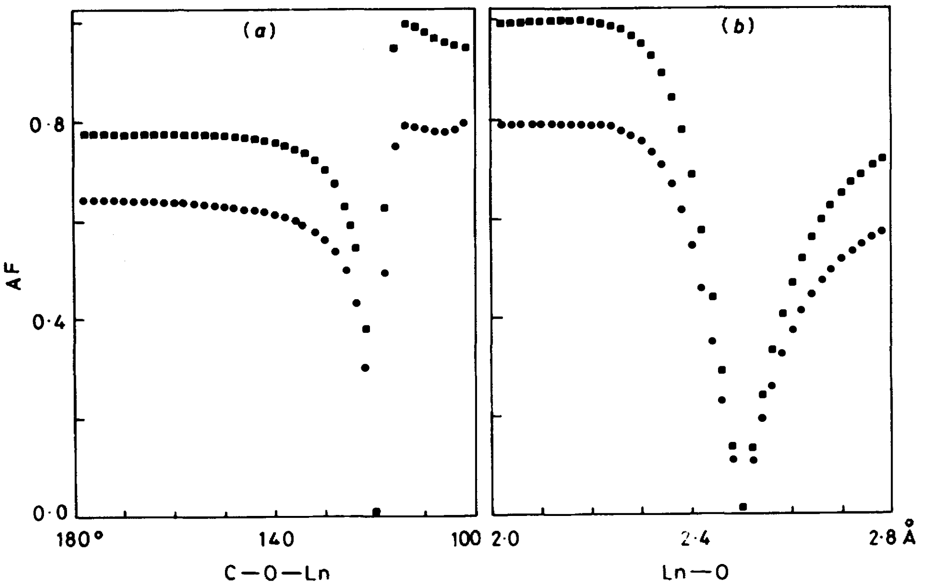

Figure 4. Plots of the agreement factor for simulated 'experimental' LIS (■) and LIS/LIR (●) as a function of the co-ordination geometry assumed for the two-site model. (*a*) Variation of the C–O–Ln bond angle, and (*b*) variation of the Ln–O bond length. Each of the curves represents a cross-section through the minimum on the agreement factor surface (C–O–Ln = 120° and Ln–O = 2.50 Å). 'Experimental' values were simulated for a 2-site model with a C–O–Ln bond angle of 120° and a Ln–O bond length of 2.50 Å.

Table 3. Dissected LIS for the 1:1 complex of adamantanone with Dy(fod)$_3$

Nucleus	$\Delta_{exp.}$	Δ_d[a]	Δ_c[b]	Δ_p[c]	$\Delta_{calc.}$[d,e]
C=*O*	−4 724.04	−20.93	−2 075.36	−2 020.98	−4 117.27
C=O	(−923.17)	7.53	14.62	−609.15	−587.00
C_α	−278.17	−0.06	−4.48	−260.49	−265.03
C_β	−133.13	0.50	5.79	−139.90	−133.61
C_γ	−103.86	−0.10	−0.74	−107.81	−108.65
C_δ	−77.24	−0.02	−0.83	−81.64	−82.49
H_α	−255.79	0.08	4.25	−225.42	−221.09
H_β*syn*	−125.83	0.00	0.20	−129.37	−129.17
H_β*anti*	−82.53	−0.01	−0.17	−83.52	−83.70
H_γ	−64.75	−0.04	0.49	−68.09	−67.64
H_δ	−58.64	−0.01	0.00	−60.15	−60.16

[a] From the La(fod)$_3$-induced shifts (ref. 5); [b] Calculated from $<S_z>$ and *F*-values of ref. 5; [c] Calculated using $k = -15\,048.2$ (ref. 5) with Dy–O = 2.46 Å; [d] $\Delta_{calc.} = \Delta_d + \Delta_c + \Delta_p$; [e] The agreement factor is 0.058 (with the atoms of the carbonyl group excluded).

Table 4. Dissected LIS for the 1:1 complex of adamantanone with Yb(fod)$_3$

Nucleus	$\Delta_{exp.}$	Δ_d[a]	Δ_c[b]	Δ_p[c]	$\Delta_{calc.}$[d,e]
C=*O*	359.51	−20.93	−188.09	568.62	359.60
C=O		7.53	1.32	168.61	177.46
C_α	77.71	−0.06	−0.41	71.33	70.86
C_β	39.35	0.50	0.53	38.14	39.17
C_γ	29.16	−0.10	−0.07	29.39	29.22
C_δ	21.59	−0.02	−0.08	22.23	22.13
H_α	66.05	0.08	0.39	61.25	61.72
H_β*syn*	34.48	0.00	0.02	35.10	35.17
H_β*anti*	21.99	−0.01	−0.02	22.67	22.64
H_γ	17.80	−0.04	0.04	18.49	18.49
H_δ	15.88	−0.01	0.00	16.35	16.34

[a] From the La(fod)$_3$-induced shifts (ref. 5); [b] Calculated from $<S_z>$ and *F*-values of ref. 5; [c] Calculated using $k = 4\,029.9$ (ref. 5) with Yb–O = 2.42 Å; [d] $\Delta_{calc.} = \Delta_d + \Delta_c + \Delta_p$; [e] The agreement factor is 0.043 (with the atoms of the carbonyl group excluded).

Comparison with Simulated Data.—Since all geometry calculations showed rather shallow minima, we decided to use simulated data to test the results of our experimental studies. Sets of LIS and LIR data were simulated for the two-site model using a lanthanide–oxygen bond length of 2.50 Å at four different C–O–Ln bond angles: 120°, 140°, 160°, and 180°. Note that the last of these bond angles corresponds to the one-site model. To each simulated LIS or LIR value, a random error of the same magnitude as the experimental error was added. The resulting simulated data sets were then used in geometry calculations in the same way as described above for the experimental data. The results are summarized in Figures 3 and 4 for the extremes of 180° and 120° for the bond angle used to generate the simulated data. Corresponding plots (not shown) for bond angles of 140° and 160° are intermediate between those in Figures 3 and 4.

Inspection of Figures 3 and 4 reveals that the shapes of the cross-sections through the agreement factor surfaces are highly dependent upon the co-ordination geometry used to generate the simulated LIS and LIR. Qualitatively, the curves in Figure 3 are very similar to those in Figure 2. Since the simulated LIS and LIR used to produce Figure 3 were computed for a 180° C–O–Ln bond angle, this similarity supports our conclusion that the one-site model correctly describes the co-ordination of ketones to lanthanide shift reagents. Not surprisingly, the optimum agreement factors for both LIS and LIS/LIR calculations are found at C–O–Ln = 180° and Ln–O = 2.50 Å, since these are the 'true' values used to generate the simulated data. Nevertheless, the flatness of the agreement factor surfaces indicates that experimental errors might easily displace the location of the minimum.

Even more convincing evidence in favour of the one-site model is found in the strikingly different appearance of the curves in Figure 4. Here the simulated LIS and LIR were computed for the 120° C–O–Ln bond angle which would be expected for an sp^2-hybridized oxygen in the two-site model.

For these simulated data the agreement factor surface is no longer flat, and very sharp, clearly defined minima are evident. These simulated results lead to an inescapable conclusion: if the two-site model were the correct description for binding of ketones with shift reagents, then we would have found similar, sharply defined minima for our experimental data. Consequently, the data we present here confirm unequivocally our earlier conclusion[13] that only the one-site model correctly describes the interactions of ketones with shift reagents.* In the absence of unsymmetrical steric or electronic interactions, a carbonyl group will co-ordinate to a lanthanide with a linear Ln–O–C array.

Refinement of the Calculated Lanthanide-induced Phenomena.—With the geometry of the adamantanone–Ln(fod)$_3$ complex firmly established, it is possible to refine further the procedure for separation of the various contributions to the LIS. In particular, the approximation of isostructural complexes is no longer necessary, and bond lengths based on known crystallographic data can be employed for the different lanthanides. The use of such a procedure gives more reliable values for the contact shifts, particularly for the ^{13}C, ^{17}O, and ^{1}H$_\alpha$ nuclei, and this in turn affords better values for the pseudocontact shifts of those nuclei.[1] Tables 3 and 4 illustrate the results of this refinement for Dy(fod)$_3$- and Yb(fod)$_3$-induced LIS. Comparable data for Eu(fod)$_3$ were presented in Table 3 of Ref. 1.

With the exception of the LIS for the carbonyl carbon, the carbonyl oxygen, C$_\alpha$, and H$_\alpha$, the agreement between observed and calculated data is uniformly good. The larger errors for these LIS may partly result from experimental errors but are in any case a direct consequence of the low weighting factors used for those nuclei.[1] Nevertheless, the *relative* errors for all nuclei (except the carbonyl carbon) are comparable. This improved separation of different contributions to the lanthanide-induced shifts only improves the statistical agreement between observed and calculated pseudocontact shifts. Conclusions and interpretations regarding the geometries of the adamantanone–Ln(fod)$_3$ complex remain unchanged.

The co-ordination geometry of ketones with lanthanide shift reagents has been a subject of controversy for many years.[2,13–16] Although strong evidence in support of a single, approximately linear binding geometry has been presented,[13,17] good agreement between observed and calculated shifts has also been found for two-site and four-site models.[14,15] In the present work we have employed both lanthanide-induced shifts and lanthanide-induced relaxation-rate enhancements of adamantanone to evaluate the question of binding geometry. Our results demonstrate that a combination of ^{1}H, ^{13}C, and ^{17}O LIS and LIR generated using a series of different Ln(fod)$_3$ reagents can be described more accurately by a one-site model than by a two-site model.

More importantly, we have also evaluated *simulated* LIS that were generated for both one-site and two-site models. The former yielded results (Figure 3) which were extremely similar to those obtained with our experimental data (Figure 2). A statistically better fit is found for a single, linear geometry, but the agreement factor surface is very flat. A strikingly different result was obtained, however, when the LIS were simulated for two or four symmetry-equivalent, nonlinear co-ordination geometries. These simulated data gave good agreement with calculated LIS only when the latter were calculated for a distinctly nonlinear geometry. The dramatic differences of these data from those obtained with our experimental results provide clear and unambiguous evidence that the binding of ketones to lanthanide shift reagents is properly described only by the one-site model.[13]

In addition to providing a clear answer to the question of co-ordination geometry, our results also show that a reliable separation of diamagnetic, contact, and pseudocontact shifts can be carried out for all nuclei in an organic molecule. The pseudocontact shifts are primarily of interest for evaluating the overall structure of conformation of the organic substrate, but the diamagnetic and contact shifts may also be of considerable value. Studies of polyfunctional compounds are dependent upon a reliable knowledge of those atoms which are directly co-ordinated to the lanthanide centre. Both the contact and diamagnetic shifts are ordinarily substantial only for nuclei close to the donor site, so quantitative application of these shifts will provide a direct method for determination of the donor sites.[29]

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* Simulated LIS for the four-site model (Ln–O = 2.50 Å, C–O–Ln = 120°, and C–C–O–Ln = 30°) as suggested by Abraham[14] afford results analogous to those described here for the two-site model.

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