after suitable time, identical with the spectrum of the trityl ion obtained from triphenylcarbinol in the same medium.

Kinetic Methods. For compounds 1-4 ca. 10 μl of the stock solution of the substrate in methanol (0.05-0.10 M) was introduced to 3.0 ml of aqueous acid in 1 cm uv cell thermostated at 25 ± 0.1 °C in a Cary 16 Model spectrophotometer with an external recorder. The decrease in ultraviolet absorption was measured at 276-280 nm; good linear plots of log A vs. time were obtained in all cases ($r > 0.99$). For compound 5 ca. 5 μl of the stock solution in methanol (ca. 10^{-3} M) was introduced in the same way to the mixture of aqueous perchloric acid and trifluoroacetic acid, and the increase in the absorption at 403 nm was measured. Excellent linear plots of log A vs. time were obtained ($r > 0.999$).

Activity Coefficient Measurements. For compounds 1, 2, 3, and 5, the distribution method was applied. For the *tert*-butyl derivatives 1-3, 1 ml of ca. 0.2 M solutions of substrates in cyclohexane was shaken mechanically with 5 ml of water or aqueous acid for 2 min at 25 ± 0.1 °C. The absorbance of substrates in aqueous and organic layers was measured at 276-280 nm, using a Cary 14 recording spectrophotometer. At higher acidities (above 8 M) various shaking periods from 1-3 min were applied, and the observed absorbances were extrapolated to zero shaking time. For compound 5, 1 ml of 1.6×10^{-2} M solution in chloroform was shaken with 12 ml of water or aqueous acid for 2 min, and the absorbance of substrate in aqueous layer was measured at 270 nm using 10-cm uv cells. The values of the activity coefficients were calculated from the ratio of distribution coefficients in pure water to that in a given acid solution. For compound 5, the concentration in the chloroform layer was taken as constant (distribution coefficient $< 10^{-3}$). Because of the very low solubility of compound 4 in water, activity coefficient values were obtained by solubility method. 4 (0.1 ml) was shaken with 5 ml of water or aqueous acid at 25 ± 0.1 °C for 1 h. Separate experiments showed this time to be sufficient to obtain equilibration. The concentration of the substrate in aqueous phase was then determined from the absorbance at 270 nm. At acidities above 5 M various shaking periods (1-3 h) were applied, and the observed absorbances were extrapolated to zero shaking time; extrapolation never exceeded 10% of the measured absorption values.

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Contact vs. Pseudocontact Contributions to Lanthanide-Induced Shifts in the Nuclear Magnetic Resonance Spectra of Isoquinoline and of *endo*-Norbornenol

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Abstract: The differences between calculated and observed behavior of lanthanide shift reagents vs. isoquinoline and *endo*-norbornenol have been recorded. These differences are interpreted as contact shifts. The magnitudes of the shifts are compared with several independent theoretical and experimental determinations of contact/pseudocontact ratios. Contact shifts are evident in the ^{13}C magnetic resonances of the hard base isoquinoline and the softer base norbornenol. Of the eight lanthanides studied Yb(dpm)$_3$ was found to be the most effective for determining pseudocontact indexes.

Introduction

Effects of paramagnetic ions on magnetic resonance spectra have been of research interest for more than 2 decades. The literature contains numerous articles which deal with the theoretical bases for and the experimental applications of paramagnetic ion effects to chemical problems.[2] A renewed interest in paramagnetic ion effects has been generated by reports of easily understood dispersions of the nuclear magnetic resonance signals of many organic molecules by paramagnetic lanthanide shift reagents (LSR's).[3] In this paper we will examine the source of these lanthanide-induced chemical shifts.

The total isotropic shift induced by a paramagnetic species in the NMR resonance of a molecule can be discussed in terms of two distinct effects, a through-bond effect (Fermi contact shift)[4] and a through-space effect (dipolar or pseudocontact

shift).[5] The Fermi contact term arises from the isotropic hyperfine coupling between the nucleus and the electron and provides a measure of the "unpaired spin density" present at a resonating nucleus. The dipolar or pseudocontact term arises from a dipolar interaction between the electronic magnetic moment and the nuclear spin moment, and, in principle, can provide information about the topology of the molecules being observed. The total isotropic shift can be expressed as

$$\Delta_{isotropic} = \Delta_{PC} + \Delta_{FC} \qquad (1)$$

where $\Delta_{isotropic}$ is the total observed shift, Δ_{PC} is the pseudocontact or dipolar isotropic shift, and Δ_{FC} is the Fermi contact isotropic shift.

Theoretical developments of the pseudocontact term in lanthanide shift reagents have recently been presented.[6-8] An expression for the induced pseudocontact shift of the ith nucleus of a molecule under the assumption that it has axial symmetry is:[8]

$$\Delta_{PC}{}^i = \frac{\beta^2 \nu S(S+1)}{45kT} \, F(g) \, \frac{3 \cos^2 \theta_i - 1}{r_i{}^3} \qquad (2)$$

Here, $F(g)$ is a function of $g_\parallel$ and $g_\perp$, the parallel and perpendicular components of the g tensor for the paramagnetic complex, θ_i is the angle made by the ith nucleus with the principal magnetic axis of the complex (axis of $g_\parallel$), r_i is the vector distance between the nucleus and the electron (approximated by the center of the paramagnetic metal ion). The other terms have their usual meaning. For two distinguishable resonances in a given molecule

$$\frac{\Delta_{PC}{}^i}{\Delta_{PC}{}^j} = \frac{(3 \cos^2 \theta_i - 1) \, r_j{}^3}{(3 \cos^2 \theta_j - 1) \, r_i{}^3} \qquad (3)$$

Note that if one considers only the internally scaled $\Delta_{PC}{}^i$'s for a given molecule, specific knowledge of the g tensors is not necessary.[9]

These features of the pseudocontact shift have been recognized and employed to interpret isotropic shifts in systems where the Fermi contact shift term is thought to be small (negligible). For example, the chemical shifts observed in the rare earth acetylacetonates,[10] tropolonates,[11] and acetates[12] have all been discussed as resulting primarily from the pseudocontact mechanism. The proton shifts of the pyridine and quinoline adducts of Eu(dpm)$_3$, Yb(dpm)$_3$, and Pr(dpm)$_3$, (dpm = the dipivaloylmethane anion) have been extensively interpreted by Reuben and Leigh,[13] Chalmers and Pachler,[14] Armerago et al.,[15] Huber and Pasqual,[16] Sanders et al.,[17] and Beauté et al.[18] in terms of the axially symmetric pseudocontact equation (eq 2). Horrocks and Sipe[19] have also discussed the proton shifts induced by a series of Ln(dpm)$_3$ complexes in 1-hexanol, γ-picoline N-oxide, and 4-vinylpyridine in terms of a pseudocontact interaction. With a very few exceptions,[20] the proton shifts induced by lanthanide shift reagents in the NMR spectrum of organic molecules (substrates) have all been attributed to the pseudocontact interaction.

The computational schemes developed which relate LSR behavior to structure are based on eq 2, the simplest model for the pseudocontact shift.[21] The set of r_i's and θ_i's specified by the pseudocontact portion of the lanthanide-induced shift in a given set of substrate resonances coupled with some reasonable notions of chemical bonding can provide a specific substrate-LSR topology. Moreover, the process of taking a given set of resonances dispersed by the presence of lanthanide shift reagents and generating a substrate structure (assuming that the Fermi contact part of the isotropic shift is negligible) can be performed on the basis of chemical intuition. Therefore, the information extracted from the pseudocontact term of the total isotropic shift is a useful adjunct in the study of chemical structure.

A number of the features of the Fermi contact shift have also been recognized and employed to interpret isotropic shifts in systems where the pseudocontact shift term is thought to be small.[22] A feature of the contact term is that information concerning the transmission of "spin density" through the σ- and/or π-bonding framework of the molecule in question is available. The spin density can be used to gain insights into the chemical bonding in the systems under investigation. Since spin density is transmitted by means of the molecular orbitals in the associated complex which are admixtures of the MO's centered on both the substrate and the paramagnetic species, one must, for this purpose, have detailed knowledge of the symmetry of the associated complex as well as the symmetry of the MO's of both the ligand and the paramagnetic species.

Formulations of the Fermi contact portion of the total isotropic shift for transition metals in various symmetry fields have appeared in the literature. An expression for the Fermi contact term in the lanthanide series has been developed by Taube et al.[23] and utilized by Reuben and Fiat.[12]

$$C = \frac{-Z \pi \beta \nu A J (J+1) g_L (g_L - 1)}{3kT\gamma} A \qquad (4)$$

Here ν and γ are the resultant Larmor frequency and magnetogyric ratio, β is the Bohr magneton, J is the resultant electronic spin angular momentum (in cgs units), g_L is the Landé g factor, and A is the scalar coupling constant in frequency units,

$$A = f_s A_s / 2S \qquad (5)$$

where f_s is the fractional spin occupancy, A_s is the isotropic coupling constant for one unpaired electron in an s orbital, and $2S$ is the number of unpaired electrons in the paramagnetic species. The reports of the applications of Fermi contact shifts to chemical problems have been most recently reviewed by Webb,[2d] Holik,[24] Grandjean,[25] and Ernst.[26] In contrast to the pseudocontact portion of the total isotropic shift, the Fermi contact term is not easily understood on an intuitive basis. Rather, a proper understanding of the Fermi contact shift requires the careful application of sophisticated quantum mechanical concepts.

In many cases, the total isotropic shift is necessarily a linear combination of pseudocontact and Fermi contact shift terms. The factoring of the total observed shift into these two components is a subtle problem. One of the first reports of the separation of the two terms in proton spectra deals with some bis(triarylphosphine) complexes of Co(II) and Ni(II).[27] The amount of pseudocontact shift was estimated by comparing the experimental results for Co(II) with those for Ni(II). Theory was adduced to validate the interpretation. Horrocks and Greenberg[28] have used principal molecular susceptibilities to evaluate dipolar contributions to ^{1}H NMR shifts in dichlorobis(triphenylphosphine)cobalt(II) and nickel(II) complexes. The ^{1}H shifts induced in aqueous solutions of trivalent lanthanides with quaternary alkylammonium compounds have been factored by Walker et al.[29] These workers assumed a form of the dipolar contribution based on one of the substrate resonances, calculated the dipolar shift term for the other substrate resonances, and assumed the differences (observed minus calculated) represented a contact shift. Reuben and Fiat[12] have studied a series of aqueous lanthanide ions via ^{17}O and ^{1}H NMR. They determined the contact contribution to the ^{1}H resonances by using Gd^{3+} as the isotropic probe. Subtraction of certain experimental values then factored the observed shift into a pseudocontact and contact term.

Utilization of the chemical shifts induced by lanthanide shift reagents requires the determination of the pseudocontact contribution to the isotropic shift. Assessment of the pseudocontact portion has been hampered by the limited number of resonances in the substrate employed. Even so, Mackie and

Shepherd[30] have studied the ^{1}H spectra of γ-picoline and factored the three observations into a pseudocontact, π-contact, and σ-contact terms. Birnbaum and Moeller[31] have also studied the ^{1}H spectra of γ-picoline and of three other pyridines in the presence of four different aqueous lanthanide ions. The pseudocontact contribution was estimated by assuming a geometry for the lanthanide–picoline adduct, by taking the α-H resonance as a measure of the dipolar interaction, and by computing the remaining dipolar contributions. The differences between observed and calculated values were analyzed for selfconsistency, vis-a-vis the set of lanthanides and the set of pyridines, and then attributed to a Fermi contact shift.

This methodology was also applied to LSR interpretation by Hirayama et al.[32] In this case, the authors employed matched ^{1}H and ^{13}C lanthanide induced shifts (LIS) of pyridine[32a] and aniline.[32b] The proton shifts were assumed to be dipolar in origin, a structure for the LSR–pyridine complex was deduced, and the ^{13}C pseudocontact contributions were computed. Differences between ^{13}C observed and ^{13}C calculated were taken as the contact contribution. A factoring of the LSR data for quinoline has been reported by Chalmers and Pachler.[14] Hawkes, Marzin, Johns, and Roberts[33] used to advantage the additional observations afforded by *exo*-norbornylamine and factored the ^{13}C isotropic shifts in this alicyclic substrate. We have communicated our preliminary results on factoring the ^{13}C LIS spectra of isoquinoline[34a] and of norbornenol.[34b]

In this paper we address the question: Is it possible to meaningfully factor the total shift observed in ^{13}C and ^{1}H spectra into a Fermi contact and pseudocontact term? *If so, is the accuracy of this factoring sufficient to allow ^{13}C LIS spectra to be used for determining structural features as has been done for ^{1}H NMR, or may the contact shift problem in ^{13}C NMR be otherwise successfully obviated?*

Our method has been to study the LIS behavior of several substrates vs. a variety of lanthanides.[35] These data and those of other workers will be presented in the course of this article. We elected to survey comprehensively the behavior of the ^{13}C and ^{1}H spectra of isoquinoline in the presence of eight different lanthanide tris(dipivaloylmethanato) (dpm) chelates, and to apply the lessons learned from this series to the substrate *endo*-norbornenol. The lanthanide shift reagents were limited to Eu(dpm)$_3$ and Yb(dpm)$_3$ for the latter experiments. The number of experimental variables were minimized in every case by using stock solutions of the substrate, obtaining ^{1}H and ^{13}C spectra on the same sample, and employing identical techniques for frequency measurement and a data reduction.[36,37]

Experimental Section

Sample Preparation for Correlated Proton and Carbon-13 NMR Experiments. Substrates and solvents, after careful purification, were freshly distilled and stored to dry over molecular sieves at least 3 days prior to use. The several lanthanide complexes [Lan(dpm)$_3$] utilized were prepared as described by Eisentraut and Sievers,[38] then recrystallized two times from *n*-hexane, dried overnight under vacuum above P$_2$O$_5$, and stored under vacuum above P$_2$O$_5$.

Stock solutions for the isoquinoline LIS experiments were prepared by adding 6.45 g (50 mmol) of isoquinoline, 5.00 ml of C$_6$F$_6$ (for NMR internal ^{19}F lock), and 1.0 ml of Me$_4$Si (proton and carbon-13 chemical shift reference) to a 50-ml volumetric flask and diluting to the mark with chloroform. An aliquot (3.0 ml) of this 1.0 M isoquinoline solution was transferred to a 10-mm diameter NMR tube for ^{13}C NMR spectroscopy. Immediately following this experiment, a 0.5-ml portion of the ^{13}C NMR sample was removed and utilized to obtain a proton NMR spectrum of the sample. This procedure was scrupulously followed to obtain NMR spectra of the 1.0 M substrate solutions in the presence of the lanthanide complexes, with the modification that carefully weighed amounts of the LIS reagents were added to a 3.0-ml aliquot of stock solution. This procedure was re-

peated six times to produce isoquinoline solutions in which the lanthanide/substrate molar ratio varied sequentially from 0.1 to 0.6. The identical procedure was used to obtain correlated proton and carbon-13 NMR spectra of *endo*-norbornenol.

NMR Spectrometers. Proton NMR spectra were obtained on one or more of the four NMR spectrometers available to us: a Varian Model A56/60, HA-100, T-60, or Perkin-Elmer Model R12B. These instruments were operated in the continuous wave mode using sweep rates between 0.1 and 1.0 Hz/s. The complexity of most of the spectra, paramagnetic line broadening, and some sweep nonlinearity combined to limit frequency measurement accuracy to ± 1 Hz. Chemical shifts were measured from the NMR chart in hertz, and converted to parts per million from internal Me$_4$Si (δ values) for use in this study. Proton NMR probe temperatures were measured and found to range between 32 and 38 °C. No temperature effects were seen in the spectral data. The 100-MHz spectrometer was used to measure, and the Perkin-Elmer R12B to verify, spectra requiring 10–50 ppm chemical shift ranges.

Carbon-13 NMR spectra were obtained by using a Bruker HFX-90 NMR spectrometer operating at 22.628 MHz for ^{13}C observation. An ^{19}F lock frequency of 84 MHz and a proton decoupling frequency of 90 MHz were employed. Pulse Fourier transform techniques were implemented by using a Fabri-Tek 1074-PDP-8e data acquisition and reduction system. Field–frequency stabilization was maintained by the internal lock method, the lock signal being the ^{19}F resonance of internal C$_6$F$_6$. Carbon-13 nuclei were decoupled from proton by a broad-band (1 kHz) noise modulated 90-MHz frequency centered at the proton resonance of C$_6$H$_6$.[39] Probe temperature was maintained at ca. 35 °C by standard temperature control methods.

Proton and carbon-13 NMR spectra were obtained at each lanthanide–dpm complex concentration, both spectra being measured within 5 h of sample preparation. Carbon-13 spectra were observed using a 30-μs pulse width corresponding to a 30° flip angle for the ^{13}C magnetization. The 100-μs dwell time (10-kHz sampling rate) usually employed provided a 5-kHz spectral window. The 2048-word data table available after Fourier transformation limited resolution to ± 2.5 Hz between data points, but when required, a 2.5- or 1.25-kHz (resolution of 1.25 and 0.63 Hz, respectively) spectral window was used in order to assure chemical shift accuracy for weakly shifted carbon-13 spectra. Chemical shifts were measured directly from the computer memory display of the frequency domain carbon-13 spectra. The memory channel location of each peak position was recorded and subsequently compared to that for the Me$_4$Si resonance to convert to parts per million shift units (δ scale).

Results

Correlated proton and carbon-13 NMR spectra of 1.0 M CHCl$_3$ solutions of isoquinoline and *endo*-norbornenol have been obtained for the pure substrate and for the substrate in the presence of Lan(dpm)$_3$. At least seven spectra were obtained for each substrate as concentration of the lanthanide chelate was varied over the range 0–0.6 M. For isoquinoline, spectra were obtained by using the dpm chelates of each of the eight lanthanide ions listed in Table I. Plots (not illustrated) of the δ values for proton and carbon-13 vs. increasing lanthanide:substrate ratio were linear and always of the same slope for a given lanthanide. The LIS data for isoquinoline, reported as described below, are collected in Tables I and II. A comparison study, an assessment of the structure of *endo*-norbornenol, required the collection of correlated proton and carbon-13 spectra of this substrate in the presence of Eu(dpm)$_3$ and Yb(dpm)$_3$. These data are collected in Table VI.

Data Reduction. Computation of Normalized Chemical Shifts. Resonance positions measured in chemical shift δ units from the correlated proton and carbon spectra were plotted vs. the lanthanide shift reagent/substrate molar ratio (L/S). A linear least-squares procedure (Wang Calculator Program 1997 A/ST5) was used to determine the slope of the lines, the reciprocals of which were taken as a measure of the sensitivity of the chemically distinct nuclei to added shift reagent.[40] The reciprocal is also considered the 1:1 L/S shift limit. Error limits on the slopes were typically 3% at the 90% confidence level.

Table I. Normalized Paramagnetic Shifts Induced into Isoquinoline by Lan(dpm)$_3$

Resonance	Pr	Nd	Eu	Tb	Dy	Ho	Er	Yb
H-1	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
H-3	92.8	107.0	108.4	104.5	100.0	98.0	106.6	99.1
H-4	41.8	38.1	38.4	34.0	33.9	35.0	35.7	35.6
H-5	21.7	22.4	25.7	16.7	17.4	21.1	21.1	21.2
H-6	14.0	14.8	14.3	10.9	12.0	12.5	12.2	12.6
H-7	14.0	14.8	14.3	10.8	12.0	12.5	12.1	12.6
H-8	23.4	25.8	24.5	19.8	21.6	21.1	22.1	23.3
C-1	218.8	306.2	296.2	158.9	173.8	161.1	199.8	177.8
C-3	205.7	265.5	270.0	145.8	148.9	164.1	179.5	158.5
C-4	61.7	47.1	0.8	83.8	86.7	89.4	39.6	66.3
C-5	26.2	21.6	37.6	25.4	30.4	27.9	28.9	26.1
C-6	24.0	26.4	11.8	15.1	17.9	16.5	24.8	20.1
C-7	21.4	9.3	8.9	24.6	24.3	21.6	20.3	22.2
C-8	24.2	34.8	42.6	24.7	27.8	31.3	34.0	35.6
C-9	55.8	0.1	15.1	90.5	81.1	0.1[b]	42.6	62.2
C-10	66.7	80.2	91.1	40.1	53.3	46.8	64.7	55.2
Δ_{Lan} H-1[a]	45.7	22.7	−23.7	372.3	390.8	172.3	−186.6	−75.6
R_{1H} (ideal)[c], %	5.6	4.7	5.8	7.6	6.2	5.0	5.6	3.4
$R_{(^1H,^{13}C)}$, %	21.3	43.5	44.5	12.6	9.0	7.9	18.5	6.5

[a] Actual magnitudes of induced shifts in parts per million measured for solutions with a 1:1 lanthanide:substrate ratio. [b] Probable artifact. [c] Proton R factors at the normalized (see text) lanthanide position.

Table II. Internal Coordinates Used for Isoquinoline LIS Data Reduction

Nucleus	x	y[a]	z	$(\Delta H/H)_{calcd}$[b]
H-1	−2.157	0.0	−0.154	100
H-3	2.157	0.0	−0.154	100
H-4	2.157	0.0	−2.648	39.74
H-5	0.950	0.0	−4.722	22.50
H-6	−1.204	0.0	−5.954	14.23
H-7	−3.335	0.0	−4.722	13.76
H-8	−3.335	0.0	−2.203	25.08
C-1	−1.209	0.0	−0.694	162.25
C-3	1.209	0.0	−0.694	162.25
C-4	1.209	0.0	−2.085	70.89
C-5	0.0	0.0	−4.168	29.56
C-6	−1.209	0.0	−4.852	35.7
C-7	−2.419	0.0	−4.168	21.10
C-8	−2.419	0.0	−2.757	34.43
C-9	−1.209	0.0	−2.085	70.89
C-10	0.0	0.0	−2.778	57.02

[a] This axis system is orthogonal to the usual LCAO axes. [b] Shift values scaled so that $(\Delta H/H)_{calcd}$ for H-1,3 = 100. Values calculated by using the normalized (see text) lanthanide location.

To facilitate comparison of shifts induced into the single substrate isoquinoline by the eight lanthanide chelates, we found it convenient to internally normalize the eight data sets by arbitrarily setting the shift value for H-1 at 100 and scaling to this all other values. Table I contains the normalized shifts. The reader can calculate, should he desire, all 1:1 L/S shifts by using the 1:1 L/S value for H-1 included in Table I.

The two molecules examined in this study have rigid chemical frameworks. This feature permits easy analysis of the induced chemical shifts by using the PDIGM computer program described elsewhere.[41] Briefly, the substrate was located in a Cartesian coordinate system with the heteroatom at the origin and with the remaining nuclei lying beneath the XY plane. The location of the lanthanide was then varied over the surface of spheres at a distance d from the nitrogen. In the present study, for each lanthanide position, the $(3 \cos^2 \theta - 1)/r^3$ variable from the McConnell–Robertson equation[5] was calculated for each *proton* in the molecule. This set of numbers was then scaled by least squares against the observed shifts,

$(\Delta H/H)_{oi}$, to yield a set of calculated shifts, $(\Delta H/H)_{ci}$. The R factor,[42]

$$R = [\sum_i (\Delta H/H)_{oi} - (\Delta H/H)_{ci}]^2 / \sum_i (\Delta H/H)_{oi}^2 \quad (6)$$

a statistical assessment of the lanthanide location being considered, was then evaluated. The scale factor K used to reproduce the proton pseudocontact shift indices was also used to concurrently calculate carbon pseudocontact shift values. Next, a difference spectrum ($^{13}C_{obsd} - {}^{13}C_{calcd} = {}^{13}C_{diff}$) was generated for all atoms in the substrate.

The position of the minimum R (MINR) was taken as the best location for the lanthanide, within the limits of the pseudocontact model. Naturally, each particular lanthanide–isoquinoline combination gave a different fit (MINR) array. We elect not to report the details of every lanthanide–substrate (L–S) structure, but instead to report a mean of our experience. We further note that the overall computational procedure has proven remarkably applicable for reproduction of known structures[21] and so has an operational utility. It reproduces contact shifts. We foreswear any claim that actual lanthanide–substrate distances are necessarily being accurately determined, but this is not needed for our argument.

Interpretation of the Isoquinoline Results. In the assessment of L–S structure from any set of proton LIS data, we find a lanthanide location for MINR. In our experience the precision of a structural interpretation (deduction of the L–S geometry) for a *single set* of proton LIS data is subject to uncertainties of ca. 0.2–0.3 Å in locating the lanthanide and 0.1 Å in fixing the internal coordinates of the nuclei under investigation. This viewpoint is supported by the finding that adjustments of nuclear positions by less than 0.1 Å usually give a perfect match between observed and calculated LIS indexes, while movements of the lanthanide by 0.2 to 0.3 Å typically cause the R/MINR ratio to double.

For the L/S data set of eight lanthanides vs. isoquinoline, the best MINR lanthanide location was found to vary ca. 0.5 Å in distance from the isoquinoline nitrogen binding site.[43] This uncertainty in the precision of the lanthanide position is likely caused by several factors related to the imperfection of the mathematical model used to reproduce lanthanide-induced shifts. Since our present interest is in *relative* pseudocontact and contact shifts induced by each lanthanide, rather than in the magnitude of the *total* measured induced shifts, the small

Table III. Difference Spectra between Experimental and Calculated Normalized Lanthanide-Induced Shifts for Isoquinoline

Resonance	Pr	Nd	Eu	Tb	Dy	Ho	Er	Yb
H-1	0	0	0	0	0	0	0	0
H-3	−7.8	7.0	8.4	4.5	0	−2.0	6.6	−0.9
H-4	2.1	−1.6	−1.3	−5.7	−3.8	−4.7	−4.0	−4.1
H-5	−0.8	−0.1	3.2	−5.8	−5.1	−1.4	−1.4	−1.3
H-6	−0.2	0.6	0.1	−3.3	−2.2	−2.7	−2.0	−1.6
H-7	0.3	1.1	0.6	−2.8	−5.5	−2.2	−1.6	−1.1
H-8	−1.5	0.9	−0.4	−5.1	−3.3	−3.8	−2.8	−1.6
C-1	56.6	144.0	134.0	−3.3	11.6	−1.1	37.6	15.6
C-3	43.5	103.4	107.8	−16.4	−13.3	2.9	17.3	−3.7
C-4	−9.2	−23.8	−70.1	12.9	13.8	18.5	−31.3	−4.6
C-5	−3.4	−8.0	8.0	−4.2	0.8	−1.7	−0.7	−3.5
C-6	2.8	5.6	−9.0	−5.7	−2.9	−4.3	4.0	−0.7
C-7	0.2	−12.0	−12.3	3.4	3.1	0.4	−0.9	1.0
C-8	−10.3	0.4	8.2	−9.7	−6.6	−3.1	−0.4	1.2
C-9	−15.1	−70.8	−55.8	19.6	10.2		−28.4	−8.7
C-10	9.7	23.2	34.1	−16.9	−3.7	−10.2	7.7	1.8

imprecision in actual lanthanide location deduced from the MINR criteria has little effect on our present arguments.

However, to simplify and to aid our understanding of the isoquinoline results, let us make the following regularizing hypothesis: *all isoquinoline-lan(dpm)₃ complexes have the same structure*. This restriction does not in any way force the observed and calculated proton LIS values to match *with an acceptable R factor* should the lanthanides $\Delta H/H$ field not be nearly, or on the average, axially symmetric, and/or should the proton LIS spectra contain large, variable contact shift contributions. Indeed, only small imperfections which might be attributed to these effects appeared during analysis of the eight data sets.

In accord with our hypothesis, we use the standard isoquinoline-LSR structure shown below.[45] The isoquinoline internal coordinates employed in the PDIGM calculation were taken from Dreiding models and are listed in Table II. The match between observed and calculated proton LIS parameters was forced for this structure by specifying that the LIS shift of H-1,3$_{exptl}$ = 100 and that a plot of observed vs. calculated
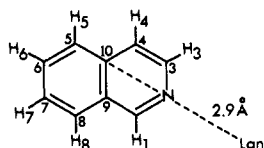
values have a 0.0 intercept. The calculated values found under these constraints are also listed in Table II. Since the experimental data are normalized, the entries of Table I can be directly compared with column 5 of Table II. The lanthanide is thus placed in a position slightly different from its MINR location (i.e., it is moved to the metal ion location in the standard structure). The *proton R* factors for this scale factor and fixed position for the eight lanthanides vary between 3 and 9% (see Table I) and so are quite satisfactory for our purposes, especially when account is taken of the compromises inherent in fitting all eight LIS data sets to a single model structure. The acceptable *R* factors also ensure that our regularizing hypothesis is not introducing unacceptably large errors into the results.

Attempts to include the observed ^{13}C LIS data directly into the MINR calculation while moving the lanthanide location ±0.5 Å in all three coordinate directions from the location determined from proton LIS data (or from the regularized position) led, except in the case of the ytterbium chelate, to markedly and unacceptably high *R* factors (i.e., greater than 15%).

The data presented in Table III illustrate the difficulties in fitting the dispersed ^{13}C spectra by using the dipolar McConnell–Robertson[5] term alone. Even so, the large differences between experimental and calculated normalized ^{13}C LIS shifts at the standard lanthanide position show certain regularities. Prominent features include the large discrepancies seen in the resonances of the proximate heterocyclic ring of isoquinoline for shifts induced by Pr, Nd, Eu, and Er. In contrast, smaller errors are found for the remaining lanthanides. In the case of the four shift reagents which give large differences, there is seen a concurrent, distinct alternation of signs of the difference spectra between carbons 1, 3, and 10 and carbons 4 and 9. The lanthanides which produce smaller difference spectra are not so consistent in exhibiting this alternation, but it is observed that the total error in carbons 1, 3, and 10 is always opposite to that in carbons 4 and 9.

These difference spectra can be interpreted in an overall sense by attributing them to Fermi contact shifts.[4] Because of imprecisions between data sets, it is convenient to introduce an average error (defined in eq 7 below) to discuss the pseudocontact/contact contributions. This experimental index can be shown to parallel results of several studies: (i) the contact/pseudocontact ratios developed from ^{17}O and ^{1}H lanthanide shifts studies of Taube[23] and Reuben;[46] (ii) the theoretical contact/pseudocontact ratios which Golding calculated by using ligand field theory;[7,47] and (iii) conclusions about contact shifts reached by Chalmers and Pachler.[14] In addition, the alternating sign pattern of up- and downfield shifts may be profitably compared with the results obtained by using Ni(II) as the paramagnetic probe[48] as well as with results of the related molecular orbital theoretical calculations by Morashima.[49,50] These comparisons, taken together, are shown below and allow us to confidently rank the Lan(dpm)₃ complexes according to their ability to induce Fermi contact shifts.

The difference spectra are made more amenable to interpretation by comparing ^{13}C pseudocontact to contact shift ratios averaged over the heterocyclic isoquinoline ring by evaluating the empirical error function:

$$(\Delta_{FC}/\Delta_{PC})_{obsd} = \text{error function}$$

$$= \frac{\sum |^{13}C_{diff} - {}^{13}C_{calcd}|}{\sum {}^{13}C_{calcd}} = \frac{\sum |^{13}C_{error}|}{\sum {}^{13}C_{calcd}} \quad (7)$$

The particular form of this error function has no intrinsic validity in theory; rather, it serves only as an index of the relative magnitudes of the errors induced into the dispersed ^{13}C spectra by each lanthanide. We have argued previously that these errors represent the Fermi contact contribution to the measured isotropic shift.[34] Values of this error function for isoquinoline are included in Table IV.

Table IV. Comparison of Error Function Data[a] and Various Theoretical Predictions for Lanthanide-Induced Contact Shifts

Data source	Pr	Nd	Eu	Tb	Dy	Ho	Er	Yb
Error function[a]	0.256	0.698	0.768	0.132	0.104	0.072	0.234	0.066
Reuben[b] ($\Delta F_{FC}/\Delta_{PC}$)	0.13	0.40	0.80	0.25	0.14	0.38	0.80	0.09
Golding[c] Δ_{FC}	2.972	4.487	−10.68	−31.82	−28.55	−22.63	−15.37	−2.587
Golding[d] Δ_{PC}	10.99	4.15	−4.05	85.26	100.	39.39	−32.41	−21.54
Golding $\lvert\Delta_{FC}/\Delta_{PC}\rvert$	0.292	1.06	2.68	0.38	0.285	0.58	0.474	0.120
Chalmers-Pachler[e]	0.17	0.34	0.46		0.02	0.03	0.13	0.08

[a] This work, see eq 7. [b] Data taken from ref 2g. [c] Data taken from ref 47, Table I, column 5. These are $A\langle S_z\rangle$ values, where $A = 3kT/\beta N$. [d] Data taken from ref 7, table entry "set 4". [e] Data taken from ref 14.

Lewis, Jackson, Lemons, and Taube[23] first studied the Fermi contact contribution to water oxygen-17 chemical shifts in aqueous solutions of the lanthanides. By treating the pseudocontact term as being small, they correlated the observed ^{17}O shifts with the expression $[g_L(g_L − 1)(J)(J + 1)]$, where g_L is the Lande g factor and J the electronic spin angular momentum in units of h. This demonstrates that the Fermi term is, in this case, strongly dominant. Reuben and Fiat[46] extended these studies and found that lanthanide-induced aqueous ^1H shifts were pseudocontact in origin. Comparison of the Taube and Reuben information via the anisotropy date of Horrocks and Sipe[48] let Reuben[2g] deduce estimates of the relative contact vs. pseudocontact shifts (Δ_{FC}/Δ_{PC}) for the Lan(dpm)$_3$ complexes. These ratios are recorded in Table IV as "Reuben". A plot of these ratios against our error function is sufficiently linear to suggest that we are observing substantial ^{13}C contact shifts in isoquinoline.

An alternative prediction of the contact/pseudocontact contribution to chemical shifts induced by a lanthanide can be formulated from two theoretical reports by Golding.[7,47] One study[47] used ligand field calculations to assess the ability of lanthanide ions to induce contact shifts; the other[7] similarly calculated the pseudocontact contributions. In both papers, several sets of results were reported, each corresponding to particular sets of precomputational assumptions. Golding[51] asserts that the $\langle S_z\rangle$ values used by us in Table IV best match known experimental data. Likewise, the calculated pseudocontact values nearest to those determined by Bleaney[6] according to a different, but similar methodology, are also collected in Table IV. When the ratios of these two terms (Δ_{FC}/Δ_{PC}) are formed, they are found to be in excellent agreement with our error function vs. lanthanide correlations. It is again clearly seen that the contact shift contribution is large for Eu and small for Yb.

The contact/pseudocontact experimental ratios for seven of the lanthanides examined in our study have also been estimated by Chalmers and Pachler[14] for quinoline. Even though their method of determining and defining the contact/pseudocontact ratio differ from ours, the correspondence between theory and experiment is again good. There seems now little question but that the interpretation of different spectra as described first by us as being contact shift in origin is essentially correct.

Now that we have established that the errors found as ^{13}C difference spectra ($^{13}C_{diff} = {}^{13}C_{obsd} − {}^{13}C_{calcd}$) are related to the Fermi contact contributions to observed experimental LIS shifts, it is informative to examine in more detail the difference data for Eu(dpm)$_3$–isoquinoline. Several studies[49,50] of contact shifts induced into isoquinoline by paramagnetic ions other than lanthanides and attendant molecular orbital estimations[50] of spin density may be used to compare our contact shifts to those presently in the literature.

Morashima, Okada, and Yonezawa[50] have examined ^1H and ^{13}C paramagnetic shifts induced into isoquinoline by bis(acetylacetonato)nickel(II). They find that INDO/2 molecular orbital calculations of the electron spin density in the
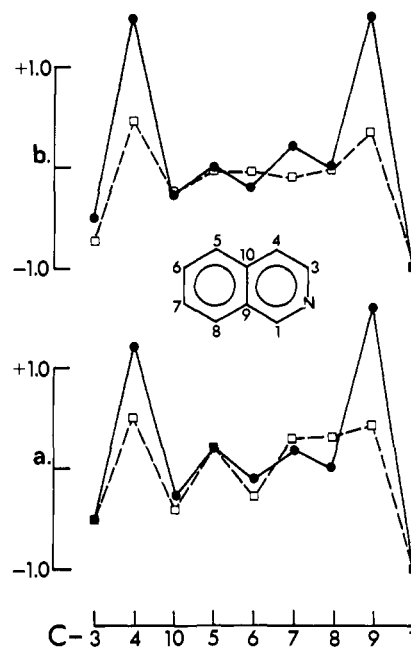
Figure 1. Relative theoretical and observed ^{13}C contact shifts induced into isoquinoline. Values scaled with the contact shift at C-1 = −1.00. (a) - ■ -, $\rho_{C_{2s}}$, σ contact shifts; - - □ - -, $\rho_{C_{2p\pi}}$, π contact shifts calculated by Morashima et al.[50] (b) - - □ - -, contact shifts taken from C-13 difference spectra; - ■ -, contact shifts induced by Ni(acac)$_2$ (signs changed to parallel β-spin delocalization; see Table V and text).

proton 1s and carbon 2s atomic orbitals of the 2-naphthyl radical can reproduce well the alternating signs and relative magnitudes of spin density induced by chelation to the metal complex.[52] In the Morashima study, the experimentally determined Fermi contact paramagnetic shifts were used to calculate relative values of A_i, the electron nuclear hyperfine coupling constant, at each atom in isoquinoline, and then, were shown to be in good agreement with both proton and carbon values predicted by INDO calculations of the sigma (σ_s) spin densities of the 2-naphthyl radical.

The INDO/2 predicted electron spin densities in both the σ and π atomic orbitals, $\rho_{C_{2s}}$ and $\rho_{C_{2p}}$, of each carbon atom of the α-naphthyl model for isoquinoline are displayed in Figure 1a. In Figure 1b are shown similar graphs of the relative ^{13}C contact shift values obtained by Morashima et al.[50] from the Ni(acac)$_2$ experiment and the relative ^{13}C difference spectra obtained in our LIS study. The calculated and experimental data are collected in Table V. A qualitative comparison of our ^{13}C difference spectra data with the Ni(II) Fermi contact information in Figure 1 certainly reinforces our contention that our Eu(dpm)$_3$-induced ^{13}C difference spectra are caused by a Fermi contact shift mechanism. Furthermore, our experimental results are seen to agree exceedingly well with the INDO-calculated C$_{2s}$ spin densities of the isoquinoline cation radical[57] (see Table V).

Careful examination of our ^{13}C difference spectra reveals

Table V. Calculated vs. Observed Fermi Contact Shifts for Isoquinoline. ^{13}C Contact Shifts for Isoquinoline

Carbon position	^{13}C contact shifts[a] from Ni(acac)$_2$	^{13}C$_{diff}$ Eu(dpm)$_3$[b]	$C_{2s}^{calcd\ c,d}$		$C_{2p\pi}^{calcd\ c,d}$	
			c	d	c	d
1	1.00	−1.00	−1.00	(−1.00)	−1.00	(−1.00)
3	0.49	−0.80	−0.54	(−0.70)	−0.56	(−0.46)
4	−1.54	0.52	1.21	(0.44)	0.52	(0.46)
5	0	−0.06	0.22	(0.26)	0.22	(0.33)
6	0.23	0.07	−0.12	(−0.15)	−0.31	(−0.39)
7	−0.19	0.09	0.18	(0.18)	0.25	(0.33)
8	0	−0.06	0.04	(−0.09)	0.29	(−0.45)
9	−1.54	0.42	1.59	(0.39)	0.37	(0.29)
10	0.28	−0.25	−0.27	(−0.28)	−0.42	(−0.34)

[a] Scaled, paramagnetic shifts induced into isoquinoline by Ni(acac)$_2$. See ref 50. [b] This work, see text. [c] Calculated spin densities in C_{2s} and $C_{2p\pi}$ obtained by INDO calculations of the α-naphthyl radical model for isoquinoline. Taken from ref 50. [d] Calculated isoquinoline cation radical spin density in C_{2s} and $C_{2p\pi}$ obtained by INDO calculations performed by Reilley et al.[57] by using the geometry of this work.

that sign alternation in the isoquinoline ring is similar to, but not identical with the pattern of sign alternation predicted by a spin polarization mechanism. The signs of the shifts (+ being upfield) predicted by spin polarization alone are shown below.
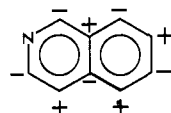
For the heterocyclic ring, the large contact shifts at C-β are reminiscent of results obtained by us for pyridine[34] and are suggestive of a σ-spin delocalization mechanism predicted by Doddrell and Roberts[53] and by Morashima et al.[50] However, the ^{13}C difference shifts and calculated C_{2s} spin densities for isoquinoline do not compare as well as similar values for pyridine. The shifts in the heterocyclic ring correlate reasonably well with either calculated C_{2s} or C_{2p} values, while ^{13}C difference shift in the distal ring are much attenuated compared to calculated values. The smaller relative contact shift observed for C-5,7 could be taken as being indicative of a π-delocalization mechanism. It seems likely that, in the case of isoquinoline, some admixture of σ and π delocalization might be invoked to explain our observed ^{13}C difference shifts, but we will not pursue that effort. Similarly, since molecular orbital (MO) calculations can provide relative proton/carbon shift ratios for molecules such as isoquinoline, one might hope to refine the proton LIS data by using these theoretical concepts in concert with the ^{13}C difference maps. Unfortunately, the results of these calculations are so sensitive to the molecular orbital method tried and, particularly, to the *exact* geometry assumed for the molecules, as to preclude accurate determination of experimentally valid spin density ratios for the ^{1}H nuclei.

A few general comments about factoring the isotropic shift into two terms (eq 1) are in order. The sum of the contact and pseudocontact term must equal the total observed shift. Since neither term is unambiguously known, we are able to achieve a variety of "reasonable" factorings. The arbitrary setting of the nitrogen–lanthanide distance at 2.9 Å and the establishment of a scale factor constrains us to a single set of contact shifts per lanthanide studied. Revisions in either the nitrogen–lanthanide distance or in the scale factor would generate a "different" set of contact shifts. We have seen that these sets are not significantly different if the lanthanide location and scale factors are not changed more than ±15%. This variation, therefore, does not affect our conclusions.

Yet another matter to be considered is the possible use of ^{13}C LIS dispersed data for deducing structural information about molecules in solution. The consecutive factoring and rescaling of correlated ^{1}H and ^{13}C data are unrewarding for

the reasons described above. Rather, it would seem more appropriate to obviate the ^{13}C contact shift problem entirely by examining ^{13}C data obtained by using the lanthanide ion which exhibits the smallest $(\Delta_{FC}/\Delta_{PC})_{theor}$ ratio. By that criterion, the most suitable ion is ytterbium; the contact shift is predicted to be only 5% of the total induced isotropic shift. Experimentally, the proton R factor observed for isoquinoline-Yb(dpm)$_3$ in our standard geometry was 3.2%. When both the ^{13}C and ^{1}H data were used, the still acceptable R factor of 4.0% was found.

Isoquinoline was chosen for these studies because it is a structurally rigid molecule which possesses a "hard" nitrogen suitable for relatively tight chelation to Lan(dpm)$_3$ "hard" acids.[54] The NMR spectra of soft bases such as phosphines are little affected by LIS reagents. The strong isoquinoline–lanthanide adduct resulted in the substantial spin density perturbation reflected in the contact shift, and, as such is perhaps not the best choice for examination of the pseudocontact term in ^{13}C spectra. Our experiments have, however, led to a relative ordering of the lanthanide ions as to their suitability as pseudocontact ^{13}C shift reagents. The data strongly suggests that Eu(dpm)$_3$ would be the least useful ^{13}C shift reagent.

Interpretation of *endo*-Norbornenol Data. Since Eu(dpm)$_3$ or other europium chelates are the most frequently used shift reagents, and since many substrates in LIS experiments are carbocyclic systems, it seemed essential for us to specifically test our conclusions about the relative utility of Eu(dpm)$_3$ vs. Yb(dpm)$_3$ as a shift reagent for ^{13}C NMR. Therefore, we investigated correlated ^{1}H and ^{13}C LIS spectra for *endo*-norborn-5-en-2-ol obtained by using Eu(dpm)$_3$ and Yb(dpm)$_3$. Shift data are collected in Table VI.

An examination of the Eu(dpm)$_3$-dispersed proton NMR spectra performed by using the PDIGM grid search revealed a minimum agreement factor of $R(^1H) = 3.3\%$ obtained by using the Dreiding model coordinates recorded in Table VII. Similarly, when Yb(dpm)$_3$-dispersed proton data were likewise examined, a minimum R factor of $R(^1H) = 1.3\%$ is obtained. However, when the combined, correlated ^{13}C and ^{1}H NMR data are examined at the proton-determined lanthanide position, and when C-2 is omitted, an $R(^1H$ and $^{13}C) = 7.0\%$ is seen for Yb(dpm)$_3$ while $R(^1H$ and $^{13}C) = 12.2\%$ for Eu(dpm)$_3$. See entry [^{13}C$_{calcd}^b$] of Table VI.

The following details of the calculations make the reasons for the Yb:Eu discrepancies clear, and illustrate some of the problems which arise from fitting ^{13}C data exclusive of the ^{1}H data. The best locations for the lanthanide ion as determined from ^{1}H data are nearly identical: Yb $(D, \rho, \varphi) = 3.0, 50°, 248°$ and Eu $(D, \rho, \varphi) = 3.0, 50°, 228°$. If the ^{13}C LIS data are evaluated in terms of structure by using all seven carbon atoms we find an R of 3.4% for Yb $(D, \rho, \varphi = 2.4, 80°, 236°)$ and

Table VI. LIS Data for *endo*-Norbornenol

	$^1H_{obsd}$[a]	$^1H_{calcd}$		$^{13}C_{obsd}$	$^{13}C_{calcd}$[b]	$^{13}C_{diff}$	$^{13}C_{calcd}$[c]
			$Eu(dpm)_3$-*endo*-Norbornenol				
H-1	−15.6	−15.0	C-1	−14.9	−20.7	5.8	−17.4
H-2	−34.1	−34.6	C-2	−58.6	−44.7	−13.9	−58
H-3$_{exo}$	−13.2	−12.7	C-3	−17.4	−20.5	3.1	−19.6
H-3$_{endo}$	−22.4	−22.3	C-4	−10.0	−11.9	1.9	−10.5
H-4	−7.6	−7.7	C-5	−15.2	−12.9	−3.3	−15.3
H-5	−9.4	−9.4	C-6	−16.1	−17.3	−1.1	−16.1
H-6	−14.7	−13.8	C-7	−10.5	−11.0	−0.5	−7.4
H-7$_{syn}$	−7.8	−8.8	$R_{(^1H)} = 3.3\%$				$R_{(^{13}C)} = 6.8\%$
H-7$_{anti}$	−7.1	−7.4	$R_{(^{13}C,^1H)} = 12.2\%$[b,d]				
			$Yb(dpm)_3$-*endo*-Norbornenol				
H-1	−37.0	−37.5	C-1	−57.7	−53.3		−60.7
H-2	−88.6	−87.9	C-2	−194.3	−113.9		−192.2
H-3$_{exo}$	−33.4	−33.6	C-3	−59.1	−51.8		−59.9
H-3$_{endo}$	−56.2	−56.0	C-4	−30.8	−30.4		−31.7
H-4	−19.7	−20.0	C-5	−36.5	−32.9		−38.7
H-5	−22.6	−23.9	C-6	−46.7	−43.4		−52.8
H-6	−34.5	−34.7	C-7	−34.6	−35.7		−33.9
H-7$_{syn}$	−22.2	−22.3	$R_{(^1H)} = 1.3\%$				$R_{(^{13}C)} = 3.4\%$
H-7$_{anti}$	−18.5	−18.6	$R_{(^{13}C,^1H)} = 7.0\%$[b,d]				

[a] Data reported are for 1:1 LIS/substrate ratios. Shifts reported are relative to shifts of pure substrate. [b] At ^1H best fit position and with ^1H scale factor. [c] Best fit for ^{13}C only. [d] Omitting C_2.

**Table VII.** Internal Coordinates Used for *endo*-Norbornenol LIS Data Reduction

Nucleus	x	y	z
H-1	1.60	−1.01	−2.37
H-2	−0.64	−0.72	−1.77
H-3 (exo)	−1.65	1.58	−2.29
H-3 (endo)	−0.78	2.13	−0.90
H-4	0.33	2.94	−3.40
H-5	2.09	3.13	−1.59
H-6	2.95	0.84	−1.01
H-7 (syn)	0.46	0.27	−4.02
H-7 (anti)	2.09	0.89	−3.99
C-1	1.37	0.0	−2.10
C-2	0.0	0.0	−1.43
C-3	−0.58	1.55	−1.92
C-4	0.53	2.11	−2.81
C-5	1.63	2.27	−1.94
C-6	2.11	1.01	−1.57
C-7	1.15	0.76	−3.41
Oxygen	0.0	0.0	0.0

6.8% for Eu ($D, \rho, \varphi = 2.0, 70°, 250°$). See [$^{13}C_{calcd}$[c]] of Table VI. Now the Yb local geometry is similar for ^1H and ^{13}C, but the Eu local geometry is substantially different. Any contact shift in the ^{13}C spectra should be most strongly reflected in an anomalous C-2 LIS value.[33,36] When C-2 is removed from the calculation the Yb returns to ($D, \rho, \varphi = 3.0, 50°, 228°$) with an $R = 4.4\%$ while Eu expands to $R = 15.3\%$ ($D, \rho, \varphi = 20, 70°, 255°$). These results are easily reconciled by postulating that Eu causes contact shifts over the entire molecule and Yb gives appreciable contact shift of C-2 and nowhere else. This is, of course, in keeping with the isoquinoline analysis.

To summarize, these data evaluations indicate that ^{13}C NMR LIS data obtained for this carbocyclic substrate by using $Yb(dpm)_3$ as the LSR can be fit to the pseudocontact model within the limits of experimental error and certainly fit as well as *proton* LIS data obtained by using $Eu(dpm)_3$. The anomalous lanthanide location obtained with the MINR (^{13}C)$_{Eu}$ and the large agreement factor suggest that both Fermi contact and pseudocontact ^{13}C shifts are induced by $Eu(dpm)_3$.

If ^{13}C difference spectra are obtained from Table VI by using the MINR location for the $Eu(dpm)_3$ proton data, the following sign pattern in the difference spectrum is obtained.
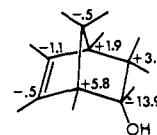
Sign alternation and rapid attenuation of the contact shift is observed. The negative contact shift at C-2 again suggests that $Eu(dpm)_3$ induces β-spin on the alcohol functional group, as discussed previously.[34a,36]

Conclusions

Our survey of the proton and carbon-13 paramagnetic shifts induced into isoquinoline by eight $Lan(dpm)_3$ complexes has determined an ordering of the relative ability of the lanthanides to induce Fermi contact shifts into substrates. Those which introduce the smallest contact shifts are the most useful. It has become clear that such shifts are quite troublesome if one attempts to apply the pseudocontact model to ^{13}C LIS shifts. It is equally clear that any of the $Lan(dpm)_3$ complexes produce usable proton LIS shift data. As an experimental observation, we note that spectral lines are invariably narrowest for $Eu(dpm)_3$, but because of the difference in ^{13}C vs. ^1H gyromagnetic ratios, ^{13}C spectra obtained by using $Eu(dpm)_3$ and $Yb(dpm)_3$ are quite similar in spectral quality. For several other of the lanthanides, e.g., Dy and Ho, the line broadening problems manifest in both ^{13}C and ^1H data render them virtually useless as shift reagents. The relative chemical shifts induced by $Yb(dpm)_3$ are ca. 250% larger than for $Eu(dpm)_3$, a factor which becomes important when examining ^{13}C Fourier transform NMR spectra where computer memory is limited. We note that by using combined ^{13}C and ^1H LIS data the number of observed spectral lines is often markedly increased, thus facilitating structural assignment. Because of this, and because of the relatively small contact shift problem for $Yb(dpm)_3$, we suggest its use as a shift reagent for dispersion of proton and carbon-13 NMR spectra.

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