Lanthanide-induced Shifts in Nuclear Magnetic Resonance Spectroscopy: Application to Ketones

By P. BÉLANGER*
(*Merck Sharp & Dohme Canada Limited, Montreal*)
and C. FREPPEL, D. TIZANÉ, and J. C. RICHER
(*Université de Montréal*)

Summary The shifts induced by tris(dipivalomethanato)-praseodymium, Pr(dpm)$_3$, in the n.m.r. spectra of 4-t-butylcyclohexanone and 2,2-dimethyl-4-t-butylcyclohexanone vary linearly with concentration of Pr(dpm)$_3$ and are *ca.* 1·4 times as large as those obtained with Eu(dpm)$_3$.

THE REPORTS of Hinckley[1] and of Sanders and Williams[2] on the paramagnetic shifts induced in organic compounds using tris(dipivalomethanato)europium(III), Eu(dpm)$_3$, have led to studies by other workers.[3–5] The majority of the structures so far examined were alcohols while only one study has been reported on the use of Eu(dpm)$_3$ with ketones.[6] In another report, Hart and his co-workers[7] have claimed that the praseodymium complex, Pr(dpm)$_3$, causes a high field shift which is three times larger than that of the europium complex.

We here report work on the effect of Pr(dpm)$_3$ on 4-t-butylcyclohexanone (I) and 2,2-dimethyl-4-t-butylcyclohexanone (II).

Our best results were obtained by dissolving 50 mg of (I) or (II) and 100 mg of Pr(dpm)$_3$ in 0·5 ml CCl$_4$ containing 1% Me$_4$Si. In all cases, it was necessary to filter or centrifuge the solution to remove finely-suspended particles which were not identified. The t-butyl groups of the ligand did not interfere with the n.m.r. analyses because of the relatively small size of the structures under investigation. All peaks belonging to the ketones were at higher field than Me$_4$Si, whereas the t-butyl groups of the ligand appeared at 3·4 p.p.m. downfield from Me$_4$Si. In all cases, first-order spectra were obtained. A study of the effect of the concentration of Pr(dpm)$_3$ on the induced shift led to the observation of a linear relationship. The values of the shifts and a comparison of induced shifts by Eu(dpm)$_3$ and Pr(dpm)$_3$ are given in the Table.

The results from this study have led to the following observations. The well-established relationship between the distance Pr–H and the induced chemical shift is clearly evident as the hydrogens closest to the metal are those which are shifted most, whereas those far removed are affected to a much smaller extent. It is estimated that a proton 20 Å from the complexing metal will still be shifted upfield by some 0·1 p.p.m. Two contradictory reports exist on the nature of this relationship. Hinckley[1] has observed a dependency between the cube of reciprocal distance and the induced shift. Demarco *et al.*[4] reported a straight-line correlation between the log of induced shift and the log of distance. However, it should be noted that Hinckley's results on cholesterol, plotted as suggested by Demarco, yield a straight line and Demarco's results plotted according to Hinckley also fall on a straight line. Because of the well-established $1/R^3$ dependency for the pseudocontact shift, we have favoured this relationship to correlate the shift and the distance.

Shifts induced by Pr(dpm)$_3$ *and* Eu(dpm)$_3$ *on ketones* (I) *and* (II)

Ketone	Protons	Distance (Å)	$\Delta\omega$(Eu)[a] (p.p.m.)	$\Delta\omega$(Pr)[a] (p.p.m.)	Slope[b]
(I)	2-H(*eq*)	2·6	15·4	25·4	0·78
	2-H(*ax*)	3·1	14·8	19·7	0·60
	3-H(*eq*)	4·5	—	10·5	0·32
	3-H(*ax*)	3·6	—	8·5	0·26
	4-H(*ax*)	4·5	—	6·2	0·19
	Bu^t	6·6	2·0	2·9	0·09
(II)	3-H(*ax*)	3·6	—	11·9	0·43
	4-H(*ax*)	4·5	—	5·8	0·21
	5-H(*ax*)	3·6	—	9·5	0·34
	5-H(*eq*)	4·5	—	8·3	0·30
	6-H(*ax*)	3·1	14·1	17·9	0·65
	6-H(*eq*)	2·6	16·2	24·8	0·90
	Me(*eq*)	2·7	12·9	18·4	0·67
	Me(*ax*)	3·4	8·9	11·8	0·43
	Bu^t	6·6	2·1	2·9	0·10

[a] $\Delta\omega = \delta\,(\mathrm{CCl_4}) - \delta\,[\mathrm{Pr(dpm)_3}, n = 1]$ as defined by Demarco and his co-workers.[4] These values are accurate within ±2%.

[b] The slopes were measured by a least-squares analysis of the effect of concentration on induced chemical shift. In all cases, the correlation coefficient was better than 0·99 with an expected accuracy of 2%. These values were obtained using Pr(dpm)$_3$.

From our concentration study, it is seen that the slope of the line is a more precise measure of the distance between the complexing metal and protons of the substrate as it does not depend on extrapolations to a value where the concentrations of $Pr(dpm)_3$ and ketone are equal, nor to the extrapolation to values of chemical shifts of ketone without any $Pr(dpm)_3$, values which are not always readily available from the spectrum.

It was also observed that a large induced shift will generally cause a rather important broadening of the peak with resultant loss of the fine coupling constants. This is clearly shown for the 2-H–6-H(*eq*) of (I) and for 6-H(*eq*) of (II) which has a half-width of 9 Hz. Similar results have been noted for acetaldehyde.

The results in the Table also prove the superiority of $Pr(dpm)_3$ over $Eu(dpm)_3$ as a shift reagent. The induced shifts are about 1·4 times as large as those obtained with $Eu(dpm)_3$.

A by-product of this work is its application in the routine determination of the extent of deuteriation in the α-position of cyclic ketones. Integration of the n.m.r. signals corresponding to these protons become very simple when they are shifted by the addition of either $Eu(dpm)_3$ or $Pr(dpm)_3$.

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