Conformational Analysis by Lanthanide Induced Shifts. I. Applications to α,β-Unsaturated Aldehydes, Ketones, Esters, and Amides

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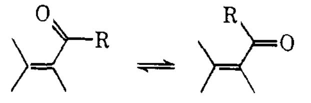
Abstract: Computer simulation of the observed lanthanide induced shifts (LIS) has been performed for a number of unsaturated aldehydes (14), ketones (8), esters (4), and amides (8), and the simulation process is described in detail. The results allow us to estimate the population ratio between the s-cis and s-trans conformers in these compounds. Aldehydes, in agreement with previous literature, are found predominantly in the s-trans form. Ketones and esters are found to exist as mixtures of the two forms, while the s-cis form predominates in amides. Data are reported also for some 2-carbonyl derivatives of furan and thiophene. It is shown that the LIS method, simple and rapid, can be suitably applied to a series of unsaturated compounds in order to obtain reliable and internally consistent estimates of the s-cis/s-trans population ratio. Finally, we report the finding that all the vinyl compounds studied, independent of the particular class to which they belong, fit the same empirical equation correlating the mole fraction of s-cis form with a function of the experimental LIS. This equation can be used as a calibration graph to determine the s-cis/s-trans population ratio *directly* from the experimental LIS data in the title compounds.

Lanthanide induced shift (LIS) method has received widespread attention since its discovery in 1969[1] and, as a consequence of the intensive efforts of numerous workers,[2] the phenomenon appears now reasonably well understood.[3-8]

Although the usefulness of the LIS technique lies in the general field of structural analysis, its potential applications to the study of the molecular conformation in solution are most appealing to us. In a first approach to this problem, we investigated[9] the molecular geometry of the lanthanide complexes with a series of amides by matching the observed shifts with those calculated according to the McConnell and Robertson equation[10] (computer simulation of the LIS).

Here we report the results of a similar study aimed at the determination of the population ratio between the (planar) s-cis (I) and s-trans (II) conformers in unsaturated aldehydes, ketones, esters, and amides.



I II

R = H, CH_3, OCH_3, $N(CH_3)_2$

Among several classical problems which could be chosen to test the utility of the LIS method in conformational analysis, this was selected for the simplicity and wide availability of these classes of compounds, and also for the large amount of data in the literature on the abundance of the s-cis and/or s-trans conformers in the title compounds. It should be noted that several different techniques have been used in these kinds of studies, so that the results obtained may not be entirely comparable or consistent.

The results reported hereafter show that the LIS method can be successfully applied to the determination of the s-cis/s-trans population ratio.

In the case of unsaturated aldehydes and ketones, the most studied classes of compounds, our results are in general agreement with existing estimates of the s-cis/s-trans ratio. Comparatively less data are available for unsaturated esters and amides, so that our figures are often the only available.

Since our data are obtained with the same technique, they should be internally consistent and directly comparable. This is demonstrated, we believe, by the finding that *all* the vinyl compounds studied here, independent of the particular class to which they belong, fit the same empirical equation correlating the mole fraction of s-cis form with a function of the experimentally observed LIS (see Discussion).

As already well known,[2] the experimental LIS can be quickly and routinely obtained. However, quantitative applications of the method have been limited by the necessity to perform a computer simulation of the experimental LIS, as we have done in the present case. The empirical equation found can be used as a calibration graph to determine the s-cis/s-trans population ratio *directly* from the experimental LIS data. The immediate interest and the implications of such conformational correlation are obvious and should stimulate further quantitative applications of the LIS method.

Experimental Section

Compounds used in this study were synthesized and characterized according to the literature. Lanthanide induced shift measurements were performed with $Eu(fod)_3$ and in some cases duplicated with $Pr(fod)_3$. Spectra of about 5% $CDCl_3$ solutions (TMS standard), containing 0–0.15 mol of lanthanide shift reagent (L)/mol of sub-

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(2) For a review of the subject, see R. von Ammon and R. D. Fischer, *Angew. Chem., Int. Ed. Engl.*, **11**, 675 (1972).

(3) Some pertinent papers that recently appeared are listed in ref 4–8.

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(9) G. Montaudo and P. Finocchiaro, *J. Org. Chem.*, **37**, 3434 (1972).

(10) H. M. McConnell and R. E. Robertson, *J. Chem. Phys.*, **29**, 1361 (1958).

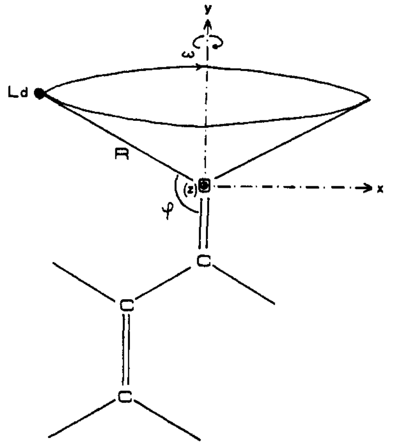

Figure 1. Possible locations of the lanthanide (Ld) ion in the space around the oxygen atom. *R* represents the Ld–O distance; *φ* is in the Ld–O–C internuclear angle; the dihedral angle Ld–O–C–C, *ω*, is zero for the configuration indicated in the figure. Varying *R*, *φ*, *ω* all the Ld possible spatial locations can be explored. The internal coordinate system is also shown.

strate (S), were obtained at 60 MHz (Varian A 60-D analytical spectrometer). The lanthanide shift reagent was added stepwise from a stock solution (0.32 *M*), with the help of a 50-μl microsyringe. Each signal was followed in the spectra, and the LIS were found directly proportional to the [L]/[S] ratio present. A least-squares fit of the experimental points was used to obtain the observed LIS.

The computer simulation process of the experimental LIS data is described in the next section. Our computations were performed on an CDC-6600 digital computer. We will be glad to provide our program listings (Fortran IV) to anybody who may desire them.

LIS Simulation Process

The LIS simulation process is best described when applied to a structurally rigid molecule (atomic coordinates are fixed and can be deduced from pertinent solid-state data or measured on Dreiding models).

The lanthanide–substrate interaction is thought[2] to be entirely or predominantly of pseudocontact nature, usually expressed by the McConnell and Robertson equation[10]

$$\Delta\nu = K(3\cos^2\chi - 1)r^{-3} \tag{1}$$

where χ is the O–Ld–H internuclear angle and *r* is the corresponding Ld–H distance. It has been common practice among workers in the field to assume the observed LIS proportional to the intrinsic LIS ($\Delta\nu$ in eq 1). The validity of this assumption has received full support in a recent[7] exacting study of the equilibria taking place between the lanthanide shift reagent and the substrate.

For structurally rigid molecules with a single coordination site (*i.e.*, oxygen), the molecular geometries of the lanthanide complexes can be obtained by determining the optimal location of the lanthanide ion in the space around the coordination site.[9] A computer program is most useful to explore all the possible lanthanide spatial locations, defined in Figure 1 by polar coordinates *R*, *φ*, *ω*, where *R* is the Ld-O distance, *φ* is the Ld-O-C angle, and *ω* is the Ld-O-C-C dihedral angle.

Input data are the atomic coordinates and the observed LIS for each proton in the molecule. In step 1 the geometrical factor $(3\cos^2\chi - 1)r^{-3}$ corresponding to each proton in the molecule is analytically calculated for a given set of *R*, *φ*, *ω* values. Step 2 performs a least-squares minimization of the observed LIS *vs.* the geometrical factors corresponding to each proton. In this way the pseudocontact constant (*K*, eq 1) is obtained, and the theoretical LIS can be calculated according to eq 1 (step 3). In step 4, the difference between observed and calculated LIS for a given set of *R*, *φ*, *ω* values (*i.e.*, for each lanthanide spatial location) is expressed[11] in terms of error by means of Hamilton agreement factor (AF).

$$\mathrm{AF} = \sqrt{\frac{\sum_i (\mathrm{LIS}_{\mathrm{obsd}\ i} - \mathrm{LIS}_{\mathrm{calcd}\ i})^2}{\sum_i \mathrm{LIS}_{\mathrm{obsd}\ i}{}^2}} \tag{2}$$

Steps 1–4 are repeated for all the possible sets of *R*, *φ*, *ω* values. The agreement factors (AF) corresponding to each molecular geometry of the lanthanide–substrate complex are obtained as output in a square matrix format (*φ vs. ω*, at constant *R*). The minimum value of AF is assumed to individuate the most likely molecular geometry of the complex.

In practice only *φ* and *ω* were allowed to vary and the Ld–O distance (*R*, Figure 1) was kept constant at 3.0 Å. We have verified, in fact, that the minimum AF value is not displaced by varying *R* in the 2.5–3.5-Å range, and that it is a very flat function of *R* in that range.[5,16,17]

In order to apply the LIS simulation process to determine the population ratio between s-cis (I) and s-trans (II) forms in the title compounds, eq 1 can be rewritten

$$\Delta\nu_{\mathrm{obsd}} = K(w_cG_c + w_tG_t) \tag{3}$$

where w_c and w_t are the molar fractions, and G_c and G_t the geometrical factors (eq 1) corresponding to the s-cis and s-trans forms, respectively.[18,19]

G_c and G_t can be calculated for each set of *φ*, *ω*

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(11) Computer simulation of the LIS proton spectra has been reported several times,[5,6,9,12-14] but relatively little computing details have been given. A notable exception is that of Willcott, Davis, and Lenkinski[5] who have described their method in some detail, and have proposed to adopt the Hamilton[15] agreement factor (AF) as a measure of the error in the LIS simulation and as a significance testing criterion. Accordingly, we have experienced the use of Hamilton[5,15] AF and have adopted it.

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(16) However, a referee suggested that an Eu–O distance value of 2.4 Å is more appropriate on the basis of his X-ray values.

(17) The accuracy of the (time-averaged) molecular geometry of the lanthanide–substrate complex determined in this way depends on the accuracy of atomic coordinates and observed LIS for each proton in the molecule. Uncertainties in signal assignments may determine serious errors in the resulting optimal geometry of the complex. We have found useful practice to exchange signals with uncertain assignment to compare the AF corresponding to the optimal geometries thus obtained. Higher AF are invariably obtained in cases of mistaken assignments. Signal permutation is automatically performed in our program through the activation of a subroutine. Several stereochemical problems can be handled in this way. M. R. Willcott and R. E. Davis have done similar observations and have reported them at the 13th Experimental Nuclear Magnetic Resonance Conference, Asilomar, Calif., May 1972.

(18) It should be remarked that, for a given couple of proton and lanthanide coordinates, χ and *r* in eq 1 are unequivocally defined (*i.e.*, they are not independent parameters).

(19) A tentative discussion about the significance of *K* (eq 3) and of the spatial location of the lanthanide has been given elsewhere,[9] and we feel that one should wait for still more data in order to further comment on this matter.

values and, assigning an initial zero value to w_c, computational steps can be performed as above described. w_c is then automatically incremented up to one and the AF corresponding to each couple of φ,ω values (for each w_c from 0 to 1) are obtained at the output. The minimum value of AF is here assumed to individuate the most likely molar fraction w_c.

It should be remarked that there are only two independent variables (K and w_c) in eq 3. G_c and G_t are fixed for each Ld location.

Therefore calculations on molecules with three or more observations are possible and yield solutions mathematically determined. As a matter of fact, direct analytical solution of eq 3 is possible by least-squares minimization and we will report shortly on this point.

In Table I, for each compound investigated, we have tabulated the values of w_c and K (eq 3) and φ, ω corresponding to the minimum AF obtained. The error level, as expressed by the AF (eq 2), is excellent in most cases, so that the calculated LIS values are almost coincident with those experimentally measured (Table I).

All the compounds in Table I were considered monofunctional.

It is in fact well known[20] that nuclear oxygen and sulfur in heterocycles are inactive to the lanthanide shift reagent, and the same is true for the methoxy group in esters.[20]

Results

In Table I are collected the experimental data and the calculated results for all the compounds included in our study.

As above mentioned, a great deal of literature exists on the subject, so that it is uneasy to discuss each case in detail. We give therefore only a brief summary, quoting leading references to more detailed discussions of previous studies.

The simplest α,β-unsaturated aldehydes, acrolein and *trans*-crotonaldehyde, are known to exist in the s-trans form[21–24] and similar conclusions were drawn by Wolkowski and coworkers[25,26] for a large number of α- and β-substituted acroleins, on the basis of a qualitative analysis of their LIS spectra.

Based on Wolkowski[25,26] experimental LIS, our calculations (compounds I–XII; Table I) confirm the general dominance of the s-trans forms and, furthermore, allow observation of finer effects of the steric and polar interactions (*vide infra*).

Going from unsaturated aldehydes to ketones the conformational equilibrium shifts toward the s-cis form owing to increasing steric hindrance of the s-trans form. It is well recognized that β-methyl substitution cis to the carbonyl causes the predominance of the s-cis form, while the α-methyl substitution shifts the equilibrium toward the s-trans form.[27]

Our results are in general agreement with this rule. We find that methyl vinyl ketone (compound XIII, Table I) and the α-methyl substituted compounds XIV and XV (Table I) are predominantly in the s-trans form as reported by others with different techniques.[27–32]

Compounds XVII and XVIII (Table I) and mesityl oxide (compound XVI, Table I), which is β-methyl substituted, are found predominantly s-cis, also in accord with other estimates.[25,27,29,32–36]

Recent results from various techniques[37–41] indicate that 2-formyl- and 2-acetylthiophene (compounds XIX and XXI, Table I) exist largely in the s-trans form while mixtures of the two forms are reported[37,42–47] in the case of 2-formyl- and 2-acetylfuran (compounds XX and XXII, Table I).

Our results (Table I), while providing an independent set of estimates for all four compounds, are in agreement with the findings of other workers.

The LIS proton spectra of four α,β-unsaturated esters (compounds XXIII–XXVI, Table I) have been reported quite recently,[48] and the authors have concluded that these compounds exist in the s-cis form. However, they confined themselves to a mere choice between the *pure* s-cis and *pure* s-trans forms without evaluating *mixtures* of the two conformers. Based on their experimental LIS, our calculations (Table I) show that these esters are better regarded as mixtures, in various ratios, of the two forms.

Scarce data are available in the literature[49] on the solution conformational preferences of α,β-unsaturated amides, and our data indicate that the β-cis unsubstituted ones exist preponderantly in the s-cis form as might be predicted on steric grounds. However, the s-cis form becomes unfavored in the α-

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(21) (a) R. Wagner, J. Fine, J. W. Simmons, and J. H. Goldstein, *J. Chem. Phys.*, **26**, 634 (1957); (b) F. A. Cherniak and C. C. Costain, *ibid.*, **45**, 104 (1966).

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Table I. Measured and Simulated LIS and Preferred Conformation for Unsaturated Aldehydes, Ketones, Esters, and Amides[a]

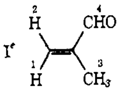
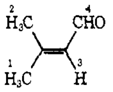
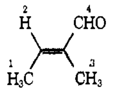
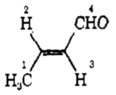
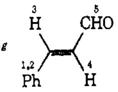
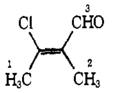
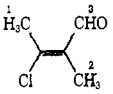
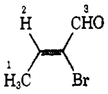
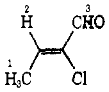
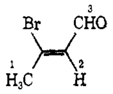
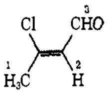
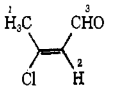
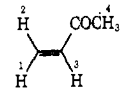
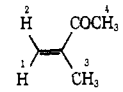
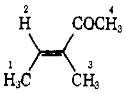
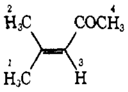
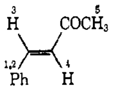
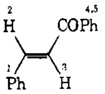
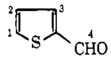
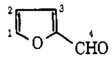
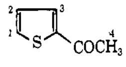
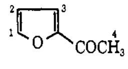
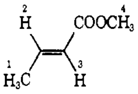
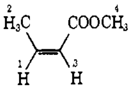
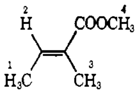
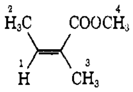
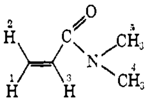
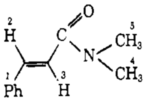
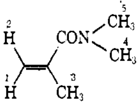
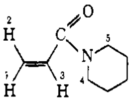
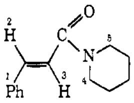
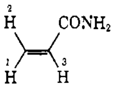
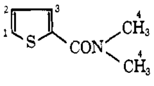
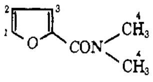
No.	Compd	1	2	3	4	5	K	φ, ω, deg	AF[b]	s-cis[c]	Ref[d]
I[e]		*f* 6.0 6.27	*f* 8.0 7.61	*f* 13.0 12.29	*f* 28.0 28.35		1390	125, 140	0.028	0	25
II[e]		*f* 5.6 4.06	*f* 6.6 6.08	*f* 19.4 18.06	*f* 29.4 30.50		1551	120, 110	0.065	1	25
III[g]		*f* 13.5 13.15	*f* 25.2 25.07	*f* 34.0 33.66	*f* 80.0 80.24		4013	125, 130	0.006	10	26
IV[g]		*f* 12.7 13.24	*f* 25.2 25.17	*f* 45.2 45.24	*f* 81.0 80.90		4046	125, 130	0.005	9	24, 26
V[g]		*f* 3.3[h] 2.66[h]	*f* 8.0[i] 9.63[i]	*f* 19.8 19.59	*f* 34.2 34.06	*f* 60.4 60.31	3068	120, 110	0.024	14	26
VI[g]		*f* 10.8 10.80	*f* 29.8 29.80	*f* 68.0 68.00			3648	130, 110	0.00005	6	26
VII[g]		*f* 14.3 14.27	*f* 32.0 31.93	*f* 80.0 80.24			3646	120, 160	0.0008	4	26
VIII[g]		*f* 6.1 6.11	*f* 11.6 11.60	*f* 37.2 37.20			1721	120, 150	0.0001	19	26
IX[g]		*f* 7.7 7.78	*f* 15.2 15.19	*f* 50.6 50.59			2444	120, 130	0.001	12	26
X[g]		*f* 9.0 8.94	*f* 36.0 36.00	*f* 56.0 56.0			3128	135, 100	0.0009	5	26
XI[g]		*f* 9.8 9.84	*f* 39.0 39.00	*f* 66.4 66.39			3473	125, 110	0.0006	11	26
XII[g]		*f* 16.0 16.01	*f* 37.2 37.22	*f* 69.8 69.78			3363	125, 150	0.0002	9	26
XIII[h]		*f* 10.0 9.81	*f* 14.0 14.06	*f* 20.0 20.05			1930	120, 180	0.007	27	27, 30
XIV[e]		*f* 9.0 8.86	*f* 11.8 11.85	*f* 15.0 15.04	*f* 18.0 18.01		1770	135, 180	0.005	12	25, 27, 30–32
XV[e]		*f* 5.9 5.88	*f* 11.5 11.51	*f* 13.8 13.82	*f* 16.8 16.78		1686	125, 140	0.001	18	25, 27, 31
XVI		1.85 3.96 3.60	2.11 9.12 9.87	6.00 6.35 8.12	2.11 11.80 9.68		903	155, 180	0.173	72	25, 27, 29, 32–34
XVI[e]		*f* 5.10 4.19	*f* 15.50 16.03	*f* 13.40 14.47	*f* 18.40 17.23		1613	170, 40	0.068	72	
XVII		7.42[i] 3.09[i] 3.39[i]	7.42[j] 1.21[j] 0.56[j]	6.71 11.99 12.27	7.51 9.55 10.17	2.33 12.89 12.02	1137	120, 100	0.064	63	35, 36

Table I (*Continued*)

No.	Compd	1	2	3	4	5	*K*	φ, ω, deg	AF[b]	s-cis[c]	Ref[d]
XVIII		7.46[i] 2.14[i] 3.04[i]	7.58 12.30 11.46	7.46 9.34 7.55	7.88[i] 9.26[i] 11.08[i]	7.46[j] 2.14[j] 2.26[j]	887	165, 20	0.0164	83	
XIX		7.71 2.99 1.52	7.13 1.67 1.24	7.63 2.17 2.06	9.80 9.51 9.82		429	115, 180	0.152	1	37–41
XX		7.60 2.69 1.82	6.55 1.98 1.66	7.17 4.52 4.46	9.53 8.51 8.78		513	155, 180	0.095	56	37, 40, 42–46
XXI		7.46 2.79 2.84	7.05 1.83 1.76	7.63 5.44 5.46	2.50 9.66 9.65		1673	90, 120	0.007	18	37–41
XXII[k]		*f* 1.9 1.99	*f* 2.1 1.99	*f* 5.7 5.68	*f* 8.1 8.12		780	175, 100	0.014	33	37, 43, 44, 47
XXIII[l]		*f* 2.5 2.39	*f* 11.6 11.64	*f* 11.6 11.66	*f* 11.5 11.42		1257	115, 100	0.007	51	48
XXIV[l]		*f* 4.4 4.36	*f* 6.5 6.51	*f* 11.4 11.42	*f* 11.10 11.09		1043	165, 20	0.002	20	48
XXV[l]		*f* 3.1 3.03	*f* 13.0 13.02	*f* 7.2 7.35	*f* 12.7 12.6		1187	170, 0	0.009	59	48
XXVI[l]		*f* 5.9 5.42	*f* 8.2 8.25	*f* 8.2 8.41	*f* 12.3 12.33		1231	170, 20	0.029	24	48
XXVII		5.67 5.08 4.30	6.25 11.88 12.19	6.83 8.88 9.44	3.10 4.61 5.64	3.10 10.72 9.50	1064	130, 90	0.096	69	
XXVII[m]		5.67 8.48 7.24	6.25 24.40 25.21	6.83 14.66 16.35	3.10 9.32 10.99	3.10 21.54 18.43	1972	135, 80	0.110	82	
XXVIII		7.33[i] 1.73[i] 0.66[i]	7.56 12.28 12.74	6.76 5.27 4.32	3.02 3.52 6.39	3.02 10.32 8.46	922	115, 80	0.149	95	49
XXIX		5.07 5.01 5.00	4.92 8.25 8.27	1.91 9.09 9.15	2.94 10.95 10.89	2.94 10.95 10.89	1252	135, 90	0.005	11	
XXX		5.66 4.32 4.35	6.20 12.59 12.85	6.68 7.35 7.89	3.58 3.94 5.85	3.58 11.70 9.81	1075	110, 90	0.102	79	
XXXI		7.35[i] 0.65[i] 0.17[i]	7.51 9.03 9.29	6.79 4.21 4.81	3.65 2.67 3.08	3.57 8.12 7.22	703	110, 80	0.097	89	
XXXII[n]		*f* 31.60 31.59	*f* 66.40 66.40	*f* 57.20 57.20			6312	120, 120	0.00006	64	
XXXIII		7.27 1.32 1.33	6.97 1.09 1.11	7.38 6.00 5.99	3.13 6.30 6.30		706	160, 60	0.002	99	
XXXIV		7.43 3.22 3.10	6.40 2.37 2.79	6.92 11.25 11.21	3.15 7.18 7.13		1138	115, 120	0.032	91	

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[a] Figures in the first row indicated chemical shifts (δ) of the free substrate; figures in the second row indicate observed molar induced shifts; figures in the third row indicated calculated molar induced shifts. [b] Minimum agreement factor. [c] s-cis molar fraction per cent. [d] Previous work from various techniques. [e] $Yb(dpm)_3$ induced shifts taken from ref 25. [f] Chemical shift value missing in the original work. [g] $Yb(dpm)_3$ induced shifts taken from ref 26. [h] $Yb(dpm)_3$ induced shifts taken from ref 28. [i] Ortho proton of the phenyl. [j] Meta and para protons of the phenyl. [k] $Eu(dpm)_3$ induced shifts taken from ref 19. [l] Data taken from ref 48. [m] $Pr(fod)_3$ induced shifts. [n] $Yb(dpm)_3$ induced shifts taken from C. Beautè, Z. W. Wolkowski, and N. Thoai, *Chem. Commun.*, 700 (1971).

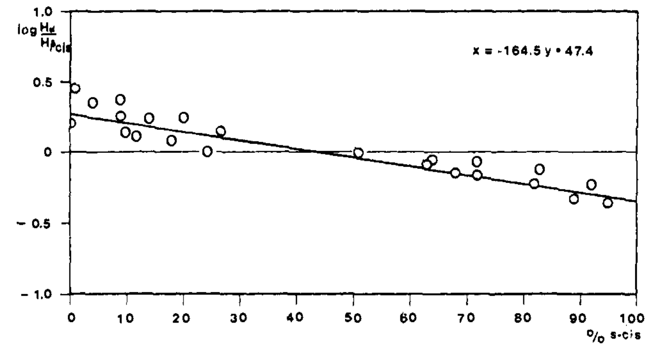

Figure 2. Plot of the percentage molar fraction of s-cis form *vs.* log $H_\alpha/H_{\beta\text{-cis}}$ for the title compounds. H_α and $H_{\beta\text{-cis}}$ are respectively the observed LIS for the protons in α and β-cis positions to the carbonyl.

methyl substituted amides (compound XXIX, Table I) and the s-trans form becomes preferred.

Discussion

The general agreement between population data presented in Table I and those available in the literature illustrates the wide applicability of the LIS method to the title compounds and also its reliability.

In fact, the LIS analysis is meaningful and its results are reliable only if the conformational equilibria in the substrate molecule are not perturbed by the lanthanide addition. Our results show that, at least for the important classes of compounds considered here, no unusual perturbation of the conformational equilibria occurs.

The reliability of our estimates is shown not only by the agreement with data from other techniques, but also by their internal consistency, as shown in Figure 2. In fact, the molar fraction of s-cis forms calculated for each vinyl compound are plotted *vs.* log $H_\alpha/H_{\beta\text{-cis}}$, where H_α is the observed LIS for the proton in α position to the carbonyl, and $H_{\beta\text{-cis}}$ is the observed LIS for the β proton in cis position to the carbonyl. A fairly linear relation exists (correlation coefficient 0.9293) among all the points in Figure 2, independent of the particular class to which they belong (aldehydes, ketones, esters, amides) and also from the lanthanide shift reagent used to obtain the experimental LIS. Although we have no theoretical explanations at hand to account for the linear behavior in Figure 2, some kind of correlation between the two parameters had to be expected since the $H_\alpha/H_{\beta\text{-cis}}$ ratio is clearly a function of the relative abundance of the s-cis and s-trans conformers in each compound, regardless of the functional group attached to the carbonyl.

Accordingly, the relation in Figure 2 can be used to determine the s-cis/s-trans population ratio *directly* from the experimental LIS data in the title compounds. This remarkable result, and its implications about further quantitative applications of the LIS method, is not the only interesting point here. Our data (Table I; Figure 2) cover the relative population range from one extreme to the other. Starting from the notion that, in absence of interferences, the s-trans form is favored over the s-cis, we have a complete set of results which illustrate the steric inhibition of one form up to the complete inversion of stability of the two forms.

Conformational Analysis of 1,3-Butadiene[1]

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Contribution from the Department of Chemistry, University of Minnesota, Minneapolis, Minnesota 55455. *Received November 9, 1972*

Abstract: The conformational analysis of 1,3-butadiene has been accomplished using the temperature dependences of two nuclear magnetic resonance spectral parameters, δ_{AB} and $J_{CC'}$, obtained from 2,3-dideuterio-1,3-butadiene (**2**) and 1,1,4,4-tetradeuterio-1,3-butadiene (**3**), respectively. These parameters have been correlated with the trans ⇌ cis conformational equilibrium (eq 1). The magnitude of the derived vicinal 2,3 proton–proton coupling of the minor conformer indicates that it is nonplanar (skew). The enthalpy difference for the trans ⇌ skew equilibrium (**1a** ⇌ **1c**, **1d**) was found to be $+2105 \pm 44$ cal/mol at $\Delta S = +1.376$ eu.

The compound 1,3-butadiene is generally represented as a mixture of two planar conformers, **1a** (s-trans) and **1b** (s-cis), in mobile equilibrium.[3] Hückel, using theoretical considerations, suggested the possibility of two such forms as early as 1932.[4]

Considerable experimental evidence supporting the existence of a major conformer having a trans-coplanar conformation has been obtained from electron diffraction,[5] infrared and Raman,[6] microwave,[7] far-infrared,[8]

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(1) Presented in part by E. W. G. at the 160th National Meeting of the American Chemical Society, Houston, Texas, Feb 1969.

(2) Correspondence may be directed to E. W. G., Center for Applied Research in Environmental Sciences, St. Michaels, Md. 21663.

(3) L. Pauling, "The Nature of the Chemical Bond," 3rd ed, Cornell University Press, Ithaca, N. Y., 1960, p 291; J. C. Grundy, "Stereochemistry," Butterworths, London, 1964, p 69; K. Mislow, "Introduction to Stereochemistry," W. A. Benjamin, New York, N. Y., 1966, p 75.

(4) E. Huckel, *Z. Phys.*, **76**, 630 (1932).

(5) (a) V. Schomaker and L. Pauling, *J. Amer. Chem. Soc.*, **61**, 1769 (1939); (b) A. Almenningen, O. Bastiansen, and M. Traetteberg, *Acta Chem. Scand.*, 12, 1221 (1958); (c) W. Haugen and M. Traetteberg, *Acta Chem. Scand.*, **20**, 1726 (1966); (d) K. Kuchitsu, T. Fukuyama, and Y. Morino, *J. Mol. Struct.*, **1**, 463 (1968).

(6) (a) K. Bradacs and L. Kahovec, *Z. Phys. Chem., Abt. B*, **48**, 63 (1940); (b) R. S. Rasmussen and R. R. Brattain, *J. Chem. Phys.*, **15**, 131 (1947); (c) C. M. Richards and J. R. Nielsen, *J. Opt. Soc. Amer.*, **40**, 438 (1950); (d) M. I. Bateuv, A. S. Onishchenko, A. D. Matveeva, and N. I. Aronova, *Proc. Acad. Sci. USSR, Chem. Soc.*, **132**, 543 (1960); (e) D. J. Marais, N. Sheppard, and B. P. Stoicheff, *Tetrahedron*,