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IMPORTANCE OF COMPLEX FORMATION AND CONTACT SHIFTS IN THE APPLICATION OF LANTHANIDE SHIFT REAGENTS TO ^{1}H AND ^{13}C NMR SPECTRA OF AROMATIC COMPOUNDS

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Much evidence has been provided for the presence of contact-term contribution to paramagnetic shifts induced by lanthanide shift reagents (1) in ^{1}H, ^{13}C, ^{14}N, ^{19}F, and ^{31}P NMR spectroscopy (2,3). Conspicuous effects of contact shifts (C.S.) have been observed in ^{13}C NMR spectra of stronger Lewis bases complexed with several shift reagents, particularly some fluorinated chelates as stronger Lewis acids (2-5). Even in ^{1}H NMR spectra, the contact effect is apparently discernible in the lanthanide-induced shifts (L.I.S.) for aromatic analogues of stronger Lewis bases (6,7). Thereby, the necessity of caution in the application of shift reagents to these systems has frequently been suggested (2,4,6,7).

However, possible shifts due to complex formation between substrate and shift reagent in an observed L.I.S. have so far been completely ignored in the application of shift reagents to organic structural problems, although such a "complex-formation shift" (C.F.S.) correction by using shifts caused by a diamagnetic lanthanide ion, La^{3+}, has sometimes been suggested necessary (7-10). We report here the importance of this correction as well as the contact-term contribution for interpreting L.I.S. in ^{1}H NMR, and in particular, in ^{13}C NMR spectra of some aromatic stronger Lewis bases.

The 60-MHz ^{1}H and 25.2-MHz ^{13}C NMR spectra of γ-picoline N-oxide (I), p-toluidine (II), p-cresol (III), and γ-picoline (IV) were examined in $CDCl_3$ containing various amounts of $Ln(FOD)_3$, where Ln = La, Eu, and Pr. Slopes of linear, initial parts of the shift curves obtained for all signals in I-IV were used as shift values (S-value)[*1] and are listed in the Table.

The C.F.S.'s caused by $La(FOD)_3$ for I and II were found to be large enough to influence significantly the S-values obtained with Eu- and $Pr(FOD)_3$. Therefore, the shift values after C.F.S. corrections utilising the S-values of $La(FOD)_3$, Δ-value, were considerably changed, in some cases even in sign, from those observed originally (see the Table). Shift values normalised to those of the nuclei closest to the binding site(s) of complexes after the C.F.S. corrections, N-values, are also listed in the Table. It should be noted that the contribution of the complex-formation effect is particularly large for 4-C signals.

By the C.F.S. corrections for I we can correct the previously reported (7) rather curious aspect of S-values with Eu- and $Pr(FOD)_3$ in ^{13}C NMR, obtaining values which are much more easily interpretable and in which the notable contribution of the C.S. to the L.I.S. is obviously reflected (7); the downfield shifts of the 4-C signals by Eu- and $Pr(FOD)_3$ were changed into an upfield and a very small shift, respectively (see the Table). The contact effects in I and II are considered to be caused as shown in FIG. 1 (6,7). For comparison, N-values for the $Ni(AA)_2$-induced contact-shifts with I, II, and IV are also listed in the Table. Although we consider that it is not easy to estimate separately the magnitudes of the C.S. and the pseudo-contact-shift (P.C.S.) effects from the present Δ-values, we have included in the Table the results of calculations of normalised values for the geometrical-factors in the P.C.S. formalism[*2] for I based on ^1H shifts observed with several $Ln(DPM)_3$ (13), as have been attempted by several authors so far (5,6,13). Thus, after the C.F.S. corrections, the C.S. contribution to the ^1H shifts in I was found to be still large for the Eu-induced shifts and to become more apparently discernible for the smaller Pr-induced shifts.

Similar examinations of the ^1H and ^{13}C N-values for II in the Table revealed the presence of C.S. effects (see FIG. 1), though to a lesser extent than in I (6).

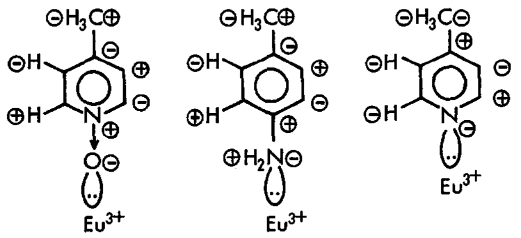
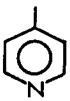


FIG. 1. Sign of spin densities on the atoms in I, II, and IV induced by Eu^{3+} (Pr^{3+} and Ni^{2+} induce spin densities of opposite signs; positive spin causes a downfield contact shift).

[*1] Induced-shift curves plotted against the molar ratio of the shift reagents to the substrates were not linear but complicated owing probably to the complicated stoichiometry of the complexes (11). For example, the shift curves of IV with $La(FOD)_3$ clearly showed an inflexion at about a 0.5 molar ratio of the La complex to IV.

[*2] Origin of the P.C.S. (2,7) and the calculation method (12) for L.I.S. are still in controversy.

Table. Lanthanide-induced ^1H and ^{13}C Shift Values in $CDCl_3$ (ppm)[a]

Compound	Shift reagent		^1H Signal[b]			^{13}C Signal[c]				
			2-H	3-H	4-CH_3	1-C	2-C	3-C	4-C	4-Me-C
	none	δ	8.10	7.11	2.35	---	138.1	126.2	137.5	20.4
	La(FOD)$_3$	S	+0.04	-0.28	-0.17	---	+3.3	-1.4	+10.2	+0.2
	Eu(FOD)$_3$	S[d]	+3.20	-0.30	-0.80	---	-0.8	+6.5	+5.3	+3.6
		Δ	+3.16	-0.02	-0.63	---	-4.1	+7.9	-4.9	+3.4
		N	+1.00	-0.01	-0.20	---	-1.00	+1.93	-1.20	+0.83
	Pr(FOD)$_3$	S[d]	-9.95	-3.00	-1.65	---	-5.4	-8.1	+10.3	-2.3
		Δ	-9.99	-2.72	-1.48	---	-8.7	-6.7	+0.1	-2.5
(I)		N	-1.00	-0.27	-0.15	---	-1.00	-0.77	+0.01	-0.29
	Calc.	N[e]	1.00	0.33	0.17					
	Ni(AA)$_2$	N	-1.00	+0.55	+1.32	---	(+1.00	-0.50	+0.73	-0.27)[d]
	none	δ	6.56	6.92	2.21	143.4	114.8	129.2	127.1	20.5
	La(FOD)$_3$	S	-1.62	-0.42	-0.28	-1.6	+2.8	+0.7	+3.3	+0.3
	Eu(FOD)$_3$	S	+13.4	+3.13	+0.73	+69.2	+13.2	+15.5	+5.8	+5.7
		Δ	+15.0	+3.55	+1.01	+70.8	+10.4	+14.8	+2.5	+5.4
		N	+1.00	+0.24	+0.07	+1.00	+0.15	+0.21	+0.04	+0.08
	Pr(FOD)$_3$	S	-22.1	-6.59	-3.20	-99.4	-23.5	-15.8	0.0	-6.5
		Δ	-20.5	-6.17	-2.92	-97.8	-26.3	-16.5	-3.3	-6.8
(II)		N	-1.00	-0.30	-0.14	-1.00	-0.27	-0.17	-0.03	-0.07
	Ni(AA)$_2$	N	(-1.00	+0.444	+1.09)[f]	-1.00	+0.68	-0.38	+0.53	-0.19
	none	δ	6.71	6.99	2.24	152.6	115.0	129.7	129.7	20.2
	La(FOD)$_3$	S	-0.45	-0.17	-0.08	+0.3	+0.6	+0.4	+0.4	0.0
	Eu(FOD)$_3$	S	+4.30	+1.23	+0.63	+25.9	+7.8	+4.5	+4.5	+2.5
		Δ	+4.75	+1.40	+0.71	+25.6	+7.2	+4.1	+4.1	+2.5
		N	+1.00	+0.29	+0.15	+1.00	+0.28	+0.16	+0.16	+0.10
	Pr(FOD)$_3$	S	-10.0	-2.94	-1.63	-32.5	-11.4	-6.1	-2.9	-2.1
		Δ	-9.55	-2.77	-1.55	-32.8	-12.0	-6.5	-3.3	-2.1
(III)		N	-1.00	-0.29	-0.16	-1.00	-0.37	-0.20	-0.10	-0.06
	none	δ	8.44	7.08	2.33	---	149.4	124.5	146.9	21.0
	La(FOD)$_3$	S	-5.27	-1.58	-0.78	---	-0.9	+0.2	+2.2	+0.1
	Eu(FOD)$_3$	S	+23.2	+7.50	+6.80	---	+83.5	-19.2	+33.6	+3.2
		Δ	+28.5	+9.08	+7.58	---	+84.4	-19.4	+31.4	+3.1
		N	+1.00	+0.32	+0.27	---	+1.00	-0.23	+0.37	+0.04
	Pr(FOD)$_3$	S	-46.3	-16.4	-12.7	---	-110.6	-25.0	-30.8	-11.6
		Δ	-41.0	-14.8	-11.9	---	-109.7	-25.2	-33.0	-11.7
		N	-1.00	-0.36	-0.29	---	-1.00	-0.23	-0.30	-0.11
(IV)	Calc.	N[g]	1.00	0.39	0.22	---	1.00	0.45	0.37	0.18
	Ni(AA)$_2$	N	(+1.00	+0.180	-0.091)[h]	---	-1.00	+2.81	-0.63	+0.37
							(-1.00	+1.930	-0.180	+0.144)[h]
							(-1.00	+1.65	-0.42	~0)[i]

[a] Plus sign denotes a downfield shift. Accuracies for S-values are about 5% or less. δ: chemical shifts downfield from TMS. [b] ^1H NMR spectra were taken with a Varian A-60A spectrometer at 38°. Substrate concentrations were about 1 mole/l. [c] ^{13}C spectra were recorded on a Varian XL-100-12 spectrometer in the frequency-swept and deuteron-locked mode at 25.2 MHz. A C-1024 time-averaging device and the proton noise-decoupling technique were used. ^{13}C NMR signals were assigned by the single-frequency off-resonance decoupling technique. Substrate concentrations were about 2 mole/l for the Ln(FOD)$_3$ cases and 4 mole/l for the Ni(AA)$_2$ cases. [d] Values taken from ref 7. [e] Values taken from ref 13. [f] Values taken from T. Yonezawa, I. Morishima, Y. Akana and K. Fukuta, Bull. Chem. Soc. Japan 43, 379 (1970). [g] Calculated according to the method described in ref 5. [h] Values taken from D. Doddrell and J.D. Roberts, J. Amer. Chem. Soc. 92, 6839 (1970). [i] Values taken from I. Morishima, T. Yonezawa and K. Goto, J. Amer. Chem. Soc. 92, 6651 (1970).

The C.F.S. were found to be relatively smaller in III and IV. Contact effects on the ^{1}H shifts for III were very weak, as seen from the fact that the Eu/Pr Δ-value ratios are quite constant (2). However, the ^{13}C Δ-values appear to include weak C.S. effects. These facts might be due to weaker Lewis basicity of III.

The C.S. effects involved in the L.I.S. with pyridine-type molecules have frequently been discussed (6). The C.S. contributions are apparently reflected in the ^{13}C N-values for IV shown in the Table, following the sequence illustrated in FIG. 1 as observed with $Ni(AA)_2$; the large upfield shift for the 3-C signal and the smaller downfield shift for the 4-Me-C signal with $Eu(FOD)_3$, and their smaller upfield shifts with $Pr(FOD)_3$ are characteristic of the presence of the C.S. effects. The effects seem weak on the ^{1}H induced shifts, however. This seems due to the fact that the C.S. effects are attenuated through bonds from 2-H to 4-CH_3 in IV in the opposite direction to that for the P.C.S., which is attenuated through space in a similar manner.

In all cases, the C.S. effects exerted by $Eu(FOD)_3$ are concluded to be stronger than and opposite in sign to those exerted by $Pr(FOD)_3$ (see FIG. 1), as already reported for other systems (2,6,7). Thus, it is concluded that an observed L.I.S. should be the sum of P.C.S., C.S., and C.F.S., and that the latter two shifts are sometimes too large to be neglected. Further investigations are now in progress in these laboratories.

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