Tetrahedron. Vol 32, pp 1211 to 1219 Pergamon Press 1976 Printed in Great Britain

STEREOCHEMICAL STUDIES—XX

CONFORMATIONS OF 1,2-*TRANS*-DISUBSTITUTED CYCLOHEXANES

N. S. ZEFIROV* and L. G. GURVICH
Department of Chemistry, Moscow State University, Moscow, 117234, U.S.S.R.

A. S. SHASHKOV
Institute of Organic Chemistry of Academy of Sciences of the U.S.S.R., Leninsky prospekt, 47, Moscow, 117334, U.S.S.R.

M. Z. KRIMER and E. A. VOROB'EVA
Institute of Chemistry of Academy of Sciences of U.S.S.R., Kishinev, U.S.S.R.

(*Received in the UK* 12 *February* 1975; *Accepted for publication* 18 *September* 1975)

Abstract—The conformational equilibria of deuterated 1,2-*trans*-disubstituted cyclohexanes has been studied by NMR spectroscopy and the values of *gauche*-interaction, $\Delta G_{X/Y}$, have been determined. The relationship between $\Delta G_{X/Y}$, steric (E_v), and dipole–dipole (E_μ) interactions, represented as the plot $\Delta G_{X/Y} - E_v$ vs ΔE_μ, is proposed as the basis for a new description of conformational effects. The conformational behaviour of the compounds investigated is discussed in terms of "*gauche*-", "hockey-sticks", "through bond" and "through space" effects.

Although the possibility of calculating of conformational energies by quantum mechanical approaches does exist, to date conformational analysis is based (at least in its most general and useful form) on examination of the energy contributions made by changes in bond lengths (E_l) and angles (E_θ), torsional strain (E_t) and by interaction between non-bonded atoms ($E_{n\text{-}b}$):[1]

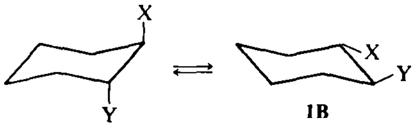
$$E = E_l + E_\theta + E_t + E_{n\text{-}b} \qquad (1)$$

Equation (1) involving all these steric factors enables the conformations of a wide range of compounds to be calculated fairly accurately.[1-3] It is evident, however, that if substituents are characterised by some additional strong interactions, the calculations of relative stability of the conformations must include these additional effects. In fact, quite a large number of cases have now accumulated in the literature in which the stability of the conformations actually observed cannot be explained solely by steric factors. This type of discrepancy is usually regarded as specific for a certain structural unit, and these cases are sometimes treated as special "conformational effects". To date many conformational effects have been proposed, all of which have had some kind of experimental "verification". Many of them have special names, e.g. "anomeric",[4] and "rabbit-ears" effects,[5] Δ^2-instability factor,[6] "*gauche*"[7-9] and "hockey-sticks"[10-12] effects, "through-bond and through-space" effects,[13-15] "superjacent effect",[14b] and so on.

Though conformational effects are often somewhat obscure, they are usually interpreted either in terms of a dipole–dipole (or charge–charge) interaction or the specific quantum mechanical mechanisms are involved for the explanation. The dipole–dipole interactions can, in principle, be characterised by the new additional term (ΔE_μ) in the eqn (1).[3]

The molecular orbital calculations operate using completely different logic, because each molecule is treated as a whole. However, a compromise is possible if one operates with the interaction ("delocalization") of localized sets of orbitals (for an excellent discussion of this point of view, see 13). In this case, the quantum mechanical effects, connected with the orbital interactions can also be treated as characteristic of the same structural units and accounted as new terms in eqn (1).

In this respect, conformational behaviour of 1,2-*trans*-disubstituted cyclohexanes is especially interesting. Sterical reasons require that these compounds prefer a diequatorial conformation **1B**. However, this conformation is destabilized by the *gauche*-interaction of substituents (*X*/*Y*). The available data concerning the conformational equilibrium of 1,2-*trans*-disubstituted cyclohexanes are somewhat piecemeal in character. The dihalogen compounds, which have been most extensively studied show the relatively increased content of diaxial **1A** conformation, which is increased across the series Cl < Br < I.[16-20] The same is seen for 1,2-*trans*-dihalogenated cyclopentanes,[21] indanes[22] and some heterocycles.[23] An increase in the fraction of a *trans*-diaxial conformation was mentioned with 1,2-ditosyloxycyclohexane,[18] 1,2-dihalohenated cyclohexanes containing different halohenes,[24] with certain 1-iodo-2-perfluoroalkyl cyclohexanes[25] and 1-chloro-2-arylthiocyclohexanes.[10a] Note also that cyclohexanedicarboxylic acid dianion is thought to possess a *trans*-diaxial conformation,[26] while the acid itself (as well as its non-ionic derivatives) exists in a diequatorial state predominantly.[27-29]



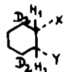
1A **1B**

The present work is a study of the conformational equilibria of a number of 1,2-*trans*-disubstituted cyclohexenes and a rationalisation of their conformational behavior in terms of "conformational effects" (preliminary communication[30]).

RESULTS

All compounds investigated have been obtained by the addition reactions to a cyclohexane (H-series) and to a 3,3,6,6-tetradeuterocyclohexene[31,32] (D-series). Halogeno-methoxy-compounds **3**, **4** and **6** (Table 1) were prepared according to Scheme 1. A main problem was to obtain *RS*-derivatives containing OR- and SR-groups as the substituent in a second position.[33] For this reason we have

Table 1. Data of NMR-spectra of the 1,2-*trans*-disubstituted cyclohexanes at the room temperature

number of compound			in CCl_4 δ(ppm; ±0.01)		J_{12} (± 0.1 Hz)	in CS_2 δ(ppm; ±0.05)		J_{12} (± 0.1 Hz)	in C_6H_6 δ(ppm; ± 0.05)		J_{12} (± 0.1 Hz)	in CH_3CN δ(ppm; ± 0.05)		J_{12} (±0.1 Hz)
	X	Y	H_1	H_2		H_1	H_2		H_1	H_2		H_1	H_2	
II	OCH_3	$OCOCH_3$	3.0_I a)	4.5_5 a)	7.5 ±0.2	3.0	4.5_3	7.2_5	2.8_6	4.6	7.5±0.2	3.0_6	4.6	8.4
III	OCH_3	Cl	3.0_8	3.7_8	6.7	3.0_6	3.7_4	6.8	-	-	-	-	3.8_3	7.5±0.2
IY	OCD_3	Br	$3.I_6$	3.9_I	7.0	3.I	3.8_5	6.8±0.2	2.9_2 b)	3.7_4 b)	7.2±0.05	3.3_3	$4.I_I$	8.0
Y	OCD_3	SCH_3	2.9_8	2.48	7.2	2.9_6	2.4	7.2±0.2	2.9_3	2.4	7.8±0.2	3.0_3 c)	2.4_6 c)	7.8±0.2 c)
YI	OCH_3	I	2.9_5	3.9	7.5	3.0_I	3.9_8	7.5	-	-	-	-	4.0_6	8.5±0.2
YII d)	$OCOCH_3$	SCH_3	4.5_9	2.4_3	8.7	4.5_8	2.4_I	8.7±0.2	4.8	2.3_6	9.2±0.2	4.6_6	-	9.5±0.2
YIII	Cl	SCH_3	3.9_8	2.6_8	6.2_5	3.9	2.7	6.5	3.7_6	2.4_6	6.9±0.2	4.0	-	7.6±0.5
IX	Br	SCH_3	4.2_3 a)	2.9_3 a)	5.0 ±0.2	4.2_4	2.8_4	5.5	4.0_3	2.6	5.5±0.2	4.0_3	2.6	7.6±0.2
X e)	$OCOCH_3$	SC_6H_5	4.7	3.06	8.7 ±0.05	4.6_8	3.0_3	8.7_5	4.8_6	3.0_3	9.2	4.7	$3.I_6$	9.4
XI	Cl	SC_6H_5	3.9 a)	3.2_3 a)	5.8	3.8_8	$3.I_8$	6.2_5	3.8	3.I	6.4	3.9	3.2	7.8±0.2
XII	Cl	SeC_6H_5	4.0_8	3.3_6	5.5	4.0_5	3.3_3	5.7_5	3.9_6	3.2_6	6.4	4.0_6	3.3_3	7.2
XIII f)	Br	SC_6H_5	4.2_6 a)	3.5_3 a)	5.0 ±0.2	-	-	-	4.0_6	3.3	5.8±0.2	4.2 c)	3.4 c)	6.8±0.2
XIY g)	SCH_3	SC_6H_5	2.6 a)	3.2 a)	6.0 ±0.2	2.5_8	$3.I_8$	6.2_5	2.5_5	$3.I_6$	6.7	-	3.2_3	8.2
XY	OH	SCH_3	$3.I_8$	$2.I_9$	9.5	$3.I_8$	2.2	9.5±0.2	3.2	$2.I_3$	9.5±0.2	3.2_6	-	9.5±0.2
XYI	OH	SC_6H_5	3.2 a)	2.6_6	9.5± 0.2	$3.I_8$	2.6	9.7	$3.I_6$	2.7	9.6	-	-	-

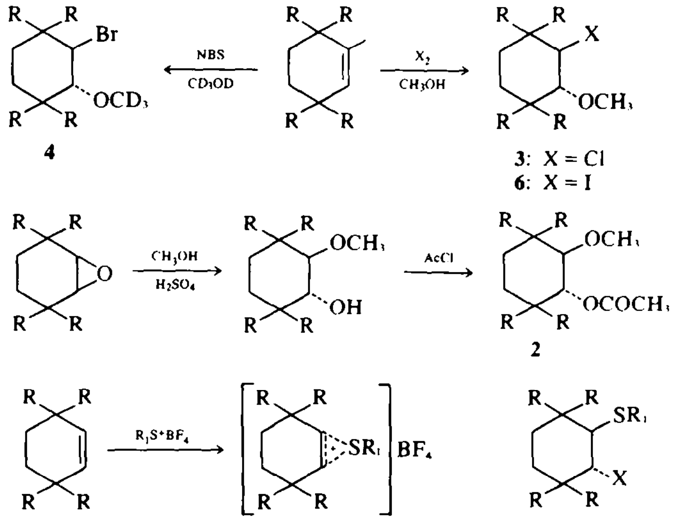
a) δ ± 0.05 ppm; b) δ ± 0.01 ppm; c) in CD_3CN;

d) in vinyl chloride; δ_{H_1} 4.65, δ_{H_2} 2.45, J_{12} 8.7 Hz;

e) in vinyl chloride: δ_{H_1} 4.66, δ_{H_2} 3.03, J_{12} 8.75 Hz;

g) in vinyl chloride: δ_{H_1} 4.1, δ_{H_2} 3.35, J_{12} 5.5+0.1 Hz;

f) in vinyl chloride δ_{H_1} 2.55, δ_{H_2} 3.15, J_{12} 6.5 Hz



$R_1 = CH_3$ or C_6H_5

H-series: R = H; D-series: R = D

Scheme 1.

used the reaction of methylsulphenyl or phenylsulphenyl fluoroborates with cyclohexene[34] (Scheme 1). All compounds investigated are listed in Table 1.

The PMR spectra of all D-compounds investigated were the simple AX or AB systems. The chemical shifts of H_1 and H_2 protons and $J_{AX}(J_{AB})$ coupling constants are shown in Table 1. It is evident from (a) the solvent shift of J_{AX} and (b) the large value of J_{AX} in CH_3CN that all compounds have the *trans*-configuration. The position of the conformational equilibrium may be found from the Eliel equation:

$$\langle {}^3J_{(HH)}\rangle = \sum_i n_i J_i = nJ^{aa} + (1-n)J^{ee}.$$

The main difficulties are usually connected with the choice of the "standard" or "limiting" coupling constants of the individual conformers (for discussion, see 35). The most precise value may be obtained from the low-temperature NMR measurement. We have found that NMR spectra at −90° contained the peaks of both conformers **1A** and **1B** (Table 2). The content of the diaxial form **1A** at room temperature has been calculated, using the low-temperature coupling constants of individual conformers as standards. These data and the values of free energy for the conformation equilibria, ΔG_{eq}, are listed in Table 3. Sometimes, we have not been able to obtain the experimental low-temperature coupling constants, and standard constants were taken from data on the closest analogous compounds. The literature data for equilibria of some 1,2-*trans*-dihalogenocyclohexanes are also included in Table 4 for comparison purposes. There is appreciable discrepancy in the experimental ΔG_{eq} values for the compounds mentioned. We have used the ΔG_{eq} values -0.02 ± 0.2 and 0.65 kcal/mol for dichloro- and dibromocyclohexanes respectively in accordance with Refs. 16, 17 (Table 4). Additionally, we have used the $\Delta G_{eq} = -0.65$ kcal/mol for 1-fluoro-2-iodocyclohexane and $\Delta G_{eq} = 0.25$ kcal/mol for 1-chloro-2-iodocyclohexane.[24a] All literature data have been obtained using CS_2 as a solvent. There is also value $\Delta G_{eq} = 1.0$ kcal/mol for the conformational equilibrium of 1,2-*trans*-diiodocyclohexane in benzene.[18,24a]

Table 2. Data of low temperature NMR measurement of the 1,2-*trans*-disubstituted cyclohexanes

Number of compound	Solvent	Temperature (-°C)	a,a-conformer (IA) δ(ppm: ±0.05) H$_1$	H$_2$	J_{12} (± 0.1 Hz)	e,e-conformer (IB) δ(ppm: ±0.05) H$_1$	H$_2$	J_{12} (± 0.1 Hz)
II	CS_2	90	-	-	-	2.95	4.3_5	9.2_5
III	CS_2	80	-	$4.I_2$	2.7_5	2.9	3.5_3	9.5
IУ	CS_2	80	3.3_6	4.2_5	2.5	2.9_3	3.6	9.7
У	CS_2	90	3.2_5	-	2.4_5	2.8_3	-	9.5
УI	CS_2	80	-	4.6	2.0	-	$4.I_6$	$I0.2_5$
УП	v.c. [a]	90	-	-	-	4.6_4	2.3_4	$I0.7_5$
УШ	CS_2	90	4.3	2.9	2.4	3.6	2.6	I0.8
IX	CS_2	80	-	-	-	3.8	-	I0.5
X	v.c. [a]	90	-	-	-	4.6_6	3.0	I0.5
XI	CS_2	80	4.I	3.5_4	I.5	-	2.7_7	$I0.7_5$
XП	CS_2	80	4.2	3.5	2.0	-	2.9	$I0.7_5$
XIУ	v.c. [a]	90	2.7_6	3.6_3	I.8	2.3_7	2.9_8	II.0

a) vinyl chloride

Table 3. Conformation equilibrium data of 1,2-*trans*-disubstituted cyclohexanes (**1A** ⇄ **1B**)

Number of compound	CCl_4		CS_2		C_6H_6		CH_3CN	
	% of IA	G (kcal/mol)	% of IA	G (kcal/mol)	% of IA	G (kcal/mol)	% of IA	G (kcal/mol)
II a)	$23.2_6 \pm 6.6$	-0.67 ± 0.2	29.4 ± 5.0	$-0.5_2 \pm 0.I_5$	$24.2_6 \pm 6.6$	$-0.6_7 \pm 0.2$	$I2.5 \pm 5.5$	$-I.I_5 \pm 0.3$
III	$4I.5 \pm 4.7$	$-0.2 \pm 0.I_2$	40.0 ± 4.7	$-0.2_4 \pm 0.I_2$	-	-	$29.6_3 \pm 6.5$	$-0.5_I \pm 0.2$
IУ	37.5 ± 4.5	$-0.3 \pm 0.I_2$	40.3 ± 5.8	$-0.2_3 \pm 0.I_5$	34.72 ± 3.9	$-0.3_7 \pm 0.I_I$	$23.6_I \pm 4.9$	$-0.6_9 \pm 0.I_7$
У	$32.6 \pm 4,7$	$-0.4_3 \pm 0.I_3$	32.6 ± 6.0	$-0.4_3 \pm 0.I_7$	$24.I \pm 6.4$	$-0.6_8 \pm 0.2_2$	$24.I \pm 6.4$	$-0.6_8 \pm 0.2_2$ b)
УI	$33.3_3 \pm 4.0$	$-0.4_I \pm 0.I_I$	$33.3_3 \pm 4.0$	$-0.4_I \pm 0.I_I$	-	-	$2I.2 \pm 5.5$	$-0.7_8 \pm 0.2_I$
УII	24.7 ± 4.2	$-0.6_6 \pm 0.I_4$	24.7 ± 5.4	$-0.6_6 \pm 0.I_8$	$I8.6_8 \pm 5.6$	$-0.8_7 \pm 0.23$	$I5.0_6 \pm 5.7$	$-I.0_2 \pm 0.06$
УIII	$54.I_7 \pm 3.5$	$0.I0 \pm 0.08$	$5I.2 \pm 3.5$	0.03 ± 0.08	$46.4_3 \pm 4.8$	$-0.08 \pm 0.I_I$	33.3 ± 8.7	$-0.4_I \pm 0.2_4$
IX c)	67.9 ± 4.5	$0.4_4 \pm 0.I_3$	$6I.7 \pm 0.09$	$0.2_8 \pm 0.09$	$6I.7 \pm 4.7$	$0.2_8 \pm 0.I_2$	35.8 ± 5.7	$-0.3_4 \pm 0.I_4$
X a)	$22.I \pm 3.7$	$-0.7_5 \pm 0.I_4$	22.7 ± 4.3	$-0.7_3 \pm 0.I_6$	$I7.I_8 \pm 4.4$	$-0.9_3 \pm 0.2$	$I3.5 \pm 4.5$	$-I.I \pm 0.2_5$
XI	$53.5_2 \pm 3.2$	0.09 ± 0.08	$48.6_5 \pm 3.3$	-0.03 ± 0.08	47.0 ± 3.3	-0.06 ± 0.07	$3I.9 \pm 4.7$	$-0.4_5 \pm 0.I_3$
XII	60.0 ± 3.2	$0.2_4 \pm 0.08$	$57.I_4 \pm 3.3$	$0.I7 \pm 0.08$	49.7 ± 3.4	$-0.0I \pm 0.08$	$40.5_7 \pm 3.6$	$-0.2_3 \pm 0.09$
XIII c)	67.9 ± 4.5	$0.4_4 \pm 0.I_3$	-	-	58.0 ± 4.7	$0.I_9 \pm 0.I_2$	$45.6_8 \pm 5.0$	$-0.I \pm 0.I_2$ b)
XIУ	$54.3_5 \pm 4.3$	$0.I \pm 0.I$	$5I.6_3 \pm 3.2$	0.04 ± 0.07	$46.7_4 \pm 3.3$	-0.08 ± 0.08	$30.4_4 \pm 3.7$	$-0.4 \pm 0.I$

a) assuming J_{ee} = 2.45 Hz; b) in CD_3 CN; c) assuming J_{ee} = 2.4 Hz; d) in CH_2 =CHCl

ΔG = 0.28 ± 0.09 kcal/mol

Table 4. Energies of internation of *gauche*-substituents

gauche-fragment (X/Y)	$\Delta G_{X/Y}$ in kcal/mol	Energy (kcal/mol)	
		ΔE_{μ}	E_v a)
O/OAc b)	0.6 ± 0.4	I.2	-0.I3
O/Cl	0.85± 0.3	0.98	-0.I8
O/Br	0.7 ± 0.3	0.82	-0.2
O/I	0.6 ± 0.2	0.64	-0.I7
O/S c)	I.2 ± 0.6	0.84	-0.I8
OAc/S	I.I5± 0.6	-	-
S/Cl	I.7 ± 0.5	0.67	0.I
S/Br	2.0 ± 0.5	0.58	0.23
S/S	2.2 ± 0.7	0.58	0.I
Cl/Cl d)	I.0 ± 0.4	0.72	-0.08
Br/Br d)	I.6 ± 0.3	0.58	0.35
F/I e)	0.I	0.6I	-0.I
Cl/I e)	I.2	0.52	0.66
I/I e)	I.9	0.36	(2.73)

a) Using the Hill equation: $E_v/\varepsilon = -2.25\alpha^{-6} + 8.28\ 10^5\ e^{-\alpha}/0.0736$.

b) O - means data for OCH_3 c) S - means data for SCH_3

d) Ref. 16,17 e) Ref. 24a

For the discussion it was necessary to calculate the values of steric and polar interactions of the substituents in the compounds investigated. To our knowledge experimental data concerning the X . . . Y distances ($r_{X/Y}$) in the conformations **1A** and **1B** for the compounds discussed are extremely poor;† because the $r_{X/Y}$ values have been calculated using the cartesian coordinates of cyclohexane itself.[1,39] The coordinates of substituents X and Y‡ were calculated by extending the C–H vector to a new vector using average standard C–X lengths; C–F 1.39 Å, C–O 1.42 Å, C–Cl 1.78 Å, C–S 1.8 Å, C–Br 1.94 Å and C–I 2.13 Å. The energy of steric interaction of *gauche*-substituents, E_v, has been calculated using the Hill equation.[1,40,41] Results of these calculations are given in Table 4. Inspection of Table 4 indicates that steric interaction terms are usually small. An appreciable value of E_v has been found only for the atoms of lower elements (Br/Br and especially I/I). However this is evidently an artifact of the calculations since undistorted cyclohexane geometry has been used. In the conforma-

---

†There are structural data for 1,2-*a,a*-dichlorocyclohexane,[36] and also for 1,2,4,5-*a,a,e,e*-tetrachloro-[37] and 1,2,3-*a,a,a*-tribromocyclohexanes.[38]

‡The coordinates of oxygen and sulphur atoms were calculated for OR and SR groups.

tion **1B**, the steric repulsion increases the *e,e*-dihedral angle to relieve the strain. This may also be supported by experimental data. For example, the dihedral, *e,e*-angle in cyclohexane-1,2-*trans*-dicarboxylic acid in 69°,[42] which exceeds the corresponding angle in cyclohexane (62.9°). At the same time, the small increase in the dihedral angle and therefore the very small increase of $r_{X/Y}$ value leads to a great decrease in steric repulsion, taking into account the shape of the dependence E_v/ϵ vs $r_{X/Y}$.[1] Hence we may regard the calculated values as the upper repulsion limits.

Some approaches exist for calculation of polar interaction (for discussion, see 3, 17). We have used the charge-charge model to calculate the electrostatic interaction between the polar $\overset{+}{C}-\overset{-}{X}$ bonds. With the charges, e_X and e_Y, in electrons and the distances, $r_{X/Y}$, in Å, the electrostatic interaction is given by equation: $E_\mu = 332 \cdot e_X \cdot e_Y / r_{X/Y}$ with E_μ in kcal/mol.[17] The excessive electron densities on X and Y atoms need to be obtained, and these charges were calculated using the equation $e_X = \mu_{C\text{-}X}/r_{C\text{-}X}$, where $\mu_{C\text{-}X}$ is the dipole moment and $r_{C\text{-}X}$ is the length of the C–X bond. Calculated values of charges are the following: $e_F = -0.21$, $e_{Cl} = -0.17$, $e_{Br} = 0.15$ and $e_I = -0.12$ e.u. One may find some different values of e_X in the literature (for example, $e_{Cl} = -0.22$[41] and -0.26[43]). This is due to use of experimental dipole moments of halogene compounds for calculation in Refs. 41, 43. We have used the "pure" moments of C–X bonds, calculated with exclusion of the moment of C–H bond.[39] For the group containing oxygen and sulphur, the dipole moments of C–O (0.75 D) and C–S (0.65 D) bonds have been calculated analoguously *cf.* 39, from the experimental dipole moments of dimethyl ether and dimethyl sulphide[44] respectively. Calculated charges are $e_O = -0.22$ and $e_S = -0.15$ e.u. All charges calculated compare very well with those assumed in Ref. 3*a* and those taken from quantum mechanical calculations,[17,45] which give some support to the validity of the charge distribution obtained. The values $\Delta E_\mu = E_\mu^{1B} - E_\mu^{1A}$, which reflect an extra destabilization in the diequatorial for **1B** due to the charge-charge interaction (or dipole–dipole, see Ref. 17), are listed in Table 4. Of course, this calculation is a relatively simple matter; however the same type of calculation has received wide application in current literature. A more precise analysis by molecular mechanics calculations are extremely difficult, especially for the compounds containing OCH_3 or SCH_3 groups.

Finally, there remains the choice of the "best values" of $-\Delta G_R$ (or A-values) for the monosubstituted cyclohexanes. In spite of intensive investigations, there is appreciable discrepancy between "the best" values.[1,46–48] We have chosen the following values of $-\Delta G_R$: F 0.25 ± 0.1, Cl 0.5 ± 0.1, Br 0.48 ± 0.1, I 0.45 ± 0.1, OMe 0.55 ± 0.1 and OAc 0.7 ± 0.1 kcal/mol. Error limits have been chosen from the comparison of the data in Refs. 46–48. There is especially large discrepance between the $-\Delta G_{SCH_3}$ values (0.7[48] and 1.07[46,47] kcal/mol). We prefer the second value because it has been obtained from the precise low-temperature NMR measurement. However, we use the $-\Delta G_{SCH_3}$ value of 1.1 kcal/mol with a large error limit ±0.3 kcal/mol to avoid doubtful conclusions. The $\Delta\Delta G = \Delta G_{SCH_3} - \Delta G_{SC_6H_5}$ value has been evaluated of −0.1 kcal/mol.[48] Hence we have also used the $-\Delta G_{SC_6H_5}$ value of 1.1 ± 0.3 kcal/mol.

DISCUSSION

Examination of Table 1 reveals that J_{AB} coupling constant for hydroxy compounds **15** and **16** are approximately 9.5 Hz, independent of solvent and temperature. Taking the standard J^{aa} coupling constant for these compounds equal to 9.5 Hz (compare with low-temperature data for compound **2–5**, Table 2), one may conclude that conformational equilibrium in this case is "anancomeric" (term from Ref. 49) and the diequatorial conformer **1B** is strongly favoured which is in a good agreement with literature data concerning the conformational equilibria of the halogenohydrin derivatives of cyclohexane.[18,31,50] This feature is explicable in terms of intramolecular hydrogen bond, which may operate in these systems.†

However the conformational behaviour of the other compounds investigated is completely different. Inspection of the data listed in Tables 1 and 3 reveals that (a) the coupling constants are strongly solvent-dependent and (b) there is appreciable content of the diaxial form **1A** in conformational equilibria.

The $-\Delta G_{Hal}$ values for halogenocyclohexanes have been found to show extremely small solvent-dependence.[16] In contrast, the equilibrium free energies, ΔG_{eq}, of the compounds studied are strongly solvent dependent (Table 3). This behaviour is due to the gross dipole moment difference between conformation **1A** and **1B** (cf. Refs. 16, 17). Figure 1 shows the relationship between $\Delta G^{eq}_{CCl_4}$ vs ΔG_{eq} in the other solvents (not all points are included). As can be seen, there is apparent linear correlation between these values. One can conclude that ΔG_{eq} values change approximately equally along with the change of solvent polarity. As can been seen from Fig. 1 and Table 1 the benzene, which is non-polar solvent, behaves anomalously, preferentially stabilising the diequatorial isomer as compared with CCl_4 or CS_2 ("benzene effect").[12a,20,51] The benzene effect for the compounds investigated is appreciable and may be roughly evaluated as 0.2 kcal/mol (Table 3).

The next step of the discussion must include the correlation of the parameters of conformational equilibrium with some characteristics of substituents (e.g. with charges, volumes, etc.) to elucidate the factors which determine the conformational equilibrium. However, one important question may be posed: what parameter of the equilibrium has to be correlated? For example, the *trans-gauche* free energy differences have been used

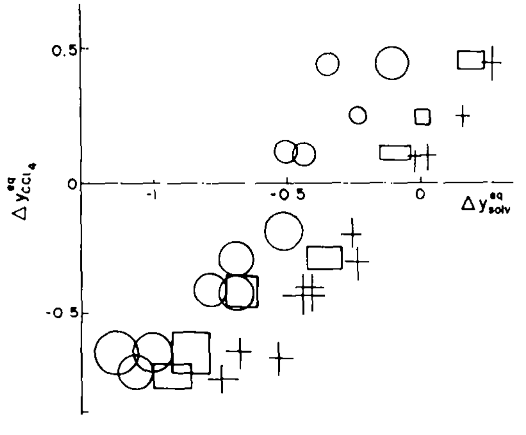


Fig. 1. Relationship between $\Delta G^{eq}_{CCl_4}$ and ΔG^{eq}_{solv} : +, in CS_2; □, in C_6H_6; ○, in CH_3CN.

---

†The same problem is discussed for 1,2-disubstituted ethanes.

directly for this purpose in the case of 1,2-disubstituted ethanes.[52] However, the situation in the case studied is more complicated. Indeed, the increase in the content of the diaxial conformation can be due to either the strong repulsion of X and Y in the conformation **1B**, or the small conformational free energy ($-\Delta G_X$ and $-\Delta G_Y$) of the substituents. Hence, it is reasonable to divide the experimental ΔG_{eq} value in accordance with the additive scheme:

$$\Delta G_{eq} = \Delta G_{X/Y} + \Delta G_X + \Delta G_Y$$

where ΔG_X and ΔG_Y are the free energies of conformational equilibria of corresponding monosubstituted cyclohexanes, and term $\Delta G_{X/Y}$ reflects the *gauche*-interaction of the substituents in the diequatorial conformation **1B**. A positive sign of $\Delta G_{X/Y}$ means repulsion, a negative one means attraction. Because the ΔG_{eq} values are solvent-dependent (in contrast with ΔG_R) the term $\Delta G_{X/Y}$ is also solvent-dependent. It is most reasonable to use the data in CCl_4 solution, because in solvents of low dielectric constant intramolecular factors dominate conformational equilibria.[†] Calculated $\Delta G_{X/Y}$ values are shown in Table 4.

We shall now discuss the factors which determine the conformational equilibria investigated. The traditional explanation for the increased content of diaxial form in conformational equilibria of 1,2-dihalogenocyclohexanes has generally been connected with polar or electrostatic interactions of substituents.[20-27] This concept has been advanced by a number of authors; nevertheless, it has no predictive power. To evaluate the contribution of the polar factor, we have to inspect the dependence of the $\Delta G_{X/Y}$ values on calculated values of charge-charge interaction, ΔE_μ (Fig. 2). However, quantum mechanical effects, based on a concept of delocalized interaction of localized sets of orbitals,[13] are included in conformational analysis as additional effects to the steric and electrostatic ones. In other words, if the molecular mechanics calculations explain the conformation equilibria observed, there is no need to postulate a more complicated explanation with the introduction of new effects (principle of "Ockham's razor"[53]). Thus, we must include the steric interaction (E_v) in the correlation to decide whether or not there is any need to involve the new effects. Hence, the correct construction of the diagram would be as follows: the experimental points must be plotted in coordinates $\Delta G_{X/Y} - E_v$ vs ΔE_μ (Fig. 2). The straight line $\Delta G_{X/Y} - E_v = \Delta E_\mu$ divides Fig. 2 in two regions: fields of additional attraction and repulsion. Then the ordinate distance from experimental point to border line $\Delta G_{X/Y} - E_v = \Delta E_\mu$ represents the energy of additional *gauche*-interaction, i.e. "effect".

Inspection of Fig. 2 shows impressive results. The values of O/Cl, O/Br and O/I fragments fall on the borderline. Hence, the conformational behaviour of compounds **3**, **4** and **6** can be adequately interpreted in terms of steric and polar interactions. However, the points of O/O and F/I fragments are distinctly in the field of additional attraction and the other points, especially those belonging to S/Cl, S/S, S/Br and Br/Br fragments, are distinctly in the field of additional repulsion.

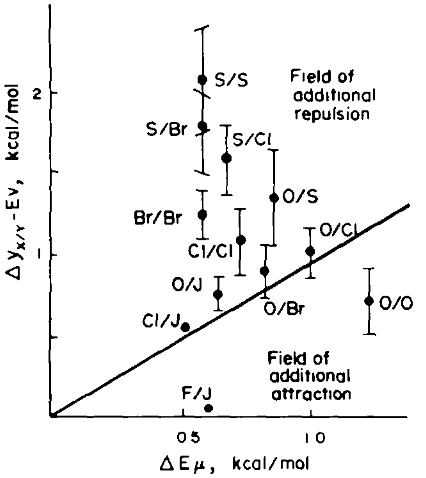


Fig. 2. Relationship between $\Delta G_{X/Y} - E_v$ and ΔE_μ.

In summary, we conclude from the data of Fig. 2 *that conformational behaviour of some compounds investigated can be rationalized only by involving the additional effects*, namely (a) additional attraction for the strong electronegative fragments (O/O, F/I) and (b) additional repulsion for the elements of low periods.

We now turn our attention to the problem of conformational effects. First, we shall consider the so-called "*gauche*-effect". Wolfe *et al.* have given some definitions for this effect;[7-9] probably the most precise one is the following: "*gauche*-effect is a tendency to adopt that structure which has a maximum number of *gauche*-interactions between the adjacent electron pairs and/or polar bond".[8] Criticism of this concept is usually due to misunderstanding, because one accepts this effect as an exact *rule* rather than as a *tendency*. Indeed, if the *gauche*-effect is understood as the *predominance* of the *gauche* form over *trans* in conformation equilibrium of 1,2-disubstituted moiety, one can find a large number of examples which follow this concept and an equally large number of examples which do not follow it.[3,7,8,52,54] In our opinion the *gauche*-effect has to operate as the sharp increasing of *gauche* attraction, which should be additional to the steric and polar factors. We may define the *gauche*-effect as follows: *it is a quantum mechanical effect which operates in 1,2-disubstituted frameworks and introduces such appreciate contribution into stabilization of the* gauche-*form, that it should be adopted as a new, additional term in the equation* (1). Thus, we treat the *gauche*-effect as a phenomenological one. As can be seen from Fig. 2, only two points, O/O and F/I, are shifted in the field of additional attraction. We believe that this shift is due to the "*gauche*-effect", which really operates in the case of strongly electronegative substituents.

Secondly we shall discuss the effects of the additional *gauche* repulsion. Earlier, one of us has suggested that some features of conformational equilibrium of 1,2-*trans*-disubstituted cyclohexanes can be generally interpreted in terms of orbital repulsion of lone pairs of substituents.[10]

In the case of 1,2-disubstituted ethane fragment with the staggered or *gauche* conformation about C–C bond **17**, overlap of lone pair orbitals of X and Y occurs to give bonding and antibonding orbitals occupied by four electrons (Fig. 3). In this case the upper level is destabilized more than the lower one is stabilized and $|E_r| > |E_a|$.[55] Thus such interaction results in relative

---

[†] The most correct procedure is to use the vapor phase energy differences for calculation of *gauche*-interaction term, $\Delta G_{X/Y}$ or even $\Delta H_{X/Y}$; however, these data are available only in rare cases.[16,17]

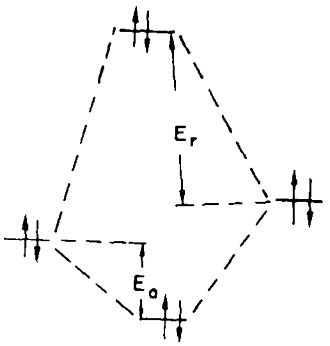
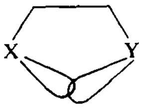
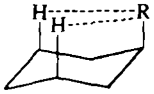


Fig. 3. First-order interaction of two orbitals with overlap included.

instability of the conformation **17**. This repulsive interaction **17** was picturesquely referred to as the "hockey-sticks" effect.[10] An analogous concept has, nearly simultaneously, been stated by Hoffmann[13,14] and by Muller.[56] Hoffmann has developed a more general approach concerning the two types of electronic interaction[13,14] labelled "through-space" and "through-bond" effects. It is evident that the "hockey-sticks" effect is the "through-space" effect applied to conformational problems.



17



18

The most important circumstance for conformational problems is the fact that "through-space" and "through-bond" effects can change relative stabilities of the conformers in opposite directions. This concept has been elegantly developed by Epiotis[15] who showed that "through-bond" orbital interaction can lead to non-bonded attraction in various types of organic molecules and, probably, the "through-bond" interaction is one of the origins of the general phenomenological "*gauche*-effect (see, however, Ref. 15*b*). Hence, the fact of interaction of orbitals as in **17** does not permit *a priori* a conclusion concerning the relative stability of conformers.

Our analysis of the relationship between $\Delta G_{X/Y} - E_v$ vs ΔE_μ reveals that *an additional repulsion of the* gauche-*substituents evidently operates for some of the compounds investigated*; probably the orbital interaction of the "hockey-sticks" type is the origin of this phenomenon. In accordance with the above discussion this effect is especially important for the atoms of lower elements (cf. Refs. 10, 11).

Finally we turn our attention to the general methodological problem of conformational effects. One important statement has to be underlined. A new effect can be inherent in some structural framework and introduced in a *purely phenomenological way as the new additive term in the equation* (1). For example, "rabbit-ears" or "anomeric" effects belong to this category. We also regard the "*gauche*-effect" as phenomenological (*vide supra*). A *phenomenological effect reflects a net result and, thus, can arise as the compromise between opposite real effects*. This leads to a paradoxical situation, because it is impossible to be sure whether some "conformational effect" really exists as the origin of some phenomenon.

We shall illustrate this conclusion using the simplest example. The well-known steric effect of the predominance of equatorial conformation in monosubstituted cyclohexanes is usually tied up with 1,3-R,H-repulsions in the axial conformation (**18**). One may pose the question: does this repulsion actually exist? If this repulsion is regarded as the essence of this phenomenon, the answer, of course, will be yes. However, if this repulsion is regarded as a phenomenological effect, the answer will be maybe yes, maybe no. Indeed, the "net 1,3-R,H-repulsion" may arise as the difference between the 1,2-R,H-attraction in equatorial conformation and 1,3-R,H-attraction in axial conformation. In this case, the 1,3-R,H-interaction would be attractive by nature, whereas it appears phenomenologically as a repulsion.

The same is also correct for the quantum mechanical conformational effects. Let us assume that we compare the energies of the conformers of 1,2-X,X-disubstituted ethanes in the series with different X (e.g. F, Cl, Br, I). Thus $\Delta E_{g\text{-}t} = (E^{attr} + E^{rep})_g - (E^{attr} + E^{rep})_t = \Delta E^{attr}_{g\text{-}t} + \Delta E^{rep}_{g\text{-}t}$ where E^{attr} and E^{rep} are the net attractive and repulsive terms respectively. Further, *assume that attraction is dominant in each case*. However, the difference between the attractive and repulsive terms can either increase or decrease along the series, and will appear as the *net phenomenological effects of attraction or repulsion*. Indeed, the content of the *gauche*-form will increase in the first case and decrease in the second in going along the series. Evidently, the phenomenological "effect of repulsion" does not reflect the origin of the conformational behaviour, because as we assumed above, the attraction is dominant in each case.

To avoid meaningless discussion about "the explanation" of some conformational phenomena, one must differentiate precisely (a) phenomenological effects and (b) effects which reflect the "origin" or "mechanism" of these phenomena. This differentiation should be reflected in nomenclature. We propose to use the terms "*gauche*-attraction" and "*gauche*-repulsion" effects for the phenomenological (non-steric and non-electrostatic) effects, and to keep such terms as "through-space" or probably in some cases "hockey-sticks effects", "through-bond" and "superjacent" effects, "lone pairs attraction or repulsion" effects etc, for dealing with the origin of conformational (or electronic) effects, rationalized in terms of orbital interaction.

CONCLUSION

We attempt to show that (a) there is no simple explanation for the conformational behaviour of the whole series of 1,2-*trans*-disubstituted cyclohexanes, and traditional rationalization in terms of a polar interaction is invalid; (b) the conformational behaviour of these compounds may be rationalized only by involving additional effects, namely, the additional attraction for the strong electronegative substituents (O, F) and the additional repulsion for lower elements (c) dependence on $\Delta G_{X/Y} - E_v$ vs ΔE_μ may be regarded as the methodological basis for introducing the new conformational effects.

More experimental data concerning the conformational equilibria of the compounds discussed and especially more precise molecular mechanics calculations will provide more careful analysis of the importance of the quantum mechanical effects.

EXPERIMENTAL

NMR spectra were recorded on the Varian XL-100 and TA-60 instruments. Synthesis of the following compounds was made according to references cited: **2**[57], **3**[58], **4**[58], **5**[34], **8**[34] and **9**[34]. Synthesis of **7** and **14** were made according to the general procedure.[34] In the first case **7** the mixture has been treated with CH_3COOH and the product has been isolated with chromatography on alumina (pentane: $CHCl_3$-5:3). In the second case **14** the mixture was treated with sodium thiophenolate and the product has also been isolated with chromatography (silica gel; CCl_4. pentane: $CHCl_3$-3:2:2).

General procedure for synthesis of **20**, **11**, *and* **16**. In a typical run, a solution of cyclohexane D_4 (0.34 g) and $AgBF_4$ (0.98 g) in CH_3NO_2–CH_2Cl_2 (3:2) was added to a cooled (−40°) solution of phenylsulphenyl chloride in 4 ml of CH_2Cl_2. Stirring was continued for 5 min at −40° and appropriate nucleophile (CH_3COOH for **10**, tetraethylammonium chloride for **11** and water for **16**) was added. The following work-up included neutralisation with aq sodium bicarbonate, extraction with chloroform, washing with water, drying and purification.

1-*Chloro-2-methoxycyclohexane* **3**. A slight excess of chlorine was bubbled through a stirred mixture of cyclohexene (3 g) and Ag_2O (12 g) in 150 ml of dry MeOH at 0°. Usual work-up gave **3** (1.2 g), b.p. 59–60°/10 mm, n_D^{20} 1.4680 (Found: C, 56.23; H, 8.57. $C_7H_{13}ClO$ requires: C, 56.54; H, 8.81%). **3**-D_4 was synthesized in an analogous manner.

1-*Iodo-2-methoxycyclohexane* **6**. 13.2 g of iodine was slowly added to a stirred mixture of cyclohexene (3 g) and Ag_2O (12 g) in 250 ml of dry MeOH at 0°. The mixture was stirred for 2 h and left standing overnight. The usual work-up gave 2.2 g of **6**, b.p. 65–67°/25 mm n_D^{21} 1.526 (Found: C, 35.07; H, 5.55. $C_7H_{13}IO$ requires: C, 35.0, H, 5.46%). **6**-D_4 was synthesized analogously.

1-*Chloro-2-phenylselenocyclohexane* **12**. 5 g of cyclohexene was slowly added to the stirred solution of 2 g of phenylselenenyl chloride in 15 ml of CCl_4. The mixture was stirred for 5 h and left, standing overnight. The solvent was removed *in vacuo* and residue was chromatographed on alumina (hexane: ether-2:1). The solvents were removed *in vacuo* and the resulting oil was distilled to give 1.8 g of **12**, b.p. 137–140°/2 mm, n_D^{20} 1.5996 (Found: C, 56.23; H, 8.57. $C_{12}H_{15}ClSe$ requires: C, 52.67; H, 5.52%).

Acknowledgements—We are indebted to Profs. N. Epiotis, V. I. Minkin, V. A. Smit and S. Wolfe for most helpful comments and discussions. The authors are very grateful to Marjorie Moore for help in the translation of our manuscript.

REFERENCES

[1] E. L. Eliel, N. L. Allinger, S. J. Angyal and G. A. Morrison, *Conformational Analysis*, Wiley-Interscience, New York (1965).

[2] N. L. Allinger, J. A. Hirsch, M. Miller and I. J. Tyminski, *J. Am. Chem. Soc.* **91**, 337 (1969); N. L. Allinger, M. T. Tribble, M. A. Miller and D. H. Wertz, *Ibid.* **93**, 1637 (1971); I. B. Blackburne, R. P. Duke, R. A. Y. Jones, A. R. Katritzky and K. A. F. Record, *J. Chem. Soc., Perkin II* 332 (1973); and references therein.

[3a] R. J. Abraham and K. Parry, *J. Chem. Soc.* (*B*), 539 (1970); [b] R. J. Abraham and P. Loftus, *Chem. Comm.* 180 (1974).

[4a] Reviews: N. S. Zefirov and N. M. Shechtman, *Usp. Khim.* **40**, 593 (1971); J. C. Martin *Ann. Chim.* **6**, 205 (1971); [b] G. A. Jeffrey, J. A. Pople and L. Radom, *Carbohydrate Research* **25**, 117 (1972); S. David, O. Eisenstein, W. J. Hehre, L. Salem and R. Hoffmann, *J. Am. Chem. Soc.* **95**, 3806 (1973).

[5] E. L. Eliel and C. Giza, *J. Org. Chem.* **33**, 3754 (1968); E. L. Eliel, *Kem. Tidskr.* **81**, 22 (1969); R. O. Hutchins, L. D. Kopp and E. L. Eliel, *J. Am. Chem. Soc.* **90**, 174 (1968); E. L. Eliel, *Accounts Chem. Res.* **3**, 1 (1970).

[6] N. K. Kochetkov, A. F. Bochkov, B. A. Dmitriev, A. I. Usov, O. S. Chizhov and V. I. Shibaev, *Chemistry of Carbohydrates*, p. 35, "Chimia" publishers, Moscow, 1967; J. F. Stoddart, *Carbohydrates*, p. 1, Univ. Park Press, London, Baltimore, Vol. 7 (1973).

[7] S. Wolfe, A. Rauk, L. M. Tel and I. G. Csizmadia, *J. Chem. Soc.* (**B**), 136 (1971).

[8] S. Wolfe, *Accounts Chem. Res.* **5**, 102 (1972).

[9] S. Wolfe, L. M. Tel and I. G. Csizmadia, *Can. J. Chem.* **51**, 2423 (1973); S. Wolfe, L. M. Tel, W. J. Haines, M. A. Robb and I. G. Csizmadia, *J. Am. Chem. Soc.* **95**, 4863 (1973).

[10a] N. S. Zefirov, *Zhur. Org. Khim.* **6**, 1761 (1970); [b] N. S. Zefirov, V. S. Blagoveshchensky, I. V. Kazimirchik and N. S. Surova, *Tetrahedron* **27**, 3111 (1971).

[11] N. S. Zefirov, S. V. Rogozina, E. H. Kurkutova, A. V. Goncharov and N. V. Belov, *Chem. Comm.* 260 (1974); N. S. Zefirov, E. N. Kurkutova and A. V. Goncharov, *Zhur. Org. Khim.* **10**, 1124 (1974); N. S. Zefirov and S. V. Rogozina, *Tetrahedron* **30**, 2345 (1974).

[12a] E. L. Eliel, *Angew. Chem. Int. Ed.* **11**, 739 (1972); [b] E. L. Eliel and S. A. Evans, *J. Am. Chem. Soc.* **94**, 8587 (1972); [c] W. L. Szarek, D. M. Vyas, A. M. Sepulchre, S. D. Gero and G. Lukass, *Can. J. Chem.* **52**, 2041 (1974).

[13] R. Hoffmann, *Accounts Chem. Res.* **4**, 1 (1971).

[14a] J. R. Swenson and R. Hoffmann, *Helv. Chim. Acta* **53**, 2331 (1970); C. C. Levin, R. Hoffmann, W. J. Hehre and J. Hudec, *J. Chem. Soc. Perkin II* 210 (1973); R. Hoffmann, A. Imamura and W. J. Hehre, *J. Am. Chem. Soc.* **90**, 1499 (1968); R. Gleiter, E. Heilbronner, M. Hekman and H. Martin, *Chem. Ber.* **106**, 28 (1973); R. Gleiter, *Angew. Chem. Int. Ed.* **13**, 696 (1974); [b] O. Eisenstein, Nguen Trong Anh, Y. Jean, A. Devaquet, J. Cantacuzene and L. Salem, *Tetrahedron* **30**, 1717 (1974).

[15a] N. D. Epiotis and W. Cherry, *Chem. Comm.* 278 (1973); N. D. Epiotis, *J. Am. Chem. Soc.* **95**, 3087 (1973); N. D. Epiotis, D. Bjorkquist, L. Bjorkquist and S. Sarkanen, *Ibid.* **95**, 7558 (1973); N. D. Epiotis, S. Sarkanen, D. Bjorkquist, LàBjorkquist and R. Jates, *Ibid.* **96**, 4075 (1974); [b] P. Kollman, *Ibid.* **96**, 4363 (1974).

[16] R. J. Abraham and T. M. Sivern, *J. Chem. Soc. Perkin II*, 1587 (1972).

[17] R. J. Abraham and Z. L. Rossetti, *Ibid.* 582 (1973).

[18] R. U. Lemieux and J. W. Lown, *Can. J. Chem.* **42**, 893 (1964).

[19] O. D. Ul'yanova and Yu. A. Pentin. *Zhur. Phys. Khim.* **41**, 2675 (1967); A. I. Karelin, Yu. A. Pentin and O. D. Ul'yanova, *Ibid.* **41**, 2681 (1967); P. Klaeboe, J. J. Lothe and K. Lunde, *Acta Chem. Scand.* **11**, 1677 (1957); P. L. Barili, G. Bellucci, G. Berti, P. Marioni and I. Morelli, *J. Chem. Soc. Perkin II* **58** (1972).

[20] C. Altona, H. R. Buys, H. J. Hageman and E. Havinga, *Tetrahedron* **23**, 2665 (1967); H. R. Buys, C. H. Leenwestein and E. Havinga, *Ibid.* **26**, 845 (1970).

[21] C. Altona, H. R. Buys and E. Havinga, *Rec. Trav. Chim.* **85**, 973 (1966).

[22] H. R. Buys and E. Havinga, *Tetrahedron* **24**, 4967 (1968); L. D. Hall and D. L. Jones, *Can. J. Chem.* **51**, 2914 (1973).

[23] H. R. Buys, C. Altona and E. Havinga, *Tetrahedron* **24**, 3019 (1968); R. U. Lemieux and B. Fraser-Reid, *Can. J. Chem.* **43**, 1460 (1965).

[24a] L. D. Hall and D. L. Jones, *Ibid.* **51**, 2914 (1973) and references therein; [b] E. Premuzic and L. W. Reeves, *Ibid.* **40**, 1870 (1962); H. T. Horntvedt and P. Klaeboe, *Ibid.* **25**, 772 (1971); C. Altona, H. J. Hageman and E. Havinga, *Spectrochem. Acta* **24A**, 633 (1968); J. Thorbjornsrud and P. Klaeboe, *Acta Chem. Scand.* **25**, 781 (1971); T. Torgrimsen and P. Klaeboe, *Ibid.* **25**, 1915 (1971).

[25] N. O. Brace, *J. Am. Chem. Soc.* **86**, 665 (1964).

[26] H. A. Smith and F. P. Byrne, *Ibid.* **72**, 4406 (1950).

[27] A. N. Shidlowskaya, Ya. K. Syrkin, I. N. Nazarov and B. F. Kucherov, *Dokl. Akad. Nauk SSSR* **118**, 967 (1956).

[28] N. S. Zefirov, V. N. Chekulaeva and A. I. Belozerov, *Tetrahedron* **25**, 1997 (1969); N. S. Zefirov, V. N. Chekulaeva, N. M. Sergeev and L. G. Gurvich, *Dokl. Akad. Nauk SSSR* **190**, 345 (1970).

[29] J. P. Aycard, H. Bodot, R. Garnier, R. Lauricella and G. Pauzard. *Org. Magn. Res.* **2**, 7 (1970).

[30] E. A. Vorob'ev, L. G. Gurvich, N. S. Zefirov, N. Z. Kirimer and V. A. Smit, *Zhur. Org. Khim.* **10**, 883 (1974).

[31] S. Wolfe and P. Cambell, *Can. J. Chem.* **43**, 1184 (1965).

[32] N. S. Zefirov and V. N. Chekulaeva, *Vestn. Moscow Univ.*, Chimia, 117 (1968).

[33] V. R. Kartashov, I. V. Bodrikov, F. V. Skorobogatova and N. S. Zefirov, *Int. J. Sulfur Chem.* **9**, N2 (1974); and references therein.

[34] N. Z. Krimer, V. A. Smit and A. A. Schamschurin, *Dokl. Akad. Nauk, SSSR*, **208**, 864 (1967).

[35] N. M. Viktorova, M. A. Fedorovskaya and N. S. Zefirov, *Zhur. Org. Khim.* **9**, 1334 (1973); N. S. Zefirov, M. A. Fedorovskaya and T. P. Godunova, *Zhur. Org. Khim.* **10**, 626 (1974); N. M. Viktorova, S. P. Knyazev, N. S. Zefirov, Yu. D. Gavrilov, G. M. Nikolaev and V. F. Bystrov, *Org. Magn. Res.* **6**, 236 (1974).

[36] O. Bastiansen, O. Hassel and A. Munthe-Kass, *Acta Chem. Scand.* **8**, 872 (1954).

[37] O. Hassel and E. Wang Zund, *Acta Cryst.* **2**, 309 (1949).

[38] V. A. Atkinson and K. Thurmann- Moe, *Acta Chem. Scand.* **14**, 497 (1960).

[39] V. I. Minkin, O. A. Osipov and Yu. A. Zhdanov, *Dipole moments in organic chemistry*, Chimia, Leningrad (1968).

[40] T. L. Hill, *J. Chem. Phys.* **16**, 399 (1948).

[41] B. E. Smart, *J. Org. Chem.* **38**, 2039 (1973).

[42] E. Benedetti, P. Corradini and C. Pedone, *J. Am. Chem. Soc.* **91**, 4075 (1969).

[43] R. D. Stolow, D. I. Lewis and P. A. D'Angelo, *Tetrahedron* **26**, 5831 (1970).

[44] O. A. Osipov, V. I. Minkin and A. D. Garnovsky, *List of dipole moments*, "Vysshaya shkola"—publ., Moscow, (1971).

[45] J. A. Pople and M. S. Gordon, *J. Am. Chem. Soc.* **89**, 4253 (1967).

[46] F. R. Jensen and C. H. Bushweller, In *Advances in Alicyclic Chemistry* (Edited by H. Hart and G. C. Karabatsos), Vol. 3, p. 139. Academic Press, New York (1971).

[47] F. R. Jensen, C. H. Bushweller and B. H. Beck, *J. Am. Chem. Soc.* **91**, 344 (1969).

[48] J. Hirsh, In *Topics in Stereochemistry* (Edited by L. Allinger and E. L. Eliel (Russian translation), Vol. 1 and 2, p. 199. "MIR", Moscow (1970).

[49] M. Anteunis, D. Tavernier and F. Borremans, *Bull. Soc. Chim. Belg.* **75**, 396 (1966).

[50] H. R. Buys, H. J. A. De Vries, H. J. Hageman and C. Altona, *Rec. Trav. Chim.* **89**, 245 (1970); H. Bodot, D. D. Dicko and Y. Gounelle, *Bull. Chim. Soc. Fr.* 870 (1970); P. Buckley, P. A. Giguere and M. Schneider, *Can. J. Chem.* **47**, 901 (1969); A. D. Bowl, D. J. Chadwick and G. D. Meakins, *Chem. Comm.* 1624 (1971).

[51] C. Altona and H. J. Hageman, *Rec. Trav. Chim.* **87**, 279 (1968); E. L. Eliel and O. Hofer, *J. Am. Chem. Soc.* **95**, 8041 (1973).

[52] L. Phillips and V. Wray, *Chem. Comm.* 90 (1970).

[53] Stanislaw Lem, "*Summa technologiae*" (Russ. Translation), p. 82. "MIR", Moscow (1968).

[54] H. Bodot, A. Leray, L. Pujol, *Bull. Soc. Chim. Fr.* 251 (1968); R. J. Abraham and J. P. Monasterios, *Org. Magn. Res.* **5**, 305 (1973); L. H. L. Chia, Eng Huang and Hsing-Hua Huang, *J. Chem. Soc. Perkin II*, 766 (1973).

[55] See, for example, L. Salem, *J. Am. Chem. Soc.* **90**, 543 (1968); N. C. Baird and R. M. West, *Ibid.* **93**, 4427 (1971).

[56] K. Müller, *Helv. Chim. Acta* **53**, 1112 (1970).

[57] S. Winnstein and R. B. Henderson, *J. Am. Chem. Soc.* **65**, 2196 (1943); C. O. Guss and R. Rosenthal, *Ibid.* **77**, 2549 (1955).

[58] G. L. Grady and S. K. Chohshi, *Synthesis* **9**, 483 (1972).