Nuclear Magnetic Resonance Spectroscopy. Rates of Ring Inversion of Polyfluorinated Cyclohexenes[1a]

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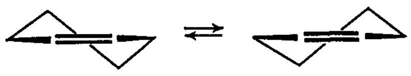
Abstract: Kinetic parameters for ring inversion of perfluorocyclohexene and 1,2-dichlorooctafluorocyclohexene have been measured at several temperatures by the nmr method. Possible pathways of inversion of the cyclohexene ring are discussed.

It is well known that cyclohexene prefers to adopt a half-chair conformation, **1**, which is in rapid equilibrium with the ring-inverted form **2**.[2,3] Something is known of this equilibrium from nmr studies of cyclohexene itself[4] and of monosubstituted cyclohexenes,[5] and free energies of activation ($\Delta G^{\ddagger}$) for interconversion of the two forms have been measured. These energies are so low (that of cyclohexene is 5.3 kcal/mole) as to fall just within the range which can be studied by the nmr method, and one consequence of this is that the determination of all thermodynamic parameters for the interconversion process has not been possible.



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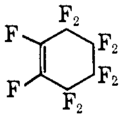
It has already been pointed out[6] how fluorinated compounds, by virtue of their larger chemical shifts, can be used to extend, to some degree, the range of activation energies which can be determined by nmr spectroscopy. This paper reports studies of perfluorocyclohexene **3** and 1,2-dichlorooctafluorocyclohexene **4**, and measurement of the activation parameters for the ring inversion of these compounds.



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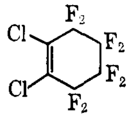

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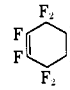
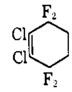
Results

At ambient temperature, the spectrum of **3** in dichlorodifluoromethane solution comprises three principal absorptions, each of which is more or less complex due to spin–spin coupling. Table I summarizes chemical-shift data, and the spectrum is shown in Figure 1. As the temperature is lowered, the signals corresponding to the two kinds of difluoromethylene groups first broaden, then split at about −108°, and finally at −152° each is an AB quartet; see Figure 1. The signal of the vinylic fluorine is essentially unchanged at low temperatures. The spectrum at −152° indicates that inversion of the ring $1 \rightleftarrows 2$ is slow on the nmr time scale. Each of the fluorines in particular CF_2 groups is either pseudoaxial or pseudoequatorial[2,3] and is strongly coupled with the geminal fluorine, while coupling with vicinal fluorines is so small as to be unobservable with the line widths attainable at −152°.

Table I. Chemical Shift and Coupling Constant Data for Polyfluorinated Cyclohexenes at Ambient Temperatures and for −150°

Compound	Chemical shift, ppm,[a] 35°	AB chemical shift, ppm, −150°	J_{AB}, Hz −150°
	145.9[b]		
	113.0[c]	19.4	287
	127.5[d]	19.2	277
	103.2[c]	12.7	280
	126.7[d]	17.6	277

[a] Upfield from CF_2Cl_2 internal reference. [b] Vinylic fluorines. [c] Allylic fluorines. [d] "Saturated" fluorines.

A series of theoretical spectra was generated[7] corresponding to different values of τ, the average time spent in either conformation **1** or **2**, and matched to the experimental spectra recorded as a function of the temperature (Figure 1). The rate constant k_{inv} for interconversion of **1** and **2** is equal to $1/\tau$ and study of the variation of this with temperature yielded the free energy of activation ($\Delta G^{\ddagger}$) for ring inversion as 6.83 ± 0.10 kcal/mole at −111.5°, the enthalpy of activation ($\Delta H^{\ddagger}$) as 7.2 ± 0.2 kcal/mole, and the entropy of activation ($\Delta S^{\ddagger}$) as +2.6 ± 1.6 eu.

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(1) (a) Supported by the National Science Foundation; (b) Harkness Fellow of the Commonwealth Fund of New York, 1966–1968; Chemistry Department, University College, London, W. C. 1, United Kingdom.

(2) E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis," Interscience Publishers, New York, N. Y., 1965, p 109.

(3) M. Hanack, "Conformation Theory," Academic Press, New York, N. Y., 1965, p 147

(4) F. A. L. Anet and M. Z. Haq, *J. Am. Chem. Soc.*, 87, 3147 (1965).

(5) (a) F. R. Jensen and C. H. Bushweller, *ibid.*, 87, 3285 (1965); (b) C. H. Bushweller, Ph.D. Thesis, University of California at Berkeley, 1966.

(6) J. D. Roberts, *Chem. Brit.*, 529 (1966).

(7) J. T. Gerig and J. D. Roberts, *J. Am. Chem. Soc.*, 88, 2791 (1966).

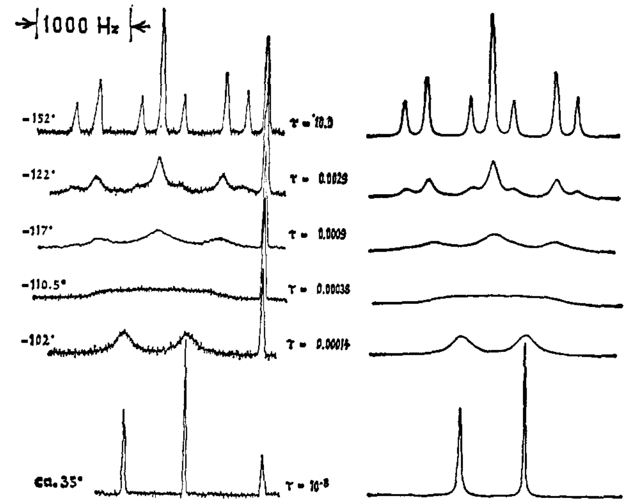

Figure 1. Experimental and calculated spectra of perfluorocyclohexene at 56.4 MHz as a function of temperature and mean lifetime before inversion. The vinylic fluorine resonance is not shown in the calculated spectra.

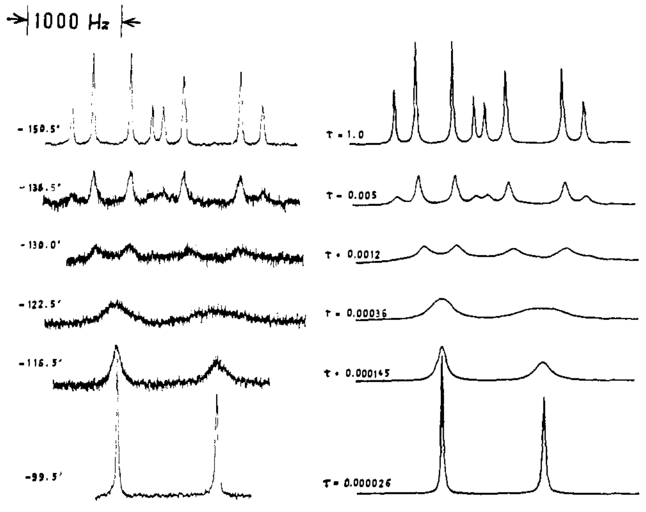

Figure 2. Experimental and calculated spectra of 1,2-dichlorooctafluorocyclohexene at 56.4 MHz as a function of temperature and mean lifetime before inversion.

The nmr spectrum of **4** in dichlorodifluoromethane solution at ambient temperature shows two absorptions having a small mutual coupling; see Table I and Figure 2. As the temperature is lowered, these signals broaden, and split below about $-124°$ to finally give, in each case, an AB quartet. Values of k_{inv} were determined as for **3**, and thence it was found that for the inversion of **4**, $\Delta G^{\ddagger}$ is 6.28 ± 0.10 kcal/mole at $-111.5°$, $\Delta H^{\ddagger}$ is 6.3 ± 0.2 kcal/mole, and $\Delta S^{\ddagger}$ is $+0.2 \pm 1.5$ eu. Figure 3 shows Arrhenius plots for the rates of inversion of **3** and **4**.

Discussion

There have been two recent rather detailed theoretical calculations[8,9] of the conformations and inversion pathways of cyclohexene molecules.[10] Previously available information from specific heat measurements[11] suggested that the difference in energy between a half-chair conformation **1** or **2** and a boat conformation such as **5** is about 2.7 kcal/mole. Anet and Haq[4] on the basis of the substantial difference between this value and their experimentally measured barrier to ring inversion, 5.3 kcal/mole, concluded that a conformation with five coplanar carbon atoms such as **6** which is intermediate between **1** and **5** must be the transition state for inversion. They suggested an interconversion cycle as shown in Figure 4, and a potential-energy profile of the form shown as curve A of Figure 5. Bucourt and Hainaut[8] calculated the energies of the series of conformations shown in Figure 4[12] and found that the half-chair conformations **1** and **2** are the most stable, while the boat conformations **5** and **9** are the highest energy forms, having energies 6.9 kcal/mole relative to **1**. The energy profile between the half-chair and boat conformations increases monotonically, the potential of forms of type **6** being one point on this profile; see Figure 5, curve B.

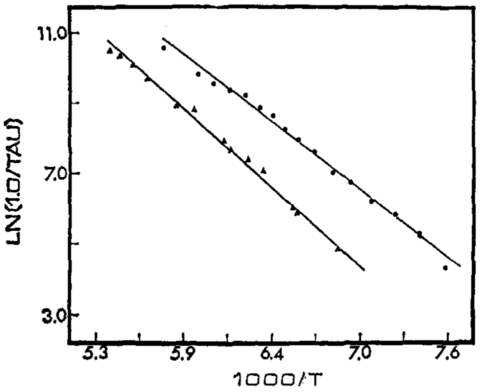

Figure 3. Arrhenius plots of inversion rates of fluorocyclohexenes: ▲, perfluorocyclohexene **3**; ●, 1,2-dichlorooctafluorocyclohexene **4**.

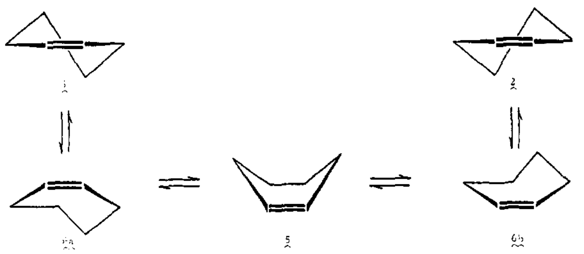

Figure 4. Interconversion cycle for conformations of cyclohexene. Forms **6a** and **6b** are optical isomers.

5

6

The calculations of Allinger and coworkers,[9] on the other hand, suggest a profile similar to that proposed by Anet. They conclude that the boat conformation **5** is indeed metastable, but that the most likely transition state is not **6** but the rather similar **11**[13] with carbon

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[8] R. Bucourt and D. Hainaut, *Bull. Soc. Chim. France*, 4562 (1967).

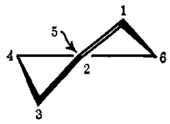
[9] N. L. Allinger, J. A. Hirsch, M. A. Miller, and I. J. Tyminski, *J. Am. Chem. Soc.*, 90, 5773 (1968).

[10] The reported calculations[8,9] are of enthalpies, ΔH, of various conformations. Calculated barriers are therefore enthalpy differences between two conformations, that is, $\Delta H^{\ddagger}$.

[11] C. W. Beckett, N. K. Freeman, and K. S. Pitzer, *J. Am. Chem. Soc.*, 70, 4227 (1948).

[12] The energy of a planar conformation (not part of the inversion cycle of Figure 4) was calculated to be 9.3 kcal/mole, 2.4 kcal/mole higher than that of any conformation in the cycle.

[13] Trivial names for conformations **6** and **11** await the attention of workers with more imagination than the present authors.



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atoms 2, 4, 5, and 6 coplanar. This pathway and the energies involved are shown as curve C in Figure 5.

There is some experimental evidence by Bushweller[5b] which might allow a choice among the transition states **5**, **6**, and **11**. The 4-halocyclohexenes have barriers to ring inversion that increase as the size of the halogen group, while *cis*-4,5-dicarbomethoxycyclohexene has a barrier to ring inversion almost 2 kcal/mole greater than that of cyclohexene itself. In **5**, the substituents along the 4–5 bond are completely eclipsed, the other bonds showing no eclipsing. In **6** there is very little eclipsing, the excess energy arising mostly from bond-angle strain. In **11** there is substantial but not complete eclipsing along the 5–6 bond. Thus a bulky substituent in the 4 position is little affected by eclipsing interactions in **6** and **11**, but must experience substantial eclipsing in a conformation **5**. Further, it is in this conformation that a 4,5-disubstituted compound will experience strongest eclipsing interactions.

Thus evidence would seem to favor a transition state of type **5** and an inversion pathway as proposed by Bucourt and Hainaut,[8] except that it is not really clear whether the enhanced barriers reported by Bushweller reflect total eclipsing as required by **5** or merely enhanced eclipsing as required by **6** or **11**.

The value to be chosen as the transmission coefficient f in calculating $\Delta G^{\ddagger}$ from values of k_{inv} depends on the inversion pathway. When there is no metastable state as in the picture of Bucourt and Hainaut[8] (curve B, Figure 5), f can be taken as unity. If **5** is a metastable form in the path (curves A and C in Figure 5), f should be taken as one-half to allow for the possibility that a molecule having once attained the barrier **1** → **5** may return to **1** and not go on to **2**. The nmr experiment records only complete transitions **1** → **2**.

For the results reported above, f has been taken as unity. If an inversion pathway with a metastable state **5** be correct, then f is correctly one-half and the corrected inversion parameters are for **3**, $\Delta G^{\ddagger} = 6.60$ kcal/mole, $\Delta S^{\ddagger} = +4.0$ eu, and for **4**, $\Delta G^{\ddagger} = 6.02$ kcal/mole, $\Delta S^{\ddagger} = +1.6$ eu.

Both steric and dipolar interactions are expected to be different in cyclohexene and in polyfluorinated cyclohexenes, but the general similarity of the barriers found suggests that the preferred conformation is as **1** or **2**. The free energies of activation for ring inversion of these compounds are both rather greater than that of cyclohexene. Barriers to ring inversion of polyfluoro compounds are sometimes larger, sometimes smaller, than those of the parent compound,[14] but there is no clear explanation of this at present. Of some significance is the difference in the barrier in **3** and **4**. It seems reasonable to attribute the lower values of both the free energy and the enthalpy of activation of **4** compared with **3** to a larger ground-state enthalpy for **4**. Examination of molecular models suggests an increase in enthalpy is to be expected from the enhanced steric interaction of the pseudoequatorial fluorine atoms at positions 3 and 6 in the ring, with the larger chlorine atoms at positions 2 and 1, respectively. However, it may be an oversimplification to neglect changes of dipolar interactions and to attribute the differences to a steric effect alone.

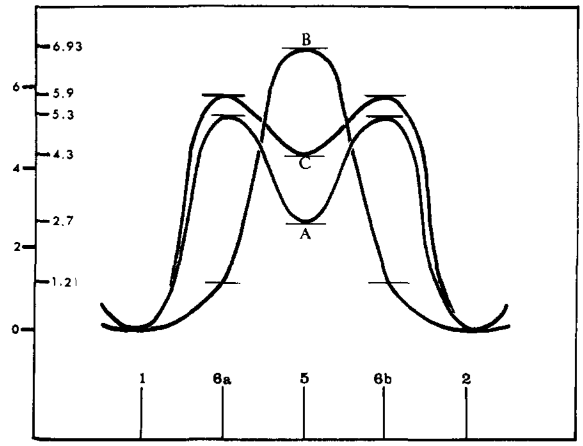
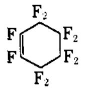
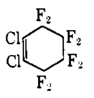


Figure 5. Possible energy profiles for interconversion of half-chair conformations of cyclohexene: A, as deduced by Anet and Haq;[4] B, from the calculations of Bucourt and Hainaut;[8] C, from the calculations of Allinger and coworkers;[9] here forms of type **11** are considered rather than **6a** and **6b**. The energies of the half-chair forms are taken as reference (zero) and the values given are in kcal/mole.

The entropies of activation for the inversion of **3** and **4** are apparently both small and positive, and perhaps not significantly different from each other. The symmetry contribution to the entropy of activation[15] is +1.4 eu for both **3** and **4**, independent of whether the

Table II. Experimental Rate Constants k_{inv} at Several Temperatures

	Temp, °C	$\tau \times 10^5$, sec	k_{inv}, sec^{-1}
	−88.0	2.8	35,700
	−90.3	3.3	30,300
	−93.0	4.3	23,250
	−96.0	6.5	15,400
	−102.0	14.0	7,140
	−105.0	16.0	6,250
	−110.5	38.0	2,630
	−111.5	49.0	2,040
	−114.5	65.0	1,535
	−117.0	90.0	1,111
	−121.5	250	400
	−122.0	290	345
	−128.0	800	125
	−99.5	2.6	38,500
	−106	5.5	18,200
	−109.0	7.5	13,300
	−111.5	9.0	11,100
	−114.0	10.1	9,900
	−116.5	14.5	6,890
	−118.5	18.0	5,560
	−120.3	26.0	3,850
	−122.5	36.0	2,780
	−124.5	50.0	2,000
	−127.3	90.0	1,110
	−129.8	120	830
	−132.5	200	500
	−135.5	290	345
	−138.5	500	200
	−141.5	1300	77

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(14) J. E. Anderson and J. D. Roberts, to be published.

(15) R. K. Harris, Ph.D. Thesis, University of Cambridge, England, 1962.

transition state is like **5**, **6**, or **11**. The experimental entropies of activation for the inversion of **3** and **4** agree with these values within experimental error. For cyclohexane,[16] the experimental entropy of activation is also close to that calculated on the basis of symmetry considerations.

Experimental Section

Compounds **3** and **4** were obtained from Pierce Chemical Co., and used without further purification dissolved in dichlorodifluoromethane. Spectra were recorded on a Varian Associates A56/60A spectrometer at operating frequency 56.4 MHz, and were calibrated by the sideband technique using a Hewlett-Packard audiooscillator. The spectrometer was equipped with a V6040 temperature control unit and a probe capable of operating at −150°. Temperatures were measured immediately after recording spectra by stopping the spinning of the sample tube, inserting a calibrated thermocouple to the bottom of the tube, and measuring the potential relative to a second thermocouple in ice–water. Temperatures were reproducible to better than 0.5° but systematic errors[17] probably reduced the accuracy to ±1–2°.

The spectra calculated as a function of τ used a program devised by Gerig[7] based on the equations of Alexander.[18] Plots of these spectra were obtained from an IBM 7094 computer linked to a Calcomp plotter. The "line width in the absence of exchange" which must be provided for this program was taken to be the line width at room temperature for spectra above the coalescence temperature, and the line width at about −150° for spectra below coalescence. There is certainly no contribution from kinetic broadening to these line-widths, but there must be contributions from small vicinal and long-range couplings, more or less obscured by field inhomogeneity. The assumed natural line width may therefore cause noticeable errors when the exchange contribution to line broadening is small, particularly near the upper temperature limit, so in these cases, the spectra with line widths less than about three times the natural line width were excluded. Nevertheless, measurements over a 40° temperature range (and more than two orders of magnitude in rate) were possible for both compounds. Within this range, which is the range of greatest change of the spectra, changes of 5% in the value of τ were quite noticeable, so that values quoted are considered to be accurate to at least this degree. Table II shows the values of τ so obtained at various temperatures.

The Arrhenius plots shown in Figure 3 were fitted by a least-squares computer program, which also provided the root-mean-square errors quoted for the $\Delta H^{\ddagger}$ and $\Delta S^{\ddagger}$ values. The figures for $\Delta G^{\ddagger}$ were calculated by the Eyring equation from the experimental value of τ at that temperature. The value of the transmission coefficient was taken as 1, as explained above. The accuracy of values of $\Delta G^{\ddagger}$ based on the accuracy of measurement of the temperature and τ is thought to be ±0.1 kcal/mole.

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(16) F. A. L. Anet and A. J. R. Bourn, *J. Am. Chem. Soc.*, **89**, 760 (1967).

(17) A. Allerhand, H. S. Gutowsky, J. Jonas, and R. Meinzer, *ibid.*, **88**, 3165 (1966).

(18) S. Alexander, *J. Chem. Phys.*, **37**, 974 (1962).

Photochemical Transformations of Small-Ring Carbonyl Compounds. XXII. Observations on the Scope of the Photoinduced Ring Expansion of Aroylazetidines[1,2]

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Abstract: The photoinduced ring expansion of selected arylaroylazetidines has been examined. Upon irradiation with ultraviolet light in ethanol solution, *cis*-N-*t*-butyl-2-phenyl-3-benzoylazetidine (**1**) rearranges smoothly and in high yield to N-*t*-butyl-2,4-diphenylpyrrole (**3**). The course of the over-all photoreaction is substantially altered for the *trans* isomer. Irradiation of *trans*-N-*t*-butyl-2-phenyl-3-benzoylazetidine (**2**) gave a mixture of 2,3- and 2,4-diphenyl-N-*t*-butylpyrroles. No photoepimerization of starting material or photoisomerization of product could be detected. Experiments with *p*-phenylbenzoylazetidines **6** and **8** and several differently deuterated azetidines helped elucidate the positions of the carbon atoms in the pyrrole ring after rearrangement occurred. Mechanistic discussion is given in the following paper.

During the past several years, it has become increasingly apparent that the photochemistry of heterocyclic small-ring ketones has provided an intriguing new source of unusual molecular rearrangements. The general types of phototransformations which have been observed with aroylaziridines have been summarized in recent papers from this laboratory.[4,5] It is evident that the three-membered heterocyclic ring exhibits versatile and intriguing properties upon electron excitation and that its behavior is strongly influenced by its chemical environment and initial stereochemistry. As part of our continuing interest in the photochemistry of small-membered rings we have investigated the chemical response to ultraviolet radiation of the related four-membered nitrogen heterocycle. In preliminary reports[2,6] we have communicated that this system is exceptionally reactive, undergoing photochemical transformations that are seemingly dependent on the initial

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(1) For part XXI, see A. Padwa and E. Alexander, *J. Amer. Chem. Soc.*, **90**, 6871 (1968).

(2) For a preliminary report of this work, see A. Padwa and R. Gruber, *ibid.*, **90**, 4456 (1968). This work was presented in part at the 154th National Meeting of the American Chemical Society, Chicago, Ill., Sept 1967.

(3) Alfred P. Sloan Foundation Research Fellow, 1968–1970.

(4) A. Padwa and L. Hamilton, *J. Amer. Chem. Soc.*, **89**, 102 (1967).

(5) A. Padwa and W. Eisenhardt, *ibid.*, **90**, 2442 (1968).

(6) A. Padwa, R. Gruber, and L. Hamilton, *ibid.*, **89**, 3077 (1967).