Conformational Preferences and Interconversion Barriers in Cyclohexene and Derivatives

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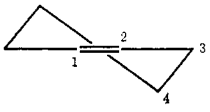
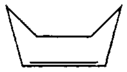
Abstract: The conformational preferences (E_4 values) for 4-fluoro-, 4-chloro-, 4-bromo-, and 4-iodocyclohexenes have been determined by low-temperature nmr spectroscopy and are 0.014, 0.200, 0.077, and -0.016 kcal/mol. Although smaller, these values show the same trend in magnitude as A values, except for iodo which actually shows a preference for the axial position. Assuming the boat as the transition state, the chair–chair interconversion barriers ($\Delta G^{\ddagger}$) in kilocalories/mole are 5.37 for cyclohexene-2,3,3,4,4,5,6,6-d_8, 5.3 for 4-fluorocyclohexene, 6.3 for 4-chlorocyclohexene, 6.3 for 4-bromocyclohexene, 6.5 for 4-iodocyclohexene, and 7.4 for *cis*-4,5-dicarbomethoxycyclohexene. The chemical-shift difference between the axial and equatorial C-4 protons in cyclohexene-2,3,3,4,4,5,6,6-d_8 is 19.0 Hz (60 MHz). For cyclohexene-d_8, assuming the only contribution to $\Delta S^{\ddagger}$ is the reaction pathway multiplicity, $\Delta S^{\ddagger} \sim R \ln 2$ and $\Delta H^{\ddagger}$ is greater than $\Delta G^{\ddagger}$ by $T\Delta S^{\ddagger}$, *i.e.*, $\Delta H^{\ddagger} \sim 5.5$ kcal/mol.

Variable-temperature nuclear magnetic resonance (nmr) spectroscopy has been valuable in the dynamic conformational analysis of carbocyclic and heterocyclic compounds.[1–8] Important problems in conformational analysis are the determination of the barriers to conformational equilibrium and the conformational preferences in cyclohexene derivatives. At present, there is a paucity of data concerning the conformational and kinetic parameters in this ring system. This paper concerns the interconversion barriers ($\Delta G^{\ddagger}$) and conformational preferences in cyclohexene-2,3,3,4,5,5,6,6-d_8 (III), the 4-halocyclohexenes (IV–V), and *cis*-4,5-dicarbomethoxycyclohexene (VI).

A six-membered carbocyclic compound with an endocyclic double bond, *i.e.*, cyclohexene, is predicted to exist almost exclusively in a half-chair conformation (I). Angyal[9] has calculated the distances between the ends of the carbon chains in *cis*-2-butene (2.88 Å) and the *trans* conformer of butane (2.94 Å). Thus, it would seem the *cis*-2-butene unit would fit the *trans* conformer of butane with substantially less angle strain than the eclipsed butane conformer resulting in the half-chair form. Indeed, angle strain and nonbonded interactions can account for calculations indicating the boat form of cyclohexene (II) is higher in energy than the half-chair.[10]



I



II

Direct experimental evidence has corroborated these predictions. Electron diffraction and X-ray data for 3,4,5,6-tetrachlorocyclohexene indicate the half-chair is the preferred conformation.[11a] X-ray data obtained for pentachlorocyclohexene[11b] and naphthalene tetrachloride[12] also confirm the half-chair to be the more stable isomer.

Barton and coworkers[13] have predicted the over-all geometry of the half-chair conformer of cyclohexene. The double bond requires C-1, C-2, C-3, and C-6 to be coplanar with all the carbon–hydrogen bonds staggered with respect to one another. The protons on C-4 and C-5 were assigned true axial and equatorial orientations, while those on C-3 and C-6 were assigned quasi-axial and quasi-equatorial orientations.

Calculation of the molecular geometry of the cyclohexene half-chair conformer by vector analysis[14] indicates the protons on C-4 and C-5 are not exactly truly axial and equatorial. The introduction of a double bond into the cyclohexane ring causes an orientation change in both the allylic and homoallylic carbon–hydrogen bonds. The axial bonds in cyclohexane are very nearly parallel to the vertical axis; however, the corresponding allylic bonds in cyclohexene are displaced by 23° from the vertical. Likewise, homoallylic axial bonds are shifted by 11° from the vertical and toward the center of the cyclohexene ring. Equatorial bonds change accordingly. A consequence of these bond orientations in cyclohexene is that *cis* allylic and homoallylic substituents experience increased eclipsing. The effect of this eclipsing and bond angle distortion may be manifested in the greater heat of hydrogenation for cyclohexene ($\Delta H = -28.6$ kcal/mol) than *trans*-2-butene ($\Delta H = 27.6$ kcal/mol).[15]

The introduction of a double bond into the cyclohexane ring also manifests itself in a dipole moment of 0.75 D for cyclohexene.[16]

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The half-chair form of cyclohexene is a dissymmetric molecule, but rapid interconversion between the two half-chair forms at normal temperatures results in racemization. In this regard, unsuccessful attempts have been made to resolve cyclohexene-4,5-dicarboxylic acid.[17] The rates of interconversion at room temperature for cyclohexene[18] and 4-bromocyclohexene[19] have been found to be very rapid indeed.

Concerning the conformational analysis of cyclohexene derivatives by a direct experimental method, Garbisch[20a,b] has examined the width at half-height ($W_{1/2}$) of the C-6 proton nmr signals of a number of 6-substituted 1-phenylcyclohexenes finding more bulky substituents, *e.g.*, 6-*t*-butyl, prefer the quasi-axial position. By comparing the rates of epoxidation of a series of alkyl-substituted cyclohexenes, Rickborn and Lwo[20c] have estimated that the 4-methyl group prefers the equatorial position by approximately 1 kcal/mol. Sakashita[21] found by variable-temperature infrared spectroscopy that the quasi-axial isomer is favored in 3-chlorocyclohexene ($\Delta H = 0.64$ kcal/mol) and 3-bromocyclohexene ($\Delta H = 0.70$ kcal/mol). A similar study for 4-bromocyclohexene[22] revealed the conformational enthalpy favoring the axial isomer by only 50 cal/mol. Evidence for mutually interconvertible isomers of 4,5-dichlorocyclohexene[23] has also been obtained.

Results

Examination of the temperature dependence of the proton (60 MHz) and fluorine (56.4 MHz) nmr spectra of a series of cyclohexene derivatives has given the barriers ($\Delta G^{\neq}$) to interconversion and conformational preferences.

The proton nmr spectrum at −123° of cyclohexene-2,3,3,4,5,6,6-d_8 (III) in a solution consisting of 0.2 ml of III, 0.1 ml of trideuteriovinyl chloride (CD_2CDCl), and 0.2 ml of chlorotrifluoroethylene ($ClFCCF_2$) is clearly consistent with rapid ring inversion on the nmr time scale. With strong irradiation at the deuteron resonance frequency (9.2 MHz), the nmr spectrum of III consists of two sharp peaks of equal intensities for the olefinic proton (δ 5.57) and the C-4 proton (δ 1.55; Figure 1). As the temperature was lowered, the shape of olefinic proton resonance showed essentially no temperature dependence except slight broadening probably due to an increased medium viscosity. However, the shape of the C-4 proton resonance showed a marked temperature dependence from −160 to −171° with typical broadening and separation into two peaks of equal intensities (Figure 1). At −171°, the chemical shift between the axial and equatorial C-4 protons had reached a constant value of 19.0 ± 0.3 Hz. This value is in marked contrast to an estimated value in the literature of 24 ± 2 Hz.[18] From an examination of the temperature dependence of the separation between the two-peak maxima, utilizing the procedure given below, the total rate constant (k_{tot}) at −166.7 ± 0.4° was calculated to be 44 sec^{-1}. The nmr spectrum of cyclohexene also showed definite changes at −165°, but extensive spin–spin interactions precluded a straightforward analysis of the spectral behavior.

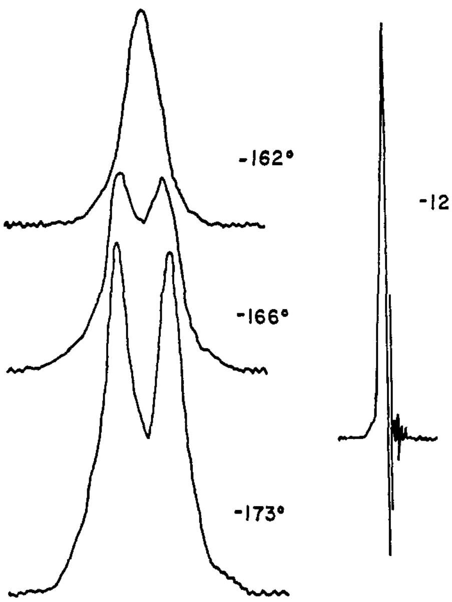
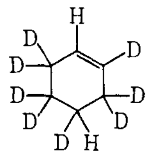
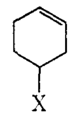
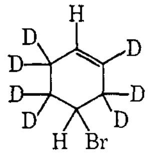
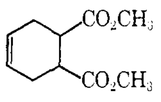


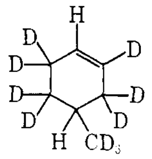
Figure 1. The nmr spectrum (60 MHz) of the C-4 proton of cyclohexene-2,3,3,4,5,5,6,6-d_8 (III) at various temperatures; $\nu_{\text{equatorial}} - \nu_{\text{axial}} = 19.0 \pm 0.3$ Hz.


III


IVa, X = F
b, X = Cl
c, X = Br
d, X = I


V


(*cis*)
VI


VII

The extensive spin–spin splitting of many of the pertinent resonances in this study and the high temperature coefficient of viscosity at the low temperatures necessary to cause spectral changes precluded a rigorous prediction of line shapes in the region of partial peak collapse. However, rate constants for the conformational equilibrations were obtained from a comparison of experimentally observed separations between peak maxima in the region of partial collapse and peak separations calculated using an appropriate computer program. The program assumes a Gaussian shape for the resonances of interest. Deviations from Gaussian behavior should not be serious because the peaks of interest should exhibit first-order spin–spin splitting patterns to a good approximation. Where necessary, the program ac-

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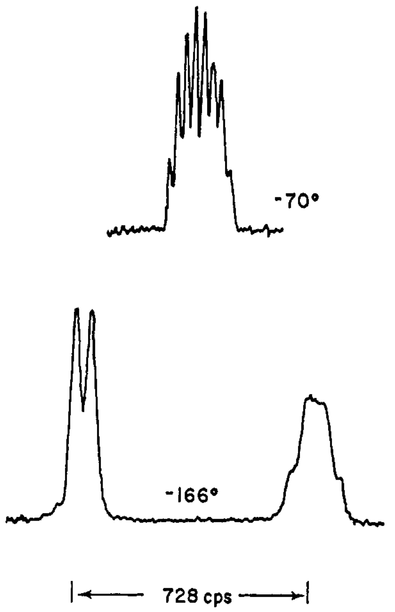

Figure 2. The ^{19}F nmr spectrum (56.4 MHz) of 4-fluorocyclohexene (IVa) at various temperatures.

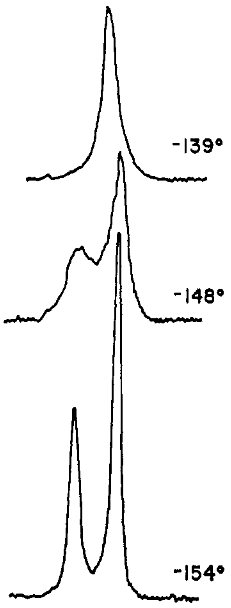

Figure 3. The nmr spectrum (60 MHz) of the H-C-Br proton of 4-bromocyclohexene-2,3,3,5,5,6,6-d_7 (V) in the region of partial collapse; $\nu_e - \nu_a = 27$ Hz.

counts for differences in conformer populations and for the rather large widths at half-height of many of the axial and equatorial resonances.[24] In every instance, no fine structure was evident in pertinent resonances but relative measures of coupling could be deduced from widths at half-height.

The 4-halocyclohexenes (IVa-d) also displayed temperature-dependent nmr spectra. In all cases, the nmr spectra were obtained from solutions of the 4-halocyclohexenes in trideuteriovinyl chloride (CD_2CDCl).

The H-C-F proton resonance of 4-fluorocyclohexene (23% by volume in CD_2CDCl) consists of two multiplets ($J_{HF} = 47$ Hz) centered at δ 4.72. In the temperature range from -160 to $-173°$, the H-C-F multiplets broaden, and at $-173°$, only a suggestion of two separate peaks is observed.

Consequently, the ^{19}F nmr spectrum (56.4 MHz) of the H-C-F resonance of 4-fluorocyclohexene was examined at various temperatures. At $-70°$, the H-C-F ^{19}F resonance is a somewhat symmetrical eight-line multiplet (Figure 2) consistent with rapid interconversion on the nmr time scale. As the temperature was lowered, the resonance broadened, separated into two peaks, and reached a maximum constant separation between a broad upfield peak and a more narrow downfield doublet ($J_{HF} = 47$ Hz) of 728 Hz (Figure 2). The total constant at $-151.8 \pm 0.5°$ was calculated to be 1.5×10^3 sec^{-1}. The ratio of the peak areas (low-field peak area/high-field peak area) at $-166°$ was found to be 1.07 ± 0.02.

Spectral transitions were observed in the temperature range from -145 to $-155°$ for 4-chlorocyclohexene (IVb), 4-bromocyclohexene (IVc), and 4-iodocyclohexene (IVd). Except for definite differences in peak area ratios, all three compounds (30% in CD_2CDCl) gave similar methine proton spectra under conditions of slow exchange on the nmr time scale. The H-C-X resonances of all three compounds consisted of a broad, upfield peak and a more narrow, downfield peak separated by 27 Hz in all three cases. The total rate constants at the various temperatures and the ratio of the upfield-peak area to the downfield peak area are compiled in Tables I-II. The chemical shifts of the various axial (δ_a) and equatorial (δ_e) proton resonances are given in Table III.

Table I. The Total Rate Constants (k_{tot}) for Half-Chair to Half-Chair Isomerism in 4-Chlorocyclohexene, 4-Bromocyclohexene, and 4-Iodocyclohexene

Halogen	k_{tot}, sec^{-1}	$T_{\ddagger}$ °C[a]
Cl	17	-151.8 ± 0.6
Br	34	-149.3 ± 0.5
I	35	-146.3 ± 0.5

[a] $T_{\ddagger}$ = temperature at which k was measured.

Table II. The Peak Area Ratios (Upfield Peak Area/Downfield Peak Area) of the H-C-X Resonances of 4-Chlorocyclocyclohexene (IVb), 4-Bromocyclohexene (IVc), and 4-Iodocyclohexene (IVd)

Halogen	H-C-X peak area ratio	T_A, °C[a]
Cl	2.33 ± 0.07	-156
Br	1.40 ± 0.06	-158
I	0.94 ± 0.03	-158

[a] T_A = temperature at which peak area ratio was measured.

Table III. The Chemical Shifts of the Axial (δ_a) and Equatorial (δ_e) Proton Resonances of the 4-Halocyclohexenes

Halogen	δ_a	δ_e
Cl	4.14	4.59
Br	4.25	4.70
I	4.30	4.75

Extensive deuteration coupled with irradiation at the deuteron resonance frequency resulted in a greatly simplified nmr spectrum for 4-bromocyclohexene-2,3,3,5,-

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(24) F. R. Jensen and B. H. Beck, unpublished results. The details of this program will be published in a subsequent paper.

5,6,6-d_7 (V). The behavior of the H–C–Br resonance in the region of partial collapse of the two resonances is illustrated in Figure 3. The nmr spectrum of V (30% by volume in CD_2CDCl) at −40° consists of two narrow resonances of equal intensities for the H–C–Br proton (δ 4.32) and the olefinic proton (δ 5.65). Except for a slight broadening at low temperatures, the olefinic proton resonances were essentially independent of temperature. However, in the temperature range from −139 to −154°, the H–C–Br resonance broadened and separated into two peaks at δ 4.22 and 4.67 (Figure 3). The total rate constant was calculated to be 45 sec^{-1} at −148.0 ± 0.4°. The peak area ratio (upfield peak/downfield peak) was found to be 1.50 ± 0.03 at −158°.

The nmr spectrum of *cis*-4,5-dicarbomethoxycyclohexene (VI) in CD_2CDCl shows changes at substantially higher temperatures than for cyclohexene or the 4-halocyclohexenes. No striking spectral changes were observed for the allylic proton resonances (δ 2.45) or for the olefinic proton (δ 5.50) resonances as the temperature was lowered. However, over the temperature range from −115 to −136°, the C-4,5 proton resonances (δ 3.03) broadened, and separated into two resonances which merged with the allylic (δ 2.45) and methoxy proton (δ 3.59) resonances, respectively. No reliable rate data could be obtained from such behavior. However, at about −135°, the methoxy proton resonances (δ 3.59) split into two peaks separated by 4.5 Hz. The total rate constant calculated at 60% separation of the two methoxy proton resonances is 12 sec^{-1} at −135.5 ± 0.5°.

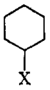
The nmr spectrum of 4-trideuteriomethylcyclohexene-2,3,3,5,5,6,6-d_7 (VII) was observed to be essentially independent of temperature to −178° in a solution of 0.30 ml of VII, 0.20 ml of trideuteriovinyl chloride, and 0.20 ml of chlorotrifluoroethylene. With strong irradiation at the deuteron resonance frequency (9.2 MHz), the sharp resonances of the olefinic proton (δ 5.60) and the C-4 proton (δ 1.61) showed no changes at low temperatures except broadening due probably to viscosity. If the C-4 proton resonance had separated into two peaks, it would have been possible to detect a peak as small as 5% of its partner. No such detection was obtained.

Similarly, the H–C–Br resonance (δ 4.72) and olefinic proton resonances (δ 5.75) of 3-bromocyclohexene (30% by volume in CD_2CDCl) were essentially temperature independent to −168° with slight broadening at the lower temperatures.

Discussion

In a comparison of the nmr spectra of monosubstituted cyclohexanes and 4-substituted cyclohexenes, one of the striking differences is the substantially reduced chemical shift between axial and equatorial C-4 protons and fluorines in cyclohexenyl compounds. The pertinent data are compiled in Table IV. The changes in bond orientations in cyclohexene suggested by Corey and Sneen[14] could contribute to the decreased chemical shift between the axial and equatorial C-4 protons or fluorines. It is also likely that the double bond is playing a part. If a C-4 axial proton or fluorine is bent toward the center of the ring, as suggested by Corey and Sneen, it would be situated near the deshielding region of the double bond.[25] An equatorial C-4 proton or fluorine would be further removed from the influence of the π system. Thus, it might be concluded that the effect of the double bond is to cause a downfield shift of the axial resonance and to have little effect on the equatorial resonance. The net result is a decreased chemical shift between axial and equatorial C-4 resonances.

Table IV. The Chemical Shift (Hz) between Axial and Equatorial Methine Protons and Fluoride in Monosubstituted Cyclohexanes and 4-Substituted Cyclohexenes

Compound		$\nu_{eq} - \nu_{ax}$, Hz[a]
	X = H	28
	X = F	1230[b]
	X = Cl	42
	X = Br	43
	X = I	45
	Y = H	19
	Y = F	728[b]
	Y = Cl	27
	Y = Br	27
	Y = I	27

[a] For protons, operating frequency = 60 MHz. [b] ^{19}F nmr spectra (56.4 MHz).

The assignment of peaks in the methine proton spectra of the 4-halocyclohexenes, *i.e.*, the broad upfield resonance to the axial proton or fluorine and the more narrow downfield peak to the equatorial proton or fluorine, is based on data obtained for such substituents in cyclohexyl systems.[26–28] In all cases, except for the α protons in α-halocyclohexanones,[29] the axial resonance appears upfield from the equatorial resonance.[25] A more unequivocal assignment is based on coupling constants. It has been well established that vicinal protons which have an axial–axial relationship to one another have coupling constants of 12–15 Hz.[30,31] However, vicinal protons which have an axial–equatorial relationship are coupled by only 2–3 Hz. Although the orientation of the C-4 protons in 4-substituted cyclohexenes is not truly axial and equatorial, the C-4 "axial" nucleus should be coupled more strongly to its neighbors than the "equatorial." Although no fine structure is observed in the upfield C-4 resonances of the 4-halocyclohexenes, the substantially greater width at half-height strongly indicates greater coupling. In addition, the marked similarity between the ^{19}F nmr spectra of 4-fluorocyclohexene and cyclohexyl fluoride, under conditions of slow exchange, corroborates these peak assignments.[32] Other workers[33] have obtained results which suggest hydrogen–fluorine coupling constants also obey the Karplus relationship.[30] It is interesting to note that the geminal hydrogen–fluorine coupling constants (47 Hz) are identical in 4-fluorocyclohexene and cyclohexyl fluoride.[32]

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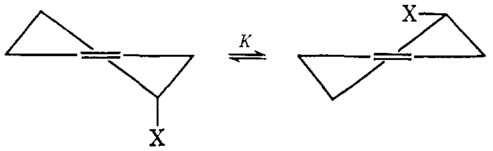
The simplification of the nmr spectra of highly deuterated compounds with irradiation at the deuteron resonance frequency is remarkable. In addition, experience in this laboratory and the work of other investigators[34] have shown that hydrogen–deuterium coupling constants are significantly smaller than hydrogen–hydrogen coupling constants. Thus, even in the absence of double irradiation, the spin–spin splitting in deuterated compounds is greatly simplified.

The independence of temperature of the methine proton resonances of 3-bromocyclohexene and 4-trideuteriomethylcyclohexene-2,3,3,5,5,6,6-d_7 (VII) can be attributed to a number of possible reasons. These include a reduced barrier to interconversion, an increased barrier (>15 kcal/mol), a large conformational preference, and a small or zero chemical shift between the protons in question. In the case of 3-bromocyclohexene, the most likely reason for the observation of no changes in the H–C–Br resonance is a small or zero chemical shift between the pseudo-axial and pseudo-equatorial protons. There is no reason to believe the barrier is lower than for cyclohexene or higher than for 4-substituted cyclohexenes. Also, Sakashita[21] has shown by infrared spectroscopy that the "axial" isomer of 3-bromocyclohexene (neat) is the favored conformer (ΔH = 0.70 kcal/mol). Such a conformational preference, although probably slightly solvent dependent, could easily be detected by nmr spectroscopy. The most likely explanation would therefore seem to be a small or zero chemical shift between the two allylic H–C–Br resonances. Indeed, it will be shown later that allylic proton resonances in most unsaturated carbocycles do not show a significant temperature dependence. From a consideration of models, it is also evident that the H–C–Br allylic proton does not exchange between significantly different chemical environments as a consequence of ring inversion in 3-bromocyclohexene.

The case with the 4-trideuteriomethylcyclohexene-2,3,3,5,5,6,6-d_7 (VII) is not so straightforward. This result is in accord with E_4 being large[20] and that the compound exists at this temperature in essentially one conformation. It is also possible that the eclipsing interactions suggested by Corey and Sneen between the methyl group and adjacent allylic protons raise the ground-state energy to such a degree that the barrier is significantly lowered. Lastly, one cannot rule out the occurrence of only a small chemical shift between the axial and equatorial C-4 protons and as a result no significant changes result between the time average and the separated spectra.

Reducing the rate of interconversion to a value slow on the nmr time scale and the existence of a chemical shift difference between the axial and equatorial C-4 protons make possible the measurement of conformer populations in the 4-halocyclohexenes. The equilibrium involves interconversion between two half-chair conformers with the halogen exchanging between equatorial and axial positions (eq 1). Analogously to the A value,[35] we now define the E_4 value according to eq 1 and 2. The E_4 value is a conformation parameter referring to the 4 position in cyclohexene. If the equatorial isomer predominates in the equilibrium (eq 1), the E_4 value is positive and is expressed in kilocalories/mole.



(1)

$$E_4 = -\Delta F = \frac{RT \ln K}{1000} \tag{2}$$

The pertinent data are summarized in Table V. It is obvious from the data that a substantial reduction in conformational preference for the equatorial position occurs in the 4-halocyclohexenes relative to the halocyclohexanes. Compared to an axial substituent on the cyclohexane ring, it is evident from models that a C-4 axial substituent on the cyclohexene ring should experience a marked decrease in steric interactions. In cyclohexane derivatives, two 1,3-interactions severely hinder an axial substituent. In the cyclohexene ring, the presence of the double bond eliminates one 1,3 interaction with a C-4 axial substituent and minimizes the other (allylic C–H bond) *via* a 23° tilt from the vertical. Also, it would appear that the increased eclipsing of *cis* allylic and homoallylic substituents on adjacent carbons in cyclohexene derivatives destabilizes the axial and equatorial isomers to about the same degree.

Table V. Conformational Parameters for the 4-Halocyclohexenes and Halocyclohexanes

Halogen	E_4 value, kcal/mol[a]	A value, kcal/mol[b]
F	0.014 ± 0.005	0.276
Cl	0.200 ± 0.010	0.528
Br	0.077 ± 0.015 (IVc) 0.093 ± 0.005 (V)	0.476
I	−0.016 ± 0.007	0.468

[a] The E_4 values were measured at −157 ± 1° for Cl, Br, and I, and at −166° for F. [b] The A values were measured at −81 ± 1° for Cl, Br, and I, and at −86° for F: F. R. Jensen, C. H. Bushweller, and B. H. Beck, *J. Am. Chem. Soc.*, **91**, 344 (1969).

Another effect which may be operative in the reduced conformational requirements observed for halogens in 4-halocyclohexenes is a mutual polarization of the halogen atom and double bond, *i.e.*, a London attractive force. Since the axial C-4 halogen is closer to the double bond due to its axial orientation and to being bent toward the center of the cyclohexene ring, such an attractive force would be expected to be greater than for the more remote equatorial C-4 halogen. The effect would seem to be manifested in the E_4 value for iodine (−0.016 kcal/mol) in which the *axial isomer* is slightly preferred. Postulation of such an attractive force is not entirely without precedent. Other workers have rationalized the thermodynamic preference for the *cis* isomers of 1-bromopropene[36] and 1,2-dichloroethylene[37] *via* London attractive forces. Dipole moment studies have also indicated that the preferred conformation of *o,o'*-dichlorobiphenyl[38] is that

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(34) F. A. Bovey, F. P. Hood, III, E. W. Anderson, and R. L. Kornegay, *J. Chem. Phys.*, **41**, 2041 (1964).

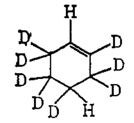
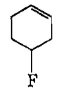
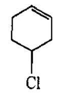
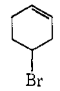
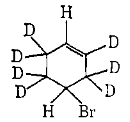
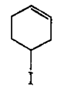
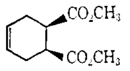
(35) S. Winstein and N. J. Holness, *J. Am. Chem. Soc.*, **77**, 5562 (1955).

(36) P. S. Skell and R. G. Allen, *ibid.*, **80**, 5997 (1958).

(37) K. S. Pitzer and J. L. Hollenberg, *ibid.*, **76**, 1493 (1954).

(38) C. Hampson and A. Weissberger, *ibid.*, **58**, 2111 (1936).

Table VI. Thermodynamic Data for the Conformational Interconversion of Cyclohexene and Cyclohexene Derivatives

Compound	$T^{\ddagger}$, °C	k_{tot}, sec^{-1}	k_{ae}, sec^{-1}	$\Delta G^{\ddagger}$, kcal/mol[a]
	-166.7 ± 0.4	44	22	5.37 ± 0.1
	-151.8 ± 0.5	1.5×10^3	7.6×10^2	5.3 ± 0.1
	-151.8 ± 0.6	17	12	6.3 ± 0.1
	-149.3 ± 0.5	34	20	6.3 ± 0.1
	-148.0 ± 0.4	45	27	6.3 ± 0.1
	-146.3 ± 0.5	35	17	6.5 ± 0.1
 (*cis*)	-135.5 ± 0.5	12	6	7.4 ± 0.1

[a] Barrier for the conversion of axial isomer to equatorial isomer, with the boat form as the transition state. The barrier was calculated using k_{ae} in the Eyring equation.

with the two chlorines close together, but not the coplanar structure.

The steric bulk *sequence* for chlorine, bromine, and fluorine in the 4-halocyclohexenes is the same as in the halocyclohexanes, *i.e.*, Cl > Br > F. However, iodine does not fit the same sequence in the two ring systems. Thus, it is apparent that the bond length and polarizability hypothesis[26] also applies to the 4-halocyclohexenes, with the possible intervention of London attractive forces causing the "anomalous" result for iodine.

The E_4 values for bromine in 4-bromocyclohexene ($E_4 = 0.077 \pm 0.015$ kcal/mol) and in 4-bromocyclohexene-2,3,3,5,5,6,6-d_7 ($E_4 = 0.093 \pm 0.005$ kcal/mol) are in excellent agreement. The small difference, 16 cal/mol, could be due to peak overlap complications and/or substitution by deuterium. The E_4 value for bromine is also in qualitative agreement with the results of Sakashita[22] by infrared spectroscopy. Sakashita's results for 4-bromocyclohexene (neat and vapor) for eq 1 (X = Br) give $\Delta H = +0.050$ kcal/mol.

It is undoubtedly true that the E_4 value of the 4-halocyclohexenes is solvent dependent. Cyclohexene has a dipole moment of 0.75 D, while the carbon–halogen bond moments are about 1.8 D. Consequently, the net dipole moment of an axial 4-halocyclohexene would be expected to be larger (vectors additive) than an equatorial 4-halocyclohexene (vectors opposed). It might be expected that less polar solvents would favor the equatorial C-4 halogen conformer.

It is unfortunate that it is not possible to observe the two conformers of the 3-halocyclohexenes. Few data have been reported on such systems. Garbisch[20] has examined the width at half-height of the C-6 proton in a number of 6-substituted 1-phenylcyclohexenes, finding more bulky substituents prefer the pseudo-axial position. The observed conformation preferences could be due to the bulky phenyl group on C-1. However, Sakashita[21] has reported that the "axial" isomer is preferred in 3-chlorocyclohexene ($\Delta H = 0.64$ kcal/mol) and 3-bromocyclohexene ($\Delta H = 0.70$ kcal/mol).

In addition to the vastly reduced conformation requirements of 4 substituents on the cyclohexene ring, the substantially reduced barriers to intraconversion in cyclohexene derivatives is remarkable. The total rate constants (k_{tot}) for the various compounds and the temperature at which k_{tot} were calculated and are listed in Table VI along with the rate constants for the conversion of the axial isomer to the equatorial isomer (k_{ae}) and the derived barriers ($\Delta G^{\ddagger}$). In order to calculate the rate constant in one direction, the conformation populations were assumed to be those tabulated in Table V.

From a consideration of models and theoretical calculations,[10] the most probable path for half-chair interconversion in cyclohexene is *via* a "true" boat transition state (VIII). The reaction pathway is illustrated in Figure 4. Indeed, Bucourt and Hainaut calculate the true boat form of cyclohexene to be 6.9 kcal/mol higher in energy than the half-chair and to be a *potential maximum* on the reaction coordinate for half-chair interconversion. Such a result is not unexpected when one realizes that the "prow–prow" interaction as well

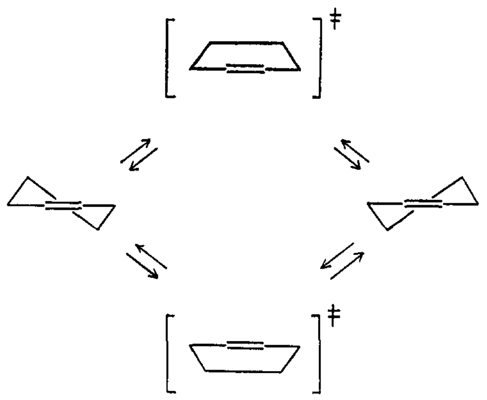
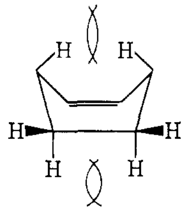


Figure 4. The reaction pathway for the conformational interconversion of cyclohexene assuming a boat transition state.

as the two carbon–hydrogen eclipsing interactions on C-4 and C-5 are maximized in the boat form (VIII). Such a pathway is at variance with earlier proposals[18,19] that the semiplanar form (IX) is the potential maximum for half-chair interconversion. Bucourt and Hainaut[10b] calculate the semiplanar form (IX) to be only 1.2 kcal/mol higher in energy than the half-chair.

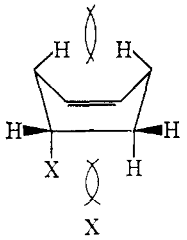
Another conceivable transition state has all six carbon atoms coplanar. However, it appears reasonable that the extent of bond-angle strain and numerous eclipsing interactions in such a structure would render it much higher in energy than the boat form.

Further evidence regarding the transition state is obtained by considering the various barriers compiled in Table VI. Regardless of which structure occurs at the potential maximum along the reaction coordinate (excluding a completely planar form as a possibility), cyclohexene must at some time attain first the configuration of structure IX, then that of VIII (one of *two* equivalent boat forms), and then pass through the mirror image of configuration IX in order to effect half-chair inversion. The data in Table VI indicate that monosubstitution (except for fluoro) causes about a 1-kcal/mol increase in the barrier, and that substitution of two *cis*-methoxycarbonyl groups in the 4,5 positions causes an increase in the barrier of about 2 kcal/mol as compared to cyclohexene. Regardless of whether the transition state is structure VIII or IX, at some stage along the reaction coordinate substituents on C-4 and C-5 which are *cis* to one another must pass, *i.e.*, they must become eclipsed. In the boat transition state, the carbon–halogen bond of a 4-halocyclohexene is eclipsed with a *cis* carbon–hydrogen bond of C-5 (X, one of two boat forms). Such an interaction is substantially increased in the boat conformer of *cis*-4,5-dimethoxycarbonylcyclohexene (XI, one of two boat forms). In the semiplanar form (IX), all C-4 and C-5 bonds are not totally eclipsed, with the major contribution to an increased energy probably due to angle strain. In the boat form (VIII, X, XI), all C-4 and C-5 bonds are totally eclipsed and all other nonbonded interactions are maximum. It would therefore seem reasonable that if the semiplanar form were the transition state, the various barriers would be relatively insensitive to substituent identity, and if the boat form were the potential maximum, the barrier would show a dependence on substituent size, polarity, etc.

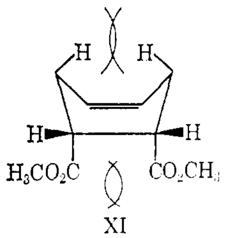


VIII

IX



X



XI

Since the barriers are highly sensitive to the magnitude of nonbonded compressions due to groups on C-4 and C-5, the boat form would seem to be the most likely transition state for half-chair inversion in cyclohexene and derivatives.

The requirement that *cis* 4,5 substituents on the cyclohexene ring *must pass* during the half-chair inversion process may provide a means of estimating pairwise contributions to rotational barriers in substituted ethanes. The increase in the barrier (2.1 kcal/mol) from that in cyclohexene to that in *cis*-4,5-dicarbomethoxycyclohexene (VI) may be considered a rough estimate of the pairwise contribution to the rotational barrier in hexacarbomethoxyethane. It will be interesting to compare future data of this type with that from substituted ethanes.

It should be noted that, within experimental error, the effect of extensive deuteration on the barrier is negligible. Thus, 4-bromocyclohexene and 4-bromocyclohexene-2,3,3,5,5,6,6-d_7 have identical barriers ($\Delta G_{ae}^{\ddagger} = 6.3$ kcal/mol). These results are in accord with previous reports for cyclohexane and cyclohexane-d_{11},[1] and tend to indicate that provided minimal overlap of pertinent resonances occurs at low temperature, little or no increase in the accuracy of barrier measurements is achieved by extensive deuteration.

The substantially lower barriers to conformational isomerism in cyclohexenyl compounds (Table VI) as compared to cyclohexyl compounds ($\Delta G^{\ddagger} \cong 10$ kcal/mol) can be attributed to a number of factors. Bond angle strain due to the restricting influence of the double bond and increased eclipsing of *cis*-allylic and homoallylic substituents would certainly seem to decrease the *energy difference* between the half-chair and boat forms of cyclohexene as compared to comparable forms of cyclohexane. Also, any spreading of bond angles in going to the transition state would seem to be better accommodated by the already large C_1–C_2–C_3 bond angle (~120°). Some of the eclipsing interactions of methylene groups in the transition state for cyclohexane inversion are eliminated in cyclohexene derivatives by the presence of the double bond. The net result is a lowering of the boat/half-chair energy difference, *i.e.*, the barrier to half-chair interconversion in cyclohexene.

The entropy of activation ($\Delta S^{\ddagger}$) for half-chair interconversion in cyclohexene may be estimated from the degeneracy of the reaction pathway. A half-chair conformer can proceed to either of two boat transition states (Figure 4). If $\Delta S^{\ddagger}$ for such a process is assumed to be $R \ln n$ (n = number of reaction paths available to the half-chair), the $\Delta S^{\ddagger}$ for half-chair inversion in cyclohexene is $R \ln 2 = 1.4$ eu. Thus, the enthalpy of activation ($\Delta H^{\ddagger}$) is estimated to be 5.5 kcal/mol.

Experimental Section

The nmr spectra were recorded on a Varian Associates HR-60 spectrometer equipped with a special variable-temperature probe adapted for double-frequency operation. Spectral calibrations were performed by the audiomodulation technique using a Hewlett-Packard 200 CD or 200 AB audio oscillator and a Hewlett-Packard 5245L electronic counter. Irradiation at the deuteron resonance frequency (9.2 MHz) was achieved using a NMR Specialties SD-60 heteronuclear spin decoupler.

Temperature measurements were performed using a carefully calibrated copper–constantan thermocouple.

***cis*-Cyclohexene-4,5-dicarboxylic Acid Anhydride.** A pressure reactor was charged with approximately 100 ml of 1,3-butadiene, 60 g (0.61 mol) of maleic anhydride, and 200 ml of benzene. The mixture was allowed to stand at room temperature for 12 hr after which it was heated to 100° for 5 hr. The benzene was removed under vacuum and the residue was recrystallized from a benzene–ligroin mixture to give 80.9 g (87%) of *cis*-cyclohexene-4,5-dicarboxylic acid anhydride: mp 101–103° [lit.[39] mp 103–104° (*cis*), 128° (*trans*)]; nmr peaks (100 Mc, $CDCl_3$) at δ 2.43 (4 H complex quartet, J_{AB} allylic protons), 3.37 (2 H multiplet, C-4 and C-5 protons), and 6.01 (2 H multiplet, olefinic protons).

Cyclohexene-4,5-dicarboxylic Acid. A 40.0-g sample of *cis*-cyclohexene-4,5-dicarboxylic acid anhydride was added to 350 ml of 20% aqueous sodium hydroxide with the liberation of heat. The reaction mixture was allowed to reflux for 2 hr and cooled, and hydrochloric acid was added to pH 2. The resulting white precipitate was filtered, dried in air, and recrystallized from benzene to give 27.2 g (62%) of cyclohexene-4,5-dicarboxylic acid: mp 165–166° [lit.[39] 165° (*trans*), 174° (166°) *cis*]; nmr peaks (60 Mc, D_2O, external TMS) at δ 2.45 (4 H multiplet, allylic protons), 3.20 (2 H multiplet, C-4 and C-5 protons), and 5.80 (2 H multiplet, vinyl protons).

Anal. Calcd for $C_8H_{10}O_4$: C, 56.45; H, 5.92. Found: C, 56.32; H, 5.84.

4-Fluorocyclohexene. In 100 ml of anhydrous hydrofluoric acid in a polyethylene reactor at −78° was dissolved 13.0 g (0.07 mol) of cyclohexene-4,5-dicarboxylic acid. The reaction mixture was stirred for 2 hr and allowed to stand overnight at −78°. The hydrofluoric acid was removed by passing nitrogen over the reaction mixture and bubbling the effluent gas through 20% aqueous sodium hydroxide. The light brown residue was dissolved in ether, dried (Na_2SO_4), and evaporated to dryness. A nmr spectrum gave no evidence of the olefinic proton resonances of cyclohexene-4,5-dicarboxylic acid.

The adduct from the above procedure was dissolved in 70 ml of anhydrous benzene and 12.5 (0.16 mol) of pyridine and the solution was purged with dry nitrogen for 0.5 hr. A 34.8-g (0.08 mol) sample of lead tetraacetate[40] was added with stirring and the reaction mixture was heated to 60° whereupon it turned orange and a gas (CO_2) was evolved. The reaction mixture was allowed to reflux for 15 min and poured into 300 ml of 10% aqueous sodium chloride, and the benzene layer was washed with two 200-ml portions of cold 1 *M* aqueous sulfuric acid, two 200-ml portions of 10% aqueous sodium chloride, one 200-ml portion of 10% aqueous sodium hydroxide, and one 200-ml portion of 10% aqueous sodium chloride. The benzene solution was dried (Na_2SO_4) and fractionated on an 18-in. spinning-band column to give 0.5 g (6%) of 4-fluorocyclohexene: bp 99–100° (756 mm); nmr peaks (60 Mc, CCl_4) at δ 1.50–2.60 (6 H complex multiplet, C-3, C-5, and C-6 protons), 5.58 (2 H multiplet, vinyl protons), and 4.76 (1 H complex doublet, J_{HF} = 48 Hz, H–C–F). The 4-fluorocyclohexene was further purified by glpc on a 15% DEGS–15% sodium bicarbonate column (10 ft × 0.5 in.) at 100° with a helium flow rate of 170 cc/min.

Anal. Calcd for C_6H_9F: C, 71.97; H, 9.06; F, 18.98. Found: C, 72.26; H, 8.96; F, 18.6 ± 0.6.

Cyclohexene-4-carboxylic Acid. Into 500-ml of anhydrous benzene under an atmosphere of dry nitrogen was added 1.5 g of hydroquinone and 26 ml of titanium tetrachloride (fumes in air), after which 1,3-butadiene was bubbled through a dispersion tube into the benzene solution for 4 hr. Then, 94.0 g (1.3 mol) of dry acrylic acid was added dropwise (much foaming) with stirring, and 1,3-butadiene was bubbled into the reaction mixture for another 2 hr. The reaction mixture was poured into 900 ml of 10% aqueous potassium hydroxide, filtered, and acidified (HCl) to pH 1. The aqueous phase was extracted with two 300-ml portions of ether, the ether extracts were dried (Na_2SO_4), and the solution was fractionated on an 18-in. Podbielniak column to give 27.5 g (16%) of cyclohexene-4-carboxylic acid: bp 96° (1 mm) [lit.[41] bp 133° (20)]; nmr peaks (60 Mc, CCl_4) at δ 1.20–2.70 (7 H multiplet), 5.65 (2 H broad singlet, vinyl protons), and 11.85 (1 H singlet, $-CO_2H$).

4-Chlorocyclohexene. Cyclohexene-4-carboxylic acid (16.4 g, 0.12 mol) and dry lithium chloride (5.1 g, 0.12 mol) were added to 300 ml of anhydrous benzene and the mixture was purged with dry nitrogen for 1 hr. A 53.0-g (0.12 mol) sample of lead tetraacetate[42] was then added and the mixture was allowed to reflux for 7 hr. The benzene solution was poured into 300 ml of water, washed with 200 ml of 10% aqueous sodium hydroxide and one 200-ml portion of water, and dried (Na_2SO_4). The dry benzene solution was fractionated on an 18-in. spinning-band column to give 4.6 g (45% based on recovered acid) of 4-chlorocyclohexene: bp 69° (74 mm); nmr peaks (60 Mc, CCl_4) at δ 1.60–2.90 (6 H multiplet), 4.13 (1 H multiplet, H–C–Cl), and 5.50 (2 H multiplet, vinyl protons). The product was shown to be at least 99.5% pure by glpc on a 15% PDEAS 60–80 Firebrick column (5 ft × 0.25 in.) at 102° with helium flow at 85 cc/min.

Anal. Calcd for C_6H_9Cl: C, 61.81; H, 7.78; Cl, 30.41. Found: C, 61.94; H, 8.14; Cl, 30.11.

4-Bromocyclohexene. To 1300 ml of anhydrous benzene was added 250 g (2.15 mol) of 1,4-cyclohexanediol (recrystallized from acetone), and while the refluxing mixture was stirred, 440 g (1.63 mol) of phosphorus tribromide was added dropwise. The escaping hydrobromic acid was trapped in 20% aqueous sodium hydroxide. After the addition of phosphorus tribromide, the reaction mixture was allowed to reflux for 3 hr and was poured into 1000 ml of an ice–water mixture. The benzene solution was washed with four 500-ml portions of 10% aqueous sodium carbonate and one 500-ml portion of water and dried (K_2CO_3). Fractionation of the benzene solution gave 93 g (27%) of crude 4-bromocyclohexene [bp 48–55° (11 mm)] contaminated with about 10% 3-bromocyclohexene. The crude 4-bromocyclohexene was added to 200 ml of methanol and 5 g of calcium carbonate; the mixture was allowed to reflux for 20 min and cooled. A 100-ml portion of methylene chloride (purified) was added; the solution was washed with six 100-ml portions of water and dried ($MgSO_4$). Fractionation of the methylene chloride solution gave 57.8 g (17%) of essentially 100% pure by nmr and glpc (15% PDEAS 60–80 Firebrick at 100°) 4-bromocyclohexene: bp 52–53° (12 mm); nmr peaks (60 Mc, neat) at δ 2.12 (4 H multiplet, C-5 and C-6 protons), 2.56 (2 H multiplet, C-3 protons), 4.30 (1 H multiplet, H–C–Br), and 5.58 (2 H multiplet, vinyl protons).

Anal. Calcd for C_6H_9Br: C, 44.75; H, 5.63; Br, 49.62. Found: C, 44.75; H, 5.89; Br, 49.54.

4-Iodocyclohexene. To a stirred mixture of 10.5 g (0.43 g-atom) of magnesium in 100 ml of anhydrous ether was added dropwise a solution of 57.8 g (0.36 mol) of 4-bromocyclohexene in 100 ml of anhydrous ether. The reaction was started by the test tube method and allowed to stir for 7 hr after the addition was complete. The ethereal solution of the Grignard reagent was filtered under dry nitrogen through glass wool and added dropwise to a stirred mixture of 131 g (0.36 mol) of dry mercuric bromide and 400 ml of anhydrous ether under an atmosphere of nitrogen. The reaction mixture was allowed to stir for 12 hr, after which 50 ml of distilled water was added dropwise with stirring, and the ether was removed under vacuum. The residue was extracted with four 250-ml portions of boiling benzene, the benzene removed under vacuum, and the residue recrystallized from 50:50 absolute ethanol–benzene to give 65.7 g (51%) of 4-(bromomercuri)cyclohexene: mp 142–143° (sealed tube). The 4-(bromomercuri)cyclohexene (65.7 g, 0.18 mol) was added slowly to 220 ml of stirred pyridine at 0° followed by

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[39] I. Heilbron and H. M. Bunbury, Ed., "Dictionary of Organic Compounds," Vol. IV, Oxford University Press, New York, N. Y., 1963, p 442.

[40] C. A. Grob, M. Ohta, and A. Weiss, *Angew. Chem.*, **70**, 343 (1958).

[41] See ref 39, p 433.

[42] J. K. Kochi, *J. Am. Chem. Soc.*, **87**, 2500 (1965).

46.2 g (0.18 mol) of iodine. The dark color of the solution dissipated to light scarlet in about 10 min and the solution was allowed to stir at 0° for 1 day. The reaction mixture was poured into 400 ml of water and 400 ml of purified methylene chloride. The layers were agitated and separated, and the aqueous layer was extracted with an additional 50 ml of methylene chloride. The methylene chloride extracts were combined, washed with three 250-ml portions of water, three 250-ml portions of cold 3 *M* aqueous sulfuric acid, and one 250-ml portion of water, and dried (Na_2SO_4). Fractionation of the methylene chloride solution on an 18-in. spinning-band column gave 5.0 g (13%) of 4-iodocyclohexene (extremely sensitive to light): bp 59.5–60.0° (4 mm); nmr peaks (60 Mc, CCl_4) at δ 2.13 (4 H multiplet, C-5 and C-6 protons), 2.72 (2 H broad multiplet, C-3 protons), 4.45 (1 H multiplet, HCI), and 5.61 (2 H multiplet, vinyl protons).

Anal. Calcd for C_6H_9I: C, 34.64; H, 4.36; I, 61.00. Found: C, 34.60; H, 4.57; I, 61.18.

1,4-Cyclohexanedione-d_8. A 50-g sample of 1,4-cyclohexanedione was added to 250 ml of deuterium oxide (99.85%) and 2.5 ml of acetic anhydride and the reaction was allowed to reflux until equilibrium was reached (about 2 days as determined by nmr). The aqueous phase was then continuously extracted with ether for 2 days to recover the dione. The above procedure was repeated five times to give 32 g (65%) of 1,4-cyclohexanedione-d_8: mp 79–80°; 99.6% deuterium by mass spectral analysis (*m/e* 120) and 99.6% deuterium by nmr analysis [internal standard: methine proton (δ 5.45) of triphenylmethane].

***cis-* and *trans*-1,4-Cyclohexanediols-2,2,3,3,5,5,6,6-d_8.** A 28.5-g (0.24 mol) sample of 1,4-cyclohexanedione-d_8 dissolved in 2000 ml of anhydrous ether was added slowly to a stirred suspension of 15.0 g (1.6 equiv) of lithium aluminum hydride in 500 ml of anhydrous ether under an atmosphere of nitrogen. The reaction mixture was allowed to reflux for 7.5 hr and 50 ml of 99.85% deuterium oxide was added *slowly* with stirring. The water and ether were removed under vacuum, and the white residue was recrystallized from acetone to give 19.6 g (63%) of *cis*- (22.6% by nmr) and *trans*-1,4-cyclohexanediols-2,2,3,3,5,5,6,6-d_8 (77.4% by nmr): mp 98–110°; nmr peaks (60 Mc, D_2O, external TMS) at δ 3.73 (methine protons of *trans* isomer) and 3.88 (methine protons of equilibrating *cis* isomers).

4-Bromocyclohexene-2,3,3,5,5,6,6-d_7. A 78.8-g (0.64 mol) sample of *cis*- and *trans*-1,4-cyclohexanediols-2,2,3,3,5,5,6,6-d_8 in 500 ml of anhydrous benzene was treated with 127 g (0.47 mol) of phosphoros tribromide in a manner exactly analogous to that for the preparation of 4-bromocyclohexene above giving 15.0 g (14%) of pure 4-bromocyclohexene-2,3,3,5,5,6,6-d_7: bp 55.0° (13 mm); nmr peaks (60 Mc, CCl_4) at δ 4.24 (1 H, HCBr) and 5.66 (1 H, vinyl proton). The 4-bromocyclohexene-2,3,3,5,5,6,6-d_7 was shown to be 99.9+% pure by glpc on a 15% PDEAS 60–80 Firebrick column (5 ft × 0.25 in.) at 100° and a helium flow rate of 85 cc/min.

Cyclohexene-2,3,3,4,5,5,6,6-d_8. A 5.9-g (0.035 mol) sample of 4-bromocyclohexene-2,3,3,5,5,6,6-d_7, 0.5 g (0.059 mol) of lithium deuteride, and 0.7 g (0.017 mol) of lithium aluminum deuteride in 20 ml of anhydrous tetrahydrofuran were heated to reflux. All the bromide had reacted after 68 hr of refluxing (analysis by glpc) and 4 ml of water was then added to the reaction mixture at −78°. The reaction mixture was poured into 100 ml of ice and water, acidified (HCl) to pH 5, and extracted with two 20-ml portions of pentane. The pentane extracts were combined, washed with aqueous sodium bicarbonate and water, and dried (Na_2SO_4). The pentane solution was fractionated to give 1.0 g (36%) of cyclohexene-2,3,3,4,5,5,6,6-d_8: bp 84° (756 mm); nmr peaks (60 Mc, neat) at δ 1.57 (1 H, C-4 proton) and 5.57 (1 H, C-1 proton). The product had a retention time essentially identical with that of cyclohexene on a 20% QF-1 60–80 Chromosorb W column (10 ft × 0.5 in.) at 78° with a helium flow rate of 150 cc/min. The deuterated cyclohexene was purified further on the same column.

4-Trideuteriomethylcyclohexene-2,3,3,5,5,6,6-d_7. The Grignard reagent of 6.8 g (0.038 mol) of 4-bromocyclohexene-2,3,3,5,5,6,6-d_7 was prepared in ether in the usual manner and filtered under nitrogen. To the ethereal solution of the Grignard reagent was added 10.0 g (0.069 mol) of trideuteriomethyl iodide and the mixture was allowed to reflux for 8 weeks (50% reaction by glpc). The reaction mixture was treated with 6 ml of deuterium oxide, washed with dilute aqueous sulfuric acid (pH 4) and aqueous sodium bicarbonate, and dried (Na_2SO_4). The ether solution was concentrated by fractionation and the residue fractionated by preparative glpc (30% SE-30, 45–60 Chromosorb P, 20 ft × 0.37 in.) at 150° with a helium flow rate of 100 cc/min to give 0.4 g (12%) of cyclohexene-2,3,3,4,5,-5,6,6-d_8 and 0.6 g (15%) of 4-trideuteriomethylcyclohexene-2,3,3,5,5,6,6-d_7: nmr peaks (60 Mc, CD_2CDCl) at δ 1.52 (1 H, C-4 proton) and 5.60 (1 H, vinyl proton).

***cis*-4-Carbomethoxycyclohexene-5-carboxylic Acid.** A 40-g (0.26 mol) sample of *cis*-cyclohexene-4,5-dicarboxylic acid anhydride was added to 200 ml of absolute methanol and the suspension allowed to reflux for 6 days. The methanol was removed under vacuum; the residue was dissolved in 100 ml of ether and the ether solution extracted with four 100-ml portions of aqueous sodium bicarbonate and dried (Na_2SO_4). Evaporation of the ether gave a negligible amount of an oily residue. The aqueous sodium bicarbonate extracts were acidified (HCl) to pH 3 and the resulting white precipitate was collected by suction filtration and recrystallized from an ether–chloroform mixture to give 15 g (30%) of *cis*-4-carbomethoxycyclohexene-5-carboxylic acid: mp 82.5–83.0°; nmr peaks (100 Mc, $CDCl_3$) at δ 2.40 (4 H multiplet, allylic protons), 2.99 (2 H triplet, J = 6.0 Hz), 3.60 (3 H sharp singlet, OCH_3), 5.58 (2 H multiplet, vinyl protons), and 11.25 (1 H singlet, CO_2H).

Anal. Calcd for $C_9H_{12}O_4$: C, 58.69; H, 6.57. Found: C, 58.45; H, 6.35.

***cis*-4,5-Dicarbomethoxycyclohexene.** To 5 g of potassium hydroxide dissolved in 8 ml of water was added 25 ml of 95% ethanol in a 100-ml distilling flask (*no* ground-glass joints) heated to 65°. A solution of 21 g (0.1 mol) of Diazald in 130 ml of ether was then added dropwise to the alcoholic potassium hydroxide and the distillate was directed below the surface of a solution of 7.5 g (0.040 mol) of *cis*-4-carbomethoxycyclohexene-5-carboxylic acid in 30 ml of ether. When the half-ester solution turned yellow, the distillation was stopped and excess diazomethane removed by heating. The ether solution was washed with three 100-ml portions of 10% aqueous sodium bicarbonate and dried (Na_2SO_4) and the ether removed under vacuum. Fractionation of the residue on an 18-in. spinning-band column gave 4.2 g (50%) of *cis*-4,5-dicarbomethoxycyclohexane: bp 110–111° (1 mm); nmr peaks (100 Mc, CCl_4) at δ 2.30 (4 H multiplet, allylic protons), 2.86 (2 H triplet, J = 5.0 Hz, C-4 and C-5 protons), 3.52 (6 H sharp singlet, OCH_3), and 5.50 (2 H multiplet, vinyl protons). The above product is a liquid at room temperature. The *trans* isomer has mp 39–40°.[39]

Anal. Calcd for $C_{10}H_{14}O_4$: C, 60.63; H, 7.12. Found: C, 60.71; H, 6.90.

Trideuteriovinyl Chloride. A 37% (by weight) deuterium chloride in deuterium oxide (99.85%) solution was prepared by the dropwise addition of benzoyl chloride into deuterium oxide and trapping of the effluent deuterium chloride in cold deuterium oxide. It was necessary to heat the reaction mixture subsequently to complete the reaction between the benzoic acid and benzoyl chloride to give benzoic anhydride and deuterium chloride.

Chunks of calcium carbide were then dropped into deuterium oxide at a convenient rate, and the effluent dideuterioacetylene was passed through a series of three 50 cm × 30 mm columns (heated to 50°) containing 13% by weight mercuric chloride in 37% deuterium chloride in deuterium oxide. About 45 min elasped before any product was noted in the receiver kept at −60°, and then over a period of about 7 hr there was collected 25 ml of trideuteriovinyl chloride: bp −11° (fractionated on a special low-temperature column); mp −164°.

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