References and Notes

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Communications to the Editor

^{13}C-^{1}H Coupling Constants in Cyclohexane

Sir:

Recently much interest has been shown in the study of ^{13}C-^{1}H coupling constants.[1] The data on ^{13}C-^{1}H couplings in flexible saturated systems are, however, rather limited, owing to extreme complexity of their proton-coupled ^{13}C NMR spectra.

We wish to report here the experimental values of *all* possible ^{13}C-^{1}H coupling constants in cyclohexane which is a classical example of a conformationally flexible system. The data discussed below were obtained from the low- and high-temperature proton-coupled ^{13}C spectra of cyclohexane-d_{11}.

Cyclohexane-d_{11} was synthesized by chlorination[2] of cyclohexane-d_{12} (Isocommerz, Leipzig, isotope purity 99%) followed by Grignard replacement of the chloro atom with hydrogen.[3]

Fast inversion of the cyclohexane ring at ambient temperatures leads to the complete averaging of the NMR parameters characterizing axial and equatorial proton positions.[4] Thus, the high-temperature (+34 °C) ^{13}C-$\{^{2}D\}$ spectrum (Figure 1a) should be regarded as a superimposition of four AX spectra (A = ^{1}H, X = ^{13}C) from the four possible $^{13}C^{12}C_5D_{11}H$ isotopomers, which differ in the relative positions of ^{13}C and ^{1}H nuclei and types of coupling constants (i.e., $^{1}J_{av}$, $^{2}J_{av}$, $^{3}J_{av}$, and $^{4}J_{av}$). Analysis of both the ^{13}C-$\{^{2}D\}$ NMR spectrum (25.16 MHz) and the ^{13}C satellites in the ^{1}H NMR spectrum (100.1 MHz) makes it possible to assign the signals to the individual isotopomers. This allows immediate identification of four coupling constants two of which (with wt 1) are equal to 124.56 and 0.44 Hz and the other two (with wt 2) are equal to 3.81 and 5.06 Hz. The largest value of 124.56 Hz should be assigned to $^{1}J_{av}$.[5] This gives $^{4}J_{av}$ = 0.44 Hz. In order to assign $^{2}J_{av}$ and $^{3}J_{av}$, we have used the isotope effects on ^{13}C chemical shifts caused by the replacement of ^{2}D by ^{1}H. These isotope shifts, $\Delta\nu(^{13}C)$, observed as displacements of the doublet centrums from the ^{13}C signal of cyclohexane-d_{12}, are equal to 2.70 and 0.64 Hz for the doublets spaced 3.81 and 5.06 Hz, respectively, which favor the following assignment: $^{2}J_{av}$ = 3.81 Hz, and $^{3}J_{av}$ = 5.06 Hz.[6]

At low temperatures (−104 °C in our experiments) the ring inversion slows down and the sharp lines from the individual conformers appear in the spectrum (Figure 1b).[4] A total of eight nonequivalent cyclohexane-d_{11} conformers can be resolved into two groups[7] depending on whether the proton is in an axial or in an equatorial position. The values of two ^{1}J couplings (i.e., $^{1}J_e$ and $^{1}J_a$) are equal to 126.44 and 122.44 Hz

Table I. Coupling Constants J_{CH},[a] ^{13}C Isotope Chemical Shifts Caused by the Replacement of ^{2}H with ^{1}H, $\Delta\nu(^{13}C)$,[a-c] Proton Isotope Chemical Shifts Caused by the Replacement of ^{12}C with ^{13}C, $\Delta\nu(^{1}H)$[a,c,d] in Cyclohexane-d_{11} (10% v/v Solution in CS_2 Containing ~10% v/v TMS)

Parameter		Proton H_{av}[e]	H_e[f]	H_a[f]
$^{1}J_{CH}$	Exptl	124.56	126.44	122.44
	Calcd		118.7[g]	123.6[g]
			122.9[h]	119.4[h]
$^{2}J_{CH}$	Exptl	−3.81	−3.69	−3.94
	Calcd		−6.35[g]	−6.90[g]
			−6.67[h]	−6.79[h]
$^{3}J_{CH}$	Exptl	5.06	8.12	2.12
	Calcd		8.34[g]	1.44[g]
			8.78[h]	1.36[h]
$^{4}J_{CH}$	Exptl	(−)0.44[i]	(−)0.50[i]	(−)0.31[i]
	Calcd		−0.83[g]	−0.47[g]
			−0.88[h]	−0.46[h]
$^{n}\Delta\nu(^{13}C)$	$^{1}\Delta\nu$	10.58	10.03	11.22
	$^{2}\Delta\nu$	2.70	2.91	2.59
	$^{3}\Delta\nu$	0.64	1.00	0.31
	$^{4}\Delta\nu$	0.01	0.06	−0.03
$^{n}\Delta\nu(^{1}H)$	$^{1}\Delta\nu$	−0.18	−0.26	−0.11
	$^{2}\Delta\nu$	−0.05	−0.10	−0.09
	$^{3}\Delta\nu$	−0.02	−0.04	

[a] In hertz. The accuracy is within 0.05 Hz. [b] At 25.16 MHz for ^{13}C nuclei. [c] Positive values correspond to the downfield shifts. [d] At 100.1 MHz for ^{1}H nuclei. [e] +34 °C. [f] −104 °C. [g] The FP INDO calculations with the geometry taken from ref 14. [h] The FP INDO calculations with $r(C-H_a)$ = 1.101 and $r(C-H_e)$ = 1.141 Å. Other geometric parameters as in ref 14. [i] For the assignment and the signs of $^{4}J_{CH}$s, see text.

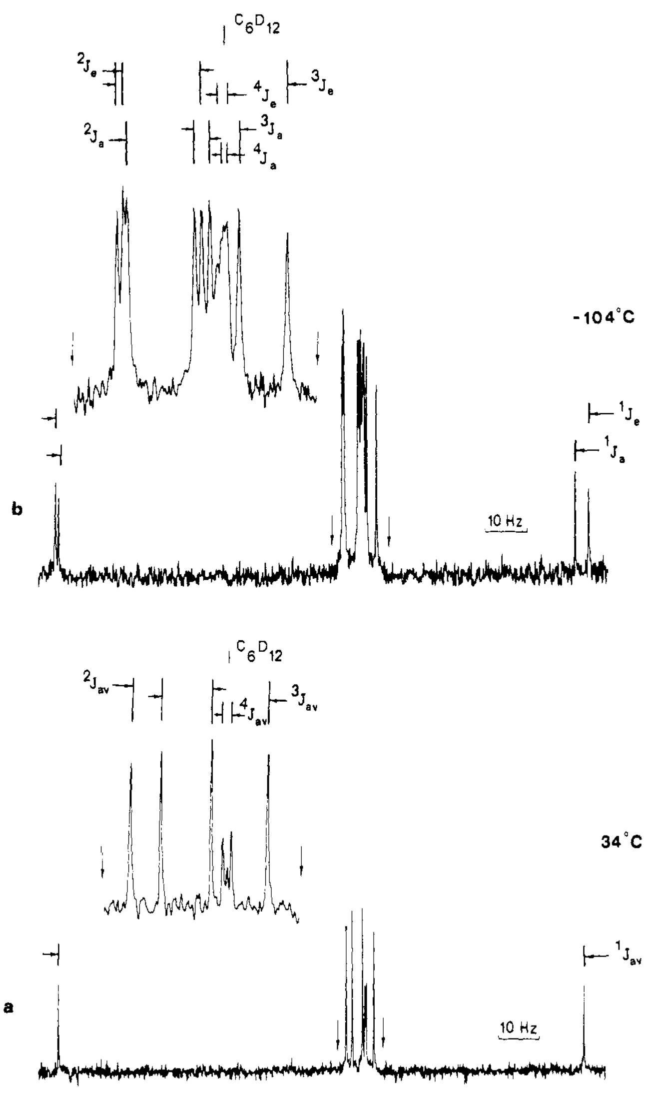

Figure 1. High- (a) and low-temperature (b) proton-coupled $^{13}C\{^2D\}$ NMR spectra of cyclohexane-d_{11}. The central parts are given in expansion. The assignments of the signals to the ^{13}C–H doublets and to the C_6D_{12} signal are also given. Spectra were recorded on a Varian XL-100-15 spectrometer (25.16 MHz, ^1H lock, FT mode, 250-Hz spectrum width, 8K data points). The numbers of transients accumulated: 200 (spectrum a) and 750 (spectrum b). The sample was a 10% v/v solution of $C_6D_{11}H$ in CS_2 containing 10% v/v of TMS degassed and sealed in a 12-mm-o.d. sample tube.

(Table I). The assignment of these couplings was made using the ^{13}C satellites in the low-temperature ^1H spectrum. As the 126.44-Hz doublet was centered around the low-field signal, i.e., that of H_e, we concluded that $^1J_e = 126.44$ and $^1J_a = 122.44$ Hz.[8] The assignment of the geminal and the vicinal couplings was performed in a similar way.

The signs of the ^{13}C–^1H coupling constants in cyclohexane-d_{11} can not be determined experimentally. However, on the basis of the literature data,[1a–c,9] one can assume that all $^1J_{CH}$ and $^3J_{CH}$ values are positive and, in saturated systems, all $^2J_{CH}$ values are negative.

There are no data available on the values of $^4J_{CH}$ in saturated compounds; comparison of the low- and high-temperature spectra[10] (see Table I) only shows that all the $^4J_{CH}$ values have the same sign. The correlation of $^nJ_{CH}$ with $^nJ_{HH}$ in structurally related fragments[11] favors the negative sign for $^4J_{CH}$. Note that $^4J_{HH}$ coupling constants in saturated fragments H–C–C–C–H with dihedral angles θ and θ' of 60 and 300°, respectively (or 60 and 180°), have small negative values.[12]

We also performed the finite perturbation (FP) INDO calculations[13] of all the J_{CH} values in cyclohexane using the geometry given in ref 14. Despite poor agreement between absolute experimental and calculated values (see Table I) the signs of J_{CH} were substantiated.

The calculations also indicate that $^2J_{CH}$s are stereochemically insensitive while the $^3J_{CH}$ values dramatically depend upon the dihedral angle ϑ. It is worthwhile to note that the Karplus type equation in the form $^3J_{CH} = A\cos^2\vartheta + B$, with A of 8.1 Hz and B equal to 0, fits well the experimental data obtained in the present work.[15]

The data in Table I show that the FP INDO calculations give incorrect ordering of $^1J_{CH}$ (cf. exptl (calcd): $^1J_a = 122.44$ (123.6), $^1J_e = 126.44$ Hz (118.7)). Though one can hardly expect to obtain accurate $^1J_{CH}$ values using the FP INDO technique, there are indications (see, e.g., ref 13, 16) that the calculations reflect actual trends in variation of $^1J_{CH}$ in series of structurally related compounds. The discrepancy thus may well be due to incorrect proton coordinates which are "the Achilles heel" of electron diffraction studies.[17] From the FP INDO calculations of $^1J_{CH}$ in methane, it is known that a 0.02-Å increase in the C–H bond length gives an ~2 Hz *increase* in the $^1J_{CH}$ coupling constants.[16] We performed another cycle of calculations with $r(C–H_a) = 1.101$ and $r(C–H_e) = 1.141$ Å (other geometric parameters used were those cited in ref 14) and thus obtained the correct ordering for $^1J_{CH}$ values. Other couplings remained practically unaffected by this change of geometric parameters. The suggested C–H bond length difference of 0.04 Å seems too large in view of the structural data available.[18] Taking into account general inconsistency of the current spin coupling constant theory,[13] the above suggestion should be considered as a mere hypothesis. The accuracy of the known structural data is not sufficient to rule out the possibility that the C–H_e bond lengths may be somewhat longer than the C–H_a ones.

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(10) Averaged values of the J_{CH} and $\Delta\nu$ obtained from low-temperature spectra proved to be very close to the H_{av} data (see Table I).

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(18) We wish to thank Drs. O. Bastiansen and V. Mastryukov for instructive comments on this point.

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Generalized Anomeric Effect and Barrier to Internal Rotation about the Oxygen–Methylene Bond in Chloromethyl Methyl Ether

Sir:

The anomeric effect,[1] although first recognized in carbohydrates, has a wide significance in organic chemistry and has been extensively studied by both experimental and theoretical methods.[2] In its generalized form,[3] the effect causes a preference for gauche over anti arrangements in compounds of the type C-X-C-Y, where X = O, N, or S, and Y = O, N, or halogen. The magnitude of the anomeric effect appears to be generally of the order of 0.5 to 3 kcal/mol. We thought that the presence of the generalized anomeric effect in halomethyl methyl ethers should lead to enhanced barriers to rotation. Although the barrier to rotation about the O-CH_3 bond in chloromethyl methyl ether has been measured to be 1.84 kcal/mol,[4] the barrier to rotation about the O-CH_2Cl bond has not been reported. We now present variable temperature NMR measurements on chloromethyl methyl ether (I), bis(chloromethyl) ether, and fluoromethyl methyl ether.

The ${}^1H$ spectrum of chloromethyl methyl ether (I)[5] in $CHFCl_2/CHF_2Cl$ (1:3) (Figure 1) shows a clear dynamic NMR effect below −170 °C. The methylene protons give rise to a distinct symmetrical doublet at −182 °C. At still lower temperature the lines become very broad because of dipole-dipole relaxation effects in the increasingly viscous solution. Since the line width at −182 °C is of the order of 50 Hz, spin-spin coupling between the diastereotopic methylene protons cannot be observed.

The presence of two methylene proton resonances at low temperatures is consistent with the gauche conformation, in agreement with most other physical data.[4,6] A line-shape calculation with an exchange rate constant of 250 s^{-1}, a T_2 corresponding to $1/\pi T_2$ = 50 Hz, and a chemical shift difference of 120 Hz reproduced the observed methylene resonance at −180 °C. From the absolute rate theory a free-energy barrier ($\Delta G^{\ddagger}$) of 4.2 kcal/mol is obtained.

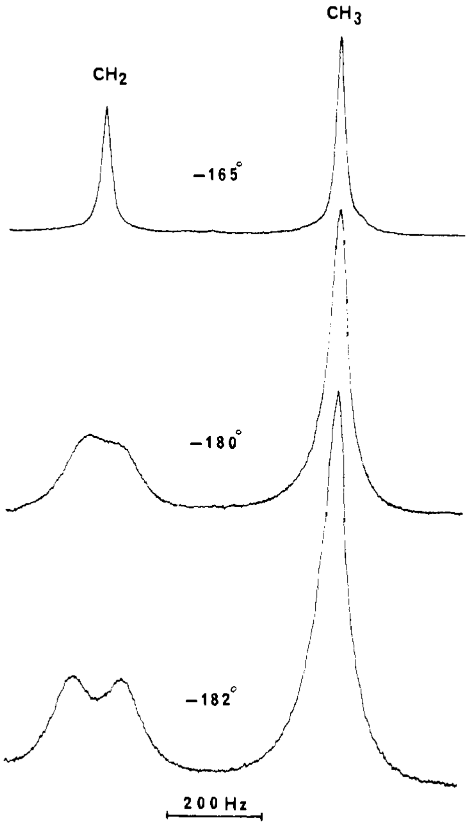
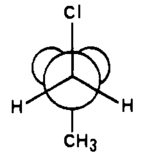
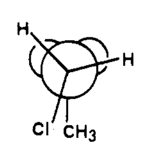


Figure 1. The 251-MHz ${}^1H$ NMR spectra of chloromethyl methyl ether in $CHFCl_2/CHF_2Cl$ (1:3).

I-G I-G′



I-A



I-E

There are two possible mechanisms for the interconversion of the two chiral gauche forms, I-G and I-G′. In one mechanism, the process takes place via the plane symmetrical eclipsed form (I-E), and in the other via the plane-symmetrical anti form (I-A). The eclipsed geometry is probably a transition state, but the anti form might be either an energy minimum or maximum. Steric repulsions in the form having the methyl group and chlorine atom eclipsed should be substantial; furthermore the orientation of the lone pairs with respect to the carbon-chlorine bond is unfavorable. Thus, this mechanism is probably unimportant because it involves a barrier which is considerably greater than 4 kcal/mol.[7] The second mechanism does not involve large nonbonded repulsions; at one stage there is eclipsing of a hydrogen and a methyl group, but the lone pair is eclipsed with the carbon-chlorine bond and this should provide some stability due to the "cis effect".[3] In the anti form, steric repulsion effects should be absent, but electronic and dipole effects are unfavorable. The observed barrier of 4.2 kcal/mol is appreciably higher than that expected for the second mechanism, if only steric repulsions are considered. A rough estimate of the steric barrier is 2 kcal/mol,[8] and thus the anomeric effect on the barrier to rotation of the O-CH_2 bond is ~2 kcal/mol.

We have also examined the ${}^1H$ NMR spectra of bis(chloromethyl) ether and fluoromethyl methyl ether,[9] but we did not observe any splitting of the methylene resonances down to −180 °C. Dimethoxymethane itself cannot be studied by dynamic NMR because the C_2 symmetry of the gauche conformation makes the methylene protons indistinguishable.[10]