of dichlorofluorescein indicator (0.1% in 70% aqueous ethanol). The resulting mixture was titrated to a pink end point with 0.0453 *M* AgNO$_3$ solution.[31] For early points with small titer, 5 ml of 0.01678 *M* NaCl (dried at 120° for 12 hr) solution was added by pipet to make the end point easier to see. The titer for this NaCl (1.85 ml) was subtracted from the observed titer to obtain the titer due to product. Infinity points were taken after at least 10 half-lives either at reaction temperature or at some higher temperature. The rate constant for a run is the average of first-order rate constants calculated for each point.

In one run (90) 0.05 g of Pyrex No. 7220 glass wool (Corning No. 3950) was forced into each ampoule after the CH$_3$Cl had been introduced. Although care was taken not to contact the liquid CH$_3$Cl, some loss no doubt occurred, since removal of the stopper for several minutes was necessary. For sampling, the ampoule was cracked open and the glass wool removed by a forceps and placed on the filter. The remaining contents of the ampoule was filtered and then the glass wool was tamped. In other respects this run was carried out just as the others.

---

[31] L. F. Hamilton and S. G. Simpson, "Quantitative Chemical Analysis," Macmillan, New York, N. Y., 1964, p 295.

Conformational Dependence of Homoallylic H–H Coupling Constants

M. Barfield*[1] and S. Sternhell

Contribution from the Department of Chemistry, University of Arizona, Tucson, Arizona 85721, and the Department of Organic Chemistry, University of Sydney, Sydney, New South Wales 2006, Australia.

Received July 12, 1971

Abstract: A theoretical study of the conformational dependence of long-range H–H coupling over four single bonds and one double bond (homoallylic coupling) is presented in terms of the semiempirical valence-bond (VB) theory as well as self-consistent perturbation theory in the INDO (intermediate neglect of differential overlap) approximation of the self-consistent-field molecular orbital (SCF–MO) formalism. Either of these theoretical formulations provides an adequate description of the conformational dependence of homoallylic H–H coupling in molecules of rigid geometry and can be used in the solution of stereochemical problems. However, the INDO–MO method, which includes all of the valence electrons, correctly predicts that the homoallylic coupling constants in *trans*-2-butene should be larger than in *cis*-2-butene. The VB method, which only included the π-electron mechanism, gives identical coupling constants for these two molecules. The advantage of the INDO–MO method arises because the inclusion of all valence electrons gives rise to additional mechanisms. For example, a comparison of the VB and MO results indicates that the major factor responsible for the differences between cisoid and transoid homoallylic coupling constants is a *direct mechanism of negative sign*, which arises for *cis*-2-butenes because of the proximity of the bonds containing the coupled nuclei. A discussion is also given of the effects of substituents on the magnitude of the homoallylic coupling constants.

Nuclear spin–spin coupling constants over four single bonds and one double bond are said to be of the homoallylic[2] type between protons H$_A$ and H$_B$ in the system H$_A$—C$_1$—C$_2$=C$_3$—C$_4$—H$_B$ with carbon atoms C$_1$ and C$_4$ having tetrahedral hybridization. Although this type of coupling has been observed extensively,[3-6] theoretical studies[7-10] have dealt with this type of coupling as only one aspect of the general long-range coupling constant phenomenon in which the dominant mechanisms are σ–π configuration interaction (exchange in valence-bond terminology) and delocalization in the π-electron system. For a C–H bond β to the double bond the interaction has a $\sin^2\phi$ dependence on the dihedral angle, ϕ. Since there are two such interactions in the homoallylic fragment, this type of coupling constant should have a $\sin^2\phi \sin^2\phi'$ dependence on the dihedral angles ϕ and ϕ'. Both of these angles are measured in the same sense relative to the plane formed by the four carbon atoms of the 2-butene fragment. This situation is depicted in Figure 1. An angular dependence of this type is entirely consistent with the gross features of homoallylic H–H coupling[3-6] but it does not account, for example, for the well-documented difference between the homoallylic coupling constants in *cis*- and *trans*-2-butenes.[11,12] These differences have been attributed to contributions from a σ-electron mechanism, which will be larger for the all trans arrangement of the bonds linking the coupled nuclei.[13,14]

---

[1] Author to whom enquiries should be directed at the University of Arizona.

[2] J. T. Pinhey and S. Sternhell, *Tetrahedron Lett.*, 275 (1963).

[3] S. Sternhell, *Rev. Pure Appl. Chem.*, 14, 15 (1964).

[4] M. Barfield and B. Chakrabarti, *Chem. Rev.*, 69, 757 (1969).

[5] L. M. Jackman and S. Sternhell, "Applications of NMR Spectroscopy in Organic Chemistry," Pergamon Press, New York, N. Y., Chapter 4-4.

[6] S. Sternhell, *Quart. Rev., Chem. Soc.*, 23, 236 (1969).

[7] M. Karplus, *J. Chem. Phys.*, 33, 1842 (1960).

[8] M. Barfield, *ibid.*, 48, 4463 (1968).

[9] W. J. van der Hart, *Mol. Phys.*, 20, 399 (1971).

[10] A. V. Cunliffe, R. Grinter, and R. K. Harris, *J. Magn. Resonance*, 3, 299 (1970).

[11] The terms cisoid and transoid will be used in this study to distinguish between the cases in which the coupling is associated with molecules in which the C$_1$ and C$_4$ carbon atoms are on the same or opposite sides of the double bond, respectively. These terms are used consistently to avoid confusion with cis and trans coupling constants in cyclic systems. For notational convenience, cisoid and transoid coupling constants will be differentiated in the left superscript, *i.e.*, $^{5c}J_{HH'}$ and $^{5t}J_{HH'}$.

[12] M. Barfield, R. J. Spear, and S. Sternhell, *J. Amer. Chem. Soc.*, 93, 5322 (1971).

[13] H. Frischleder and G. Bär, *Mol. Phys.*, 11, 359 (1966).

[14] M. Barfield and M. Karplus, *J. Amer. Chem. Soc.*, 91, 1 (1969).

Table I. Calculated INDO–MO and VB Results for Homoallylic H–H Coupling Constants in *cis*- and *trans*-2-Butene Tabulated as a Function of 30° Intervals of the Dihedral Angles, ϕ and ϕ'

ϕ, deg	ϕ', deg	INDO $^{5c}J_{HH'}$, Hz	INDO $^{5t}J_{HH'}$, Hz	VB $^{5}J^{\pi}{}_{HH'}$, Hz
0	0	−0.764	0.031	0.000
	30	−0.821	0.094	0.000
	60	−0.245	0.202	0.000
	90	0.245	0.274	0.000
	120	0.117	0.191	0.000
	150	−0.244	0.077	0.000
	180	−0.402	0.014	0.000
	210	−0.244	0.077	0.000
	240	0.117	0.191	0.000
	270	0.245	0.274	0.000
	300	−0.245	0.202	0.000
	330	−0.821	0.094	0.000
30	30	−0.032	0.492	0.312
	60	0.756	1.264	0.936
	90	1.481	1.572	1.248
	120	1.482	1.078	0.936
	150	0.597	0.301	0.312
	180	−0.067	0.059	0.000
	210	0.119	0.625	0.312
	240	0.911	1.486	0.936
	270	1.693	1.819	1.248
	300	1.451	1.371	0.936
	330	0.035	0.490	0.312
60	60	2.796	3.372	2.807
	90	4.010	4.562	3.742
	120	3.477	3.362	2.807
	150	1.482	1.268	0.936
	180	0.219	0.152	0.000
	210	0.958	1.290	0.936
	240	2.867	3.437	2.807
	270	4.168	4.738	3.742
	300	3.575	3.567	2.807
	330	1.451	1.371	0.936
90	90	5.205	6.140	4.990
	120	4.128	5.039	3.742
	150	1.612	2.108	1.248
	180	0.232	0.263	0.000
	210	1.440	1.285	1.248
	240	3.942	4.124	3.742
	270	5.263	5.920	4.990
	300	4.169	4.738	3.742
	330	1.693	1.819	1.248
120	120	2.827	4.217	2.807
	150	1.012	2.020	0.936
	180	0.196	0.285	0.000
	210	1.351	0.719	0.936
	240	3.172	2.593	2.807
	270	3.942	4.124	3.742
	300	2.867	3.437	2.807
	330	0.911	1.486	0.936
150	150	0.327	1.150	0.312
	180	0.135	0.289	0.000
	210	0.663	0.144	0.312
	240	1.351	0.719	0.936
	270	1.441	1.285	1.248
	300	0.958	1.290	0.936
	330	0.119	0.625	0.312
180	180	0.091	0.278	0.000
	210	0.135	0.289	0.000
	240	0.196	0.285	0.000
	270	0.232	0.263	0.000
	300	0.219	0.152	0.000
	330	−0.066	0.059	0.000
210	210	0.327	1.150	0.312
	240	1.012	2.020	0.936
	270	1.612	2.108	1.248
	300	1.482	1.268	0.936
	330	0.597	0.301	0.312
240	240	2.827	4.217	2.807
	270	4.128	5.038	3.742
	300	3.477	3.362	2.807
	330	1.482	1.078	0.936
270	270	5.205	6.140	4.990
	300	4.010	4.562	3.742
	330	1.481	1.573	1.248
300	300	2.796	3.372	2.807
	330	0.756	1.264	0.936
330	330	−0.031	0.492	0.312

The present study provides an alternative to the existing VB results in terms of all-valence electron calculations using self-consistent perturbation theory[15] in the semiempirical INDO approximation[16,17] of unrestricted SCF–MO theory. The calculated results are compared with a large number of experimental values. The effect of substituents is discussed in those cases in which conformational factors are expected to remain constant. The implications of these results for the mechanisms of homoallylic coupling are discussed.

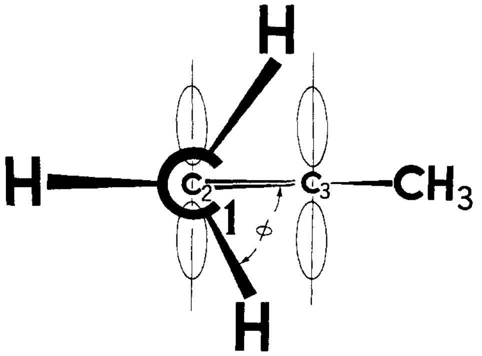


Figure 1. A fragment of the *cis*-2-butene molecule. The dihedral angle ϕ is measured in a clockwise sense from the C_1–C_2–C_3 plane. The dihedral angle ϕ' is measured in the same sense from the C_2–C_3–C_4 plane.

Computational Methods

The VB results[8] for homoallylic coupling constants were based on a previously developed formalism,[18] which includes a sum over VB triplet states in the second-order perturbation expression for the contact nuclear spin–spin coupling constant. For a six-electron homoallylic fragment, consisting of the two C–H bonds containing the coupled nuclei and the π

---

[15] J. A. Pople, J. W. McIver, Jr., and N. S. Ostlund, *J. Chem. Phys.*, **49**, 2960, 2965 (1968).

[16] J. A. Pople, D. L. Beveridge, and P. A. Dobosh, *ibid.*, 47, 2026 (1967).

[17] Program 142, Quantum Chemistry Program Exchange, Bloomington, Ind.

[18] M. Barfield, *J. Chem. Phys.*, **48**, 4458 (1968).

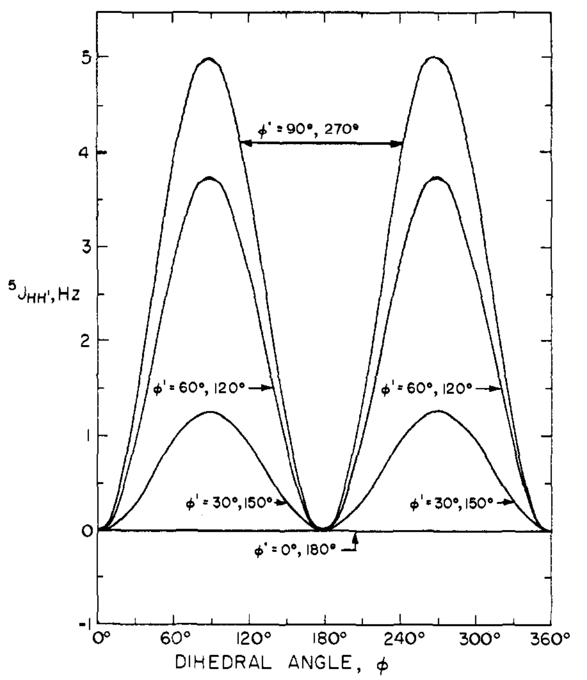


Figure 2. Calculated valence-bond results for $^5J_{HH'}$ in the *cis*- and *trans*-2-butene molecules plotted as a function of the dihedral angles ϕ and ϕ'.

bond, the π-electron contributions are adequately represented by the expression

$$^5J^{\pi}_{HH'}(\phi,\phi') = 4.99 \sin^2 \phi \sin^2 \phi' \qquad (1)$$

where ϕ and ϕ' denote the dihedral angles which are depicted in Figure 1. Contributions from the σ-electron framework were not included in these calculations[8] because the size of the secular determinants increases enormously with the size of the basis set, and because of the inherent difficulty of finding suitable semiempirical parameters for the σ-electron system.[4,19]

The mathematical details of the self-consistent perturbation method for coupling constants in the semiempirical INDO approximation have been discussed in a large number of papers[15,20–22] and will not be reproduced here. Conceptually, the method is quite simple. The Fermi contact perturbation associated with one of the coupled nuclei is *added* to the diagonal element for the s orbital centered on the nucleus in the Fock matrix for α spin. This perturbation is *subtracted* from the corresponding element of the Fock matrix for electrons of β spin. This has the effect of inducing a very small spin density throughout the molecular electronic system. The nuclear spin–spin coupling constant is proportional to the value of this spin density at the second nucleus.

In all of the calculations which are reported here, standard bond angles and bond lengths were used.[23] All calculations were performed on a Control Data Corp. 6400 digital computer.

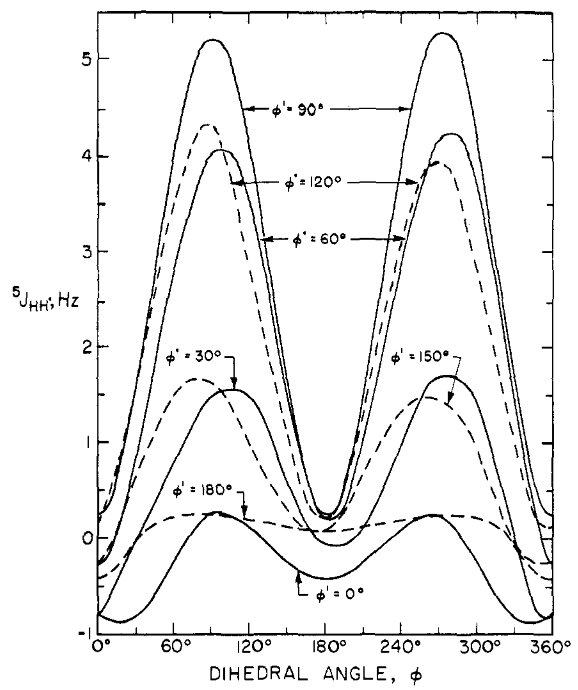


Figure 3. Calculated results for homoallylic coupling in the *cis*-2-butene molecule plotted as a function of the dihedral angles ϕ and ϕ'. These results are based on self-consistent perturbation theory and INDO wave functions.

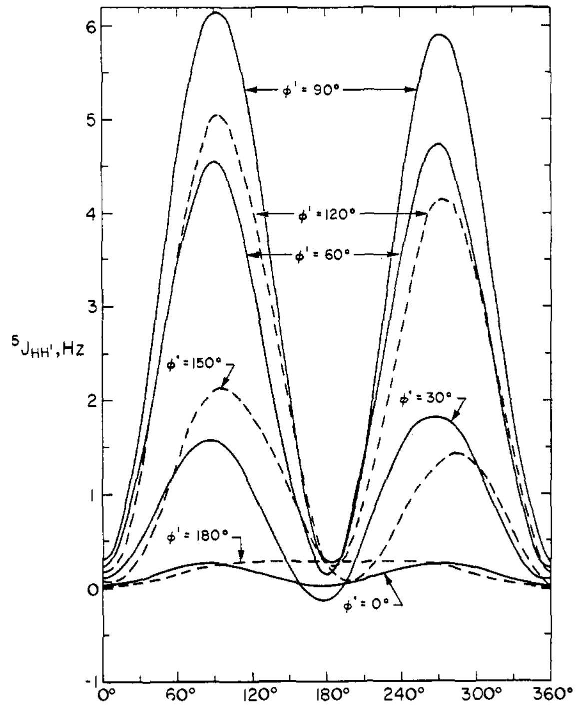


Figure 4. Calculated INDO results for $^5J_{HH'}$ in *trans*-2-butene plotted as a function of the dihedral angles ϕ and ϕ'.

Comparison of Calculated and Experimental Results

The calculated INDO-MO and VB results for *cis*- and *trans*-2-butene are entered in Table I for 30° increments of the dihedral angles, ϕ and ϕ'. The data from the table are plotted in Figures 2–4 as a function of the dihedral angles. A comparison of the MO results for *cis*- and *trans*-2-butene in Figures 3 and 4,

---

(19) M. Barfield and D. M. Grant, *Advan. Magn. Resonance*, 1, 149 (1965).

(20) G. E. Maciel, J. W. McIver, Jr., N. S. Ostlund, and J. A. Pople, *J. Amer. Chem. Soc.*, **92**, 1, 11, 4151, 4506 (1970).

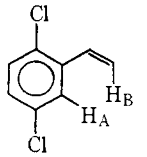
(21) M. Barfield, *ibid.*, **93**, 1066 (1971).

(22) M. D. Johnston, Jr., and M. Barfield, *J. Chem. Phys.*, **54**, 3083 (1971); **55**, 3483 (1971).

(23) Angles were taken to be either trigonal or tetrahedral; r(C=C) = 1.337 Å, r(=C—H) = 1.08 Å, r(-C—H) = 1.09 Å, and for consistency with the calculations in ref 12, r(C—C) = 1.54 Å.

respectively, with the VB results in Figure 2 indicates small but significant deviations from the double periodicity (*i.e.*, the symmetrical appearance of all of the curves in Figure 2 is lost). This asymmetry was noted previously[12] for cis ($\phi = \phi' = 120°$) and trans ($\phi = 120°$, $\phi' = 240°$) homoallylic coupling constants in *cis*-2-butene and representative five-membered rings. This difference was rationalized[24] in terms of a qualitative MO description and it was shown[12] that differences between the cis and trans coupling constants are unusually sensitive to substitution at the C_1 and C_4 carbon atoms.

A particularly interesting feature of the calculated INDO–MO results for $^{5c}J_{HH'}$ in *cis*-2-butene is the appearance of negative values for orientations corresponding to the closest possible approach ($\phi = 0°$, $\phi' = 0°$) of the coupled nuclei. There is also another minimum ($\phi = 0°$, $\phi' = 180°$) corresponding to one of the C–H bonds being twisted by 180°. It is tempting to conclude that these results provide substantial theoretical evidence for the occurrence of a direct mechanism for coupling between the protons.[14] Since the VB results are based on the assumption that only nearest neighbor interactions are important, any type of *direct* interaction would not be implicit in the calculations for coupling over four or more bonds. In a VB study[25] of coupling over four bonds one of the authors concluded that a direct mechanism of negative sign for certain proximate orientations of the bonds containing the coupled nuclei would bring the experimental and theoretical results into consistency. In a recent study[26] of long-range coupling in ring-substituted styrenes, a negative coupling, $^5J(H_A,H_B)$, was theoretically predicted and experimentally observed in 2,5-dichlorostyrene (**1**), corresponding to the closest possible approach for the coupled nuclei. A negative direct mechanism for coupling over five bonds also helps to resolve the apparent difficulty that the sum of the π-electron[7–10] and σ-electron contributions[13,14,25] gives values which are too large.



1

The INDO–MO results for coupling in the all trans arrangement of the coupled nuclei ($\phi = \phi' = 180°$ for *trans*-2-butene in Table I) is only 0.278 Hz. Thus, it must be concluded that the larger differences, which are observed between cisoid and transoid coupling constants, are, at least partially, attributable to the negative direct mechanism which occurs for the cisoid case.

Table II. Calculated INDO–MO and VB Results for Homoallylic Coupling Constants in *cis*- and *trans*-2-Butene for the Case in Which One of the Methyl Groups Assumes the Equilibrium Conformation[a]

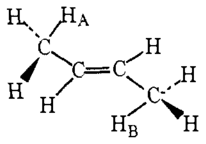
ϕ, deg	$^{5c}J_{HH'}$(INDO), Hz	$^{5t}J_{HH'}$(INDO), Hz	$^{5}J_{HH'}$(VB), Hz
0	−0.143	0.137	0.000
30	0.524	0.886	0.624
60	2.033	2.334	1.871
90	2.772	3.145	2.495
120	2.039	2.334	1.871
150	0.706	0.939	0.624
180	−0.003	0.200	0.000

[a] The values in this table were computed from eq 2 and the data in Table I.

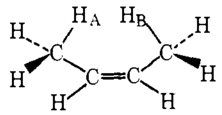
Coupling in *cis*- and *trans*-2-Butenes. Calculated INDO–MO and VB results are collected in Table II for the cases in which one of the coupled protons can assume all of the orientations associated with a methyl group. Rather than using the more complicated procedure of averaging over the barriers which hinder free rotation of the methyl group,[19] the usual expedient of averaging over the coupling constants in the equilibrium conformation was used here. For the case in which one of the C–H bonds eclipses the double bond ($\phi' = 0°$), the cisoid and transoid coupling constants were calculated from the expression

$$^5J_{HH'}(\phi) = \frac{1}{3}[^5J_{HH'}(\phi, 0°) + 2 \cdot {}^5J_{HH'}(\phi, 120°)] \quad (2)$$

and entered in Table II. In those cases in which both of the coupled nuclei can assume all of the orientations available to a methyl group, *i.e.*, *cis*- and *trans*-2-butenes, the homoallylic coupling constants are computed as the average value for the nine possible relative orientations. From electron diffraction and microwave studies,[27] it is clear that *trans*-2-butene and *cis*-2-butene have the structures **2** and **3**, respectively, in which two protons (H_A and H_B) have $\phi = \phi' = 0°$.



2



3

In the case of *cis*-2-butene it appears that the strain produced by the repulsion of the two protons is relieved by increases in the C=C—C angles.[27] For the equilibrium conformations **2** and **3** the average values based on the INDO–MO results in Table I are 1.30 and 1.60 Hz for the *cis*- and *trans*-2-butene coupling constants, respectively. The corresponding experimental values are 1.198 ± 0.009 and 1.592 ± 0.009 Hz.[28] In view of the approximate nature of these calculations, it did not seem worthwhile to attempt a detailed investigation of the dependence of the cisoid homoallylic coupling constants on the geometrical factors which relieve the strain produced by the crowding of the two proximate protons. In all of the 2-butene derivatives in which we were able to find $^{5t}J_{HH'} > {}^{5c}J_{HH'}$, and where signs of homoallylic coupling constants have been determined,[3–6] they were found to be positive.

Homoallylic coupling involving a methyl group in fragments where ϕ is well defined constitutes an important group from the point of view of structural

---

(24) C. Barbier, D. Gagnaire, and P. Vottero, *Bull. Soc. Chim. Fr.*, 2330 (1968); D. Gagnaire and P. Vottero, *ibid.*, 164 (1970).

(25) M. Barfield, *J. Chem. Phys.*, 41, 3825 (1964).

(26) M. Barfield, C. J. Macdonald, I. R. Peat, and W. F. Reynolds, *J. Amer. Chem. Soc.*, **93**, 4195 (1971).

(27) A. Almenningen, I. M. Anfinsen, and A. Haaland, *Acta Chem. Scand.*, **24**, 43 (1970); S. Kondo, Y. Sakurai, E. Hirota, and Y. Morino, *J. Mol. Spectrosc.*, **34**, 231 (1970).

(28) F. H. A. Rummens and L. Kaslander, private communication, 1971. Values close to these were reported by R. K. Harris and R. R. Howes, *ibid.*, **28**, 191 (1968), and H. G. Hecht and B. L. Victor, *J. Amer. Chem. Soc.*, **90**, 3333 (1968).

Table III. Comparison of Experimental and Calculated Homoallylic Coupling Constants in Compounds of Defined Geometry

Compd	Interacting protons	ϕ, deg	ϕ', deg	Homoallylic coupling constants, Hz			Ref
				Exptl	INDO	VB	
4	$2, 5_\beta$	120	120	2.2	2.827	2.807	31
	$2, 5_\alpha$	120	240	3.8	3.172	2.807	
5	$2, 5_\alpha$	120	120	2.2	2.827	2.807	31
	$2, 5_\beta$	120	240	3.1	3.172	2.807	
6a	$9_\alpha, 12_\beta$	100	260	3.5	4.7	4.6	32
	$9_\alpha, 12_\alpha$	100	140	2.9	2.3	1.7	
6b	$9_\alpha, 12_\alpha$	140	100	2.0	2.3	1.7	32
	$9_\alpha, 12_\beta$	140	220	<1	1.2	0.8	
7	$9_\alpha, 12_\alpha$	140	100	1.5	2.3	1.7	*a*
	$9_\alpha, 12_\beta$	140	220	<1	1.2	0.8	
8	3, 8	120 }[b]	120 }[b]	3.0	4.2 }3.4[b]	2.8	*c*
		120	240		2.6	2.8	
		120 }[d]	100 }[d]		4.9 }3.2[d]	3.6 }2.6[d]	
		120	220		1.5	1.5	
		120	140		2.6	1.5	
		120	260		3.8	3.6	
9	1, 4	180	120	0.0	0.2	0	*e*
	1, 4′	180	240	0.0	0.2	0	
10	15, 17	100	220	2.5	2.3	1.9	*g*
	15, 26	100	*f*	2.0	3.0	2.4	
11	2, 5	90	110	4.5	4.8	4.4	*h*
	2′, 5	210	110	1.5	1.4	1.1	
12	2, 4	120	150	~0	1.1	0.9	*i*
	3, 4	240	150	~2.5	1.5	0.9	
13	1, 4	150	100	1	1.5	1.2	*j*
14	3, 12	130	100	2.30 ± 0.02	2.9	2.5	*k*
	3′, 12	250	100	4.68 ± 0.02	4.4	4.2	
15a	6′, 8′	105	140	2.3 ± 0.2	2.2	1.9	*l*
15b	6′, 8′	70	210	1.6 ± 0.1	1.2	1.2	*l*
16a	6, 14	80	110	2.6	4.5	4.1	*m*
16b	6, 14	200	110	0	0.8	0.6	*m*
17a	1, 4	120	110	3.10 ± 0.02	3.5	3.3	*n*
		240[o]	110[o]		3.7	3.3	
17b	1, 4	120	110	2.52 ± 0.05	3.5	3.3	*n*
	1′, 4	240	110	3.64 ± 0.05	3.7	3.3	
	R1, 4	*f*	110	2.55 ± 0.05	2.7	2.1	
18	2Me, 4	*f*	120	2	2.3	1.9	*p*
19	3Me, 6	*f*	110	2.6	2.8	2.1	*q*
20a	4Me, 6	*f*	115	1.4	2.2	2.0	2
20b	4Me, 6	*f*	25	<0.5	0.4	0.6	2
21	4 Me, 10	*f*	110	2	2.7	2.1	*r*
	4, Me, 6	*f*	20	0	0.5	0.4	
22	11 Me, 6	*f*	115	1.8	2.2	2.0	*s*
23	19 Me, 21a	*f*	20	<0.5	0.5	0.4	*t*
	19 Me, 21b	*f*	100	2.5	3.0	2.4	
24	1, 4	180	180	≤0.2	0.1	0	*u*
25	1, 4	180	180	1	0.1	0	*v*
26	1, 4	180	180	1–1.4	*w*	*w*	*x*

[a] A. Zeeck and P. Christiansen, *Justus Liebigs Ann. Chem.*, **724**, 172 (1969). [b] Averaged values assuming both rings to be planar. [c] B. M. Goldschmidt, B. L. Van Duuren, and C. Mercado, *J. Chem. Soc. C*, 2100 (1966). For closely related data see G. B. Ansell, D. W. Moore, and A. T. Nielsen, *Chem. Commun.*, 1602 (1970); K. Ichikawa, O. Itoh, and T. Kawamura, *Bull. Chem. Soc. Jap.*, **41**, 1240 (1968); F. H. Greenberg, *J. Org. Chem.*, **30**, 1251 (1965), and H. H. Appel, R. P. M. Bond, and K. H. Overton, *Tetrahedron*, **19**, 635 (1963). The values of transoid homoallylic coupling constants reported in these references for stereochemistry closely related to that in compound **8** range from 1.5 to 5 Hz. [d] Averaged values assuming a planar five-membered ring and a half-chair conformation for the six-membered ring. [e] F. Kaplan, C. O. Schultz, D. Weisleder, and C. Klopfenstein, *J. Org. Chem.*, **33**, 1728 (1968). [f] Averaged for the equilibrium conformation of the methyl group. See eq 2 and Table II. [g] R. Henderson, R. McCrindle, K. H. Overton, and A. Melera, *Tetrahedron Lett.*, 3969 (1964); *Tetrahedron*, **24**, 1525 (1968). [h] R. J. P. Barends, W. N. Speckamp, and H. O. Huisman, *Tetrahedron Lett.*, 5301 (1970). [i] H. Prinzbach, H. Hagemann, J. H. Hartenstein, and R. Kitzing, *Chem. Ber.*, **98**, 2201 (1965). [j] R. U. Lemieux, D. R. Lineback, M. L. Wolfrom, F. B. Moody, E. G. Wallace, and F. Konitsky, *J. Org. Chem.*, **30**, 1092 (1965). For related data, including some sign determinations, see R. J. Abraham, H. Gottschalk, H. Paulsen, and W. A. Thomas, *J. Chem. Soc.*, 6268 (1965); B. Coxon, H. J. Jennings, and K. A. McLauchlan, *Tetrahedron*, **23**, 2395 (1967). [k] E. Winterfeldt, H. Radunz, and P. Strehlke, *Chem. Ber.*, **99**, 3750 (1966). The spectra were rerun in these laboratories using a sample of **14** which was kindly supplied by Professor Winterfeldt. [l] G. C. Brophy, J. Mohandas, M. Slaytor, S. Sternhell, T. R. Watson, and L. A. Wilson, *Tetrahedron Lett.*, 5159 (1969), and unpublished data from these laboratories. [m] T. J. Batterham, K. H. Bell, and U. Weiss, *Aust. J. Chem.*, **18**, 1799 (1965). This reference also contains many other data for related compounds. [n] Q. N. Porter, W. H. Cherry, and S. Sternhell, unpublished results. [o] Alternative configurations at Cl. [p] C. F. H. Allen, *Can. J. Chem.*, **45**, 1201 (1967). The literature contains other examples of five-membered rings with a double bond substituted by a methyl group and not obviously constrained by ring fusion: H. C. Volger, W. Brackman, and J. W. F. M. Lemmers, *Recl. Trav. Chim. Pays-Bas*, **84**, 1203 (1965); P. Bladon, S. McVey, P. L. Pauson, G. D. Broadhead, and W. M. Horspool, *J. Chem. Soc. C*, 306 (1966); P. Pesnelle and G. Ourisson, *J. Org. Chem.*, **30**, 1744 (1965); A. G. Hortmann, D. S. Daniel, and J. Schaefer, *ibid.*, **33**, 3988 (1968); L. van Wijnsberghe and M. Vandewalle, *Bull. Soc. Chim. Belg.*, **79**, 699 (1970). The values of the homoallylic coupling constants range from 1.8 to 2.0 Hz. [q] A. C. G. Gray and H. Hart, *J. Amer. Chem. Soc.*, **90**, 2569 (1968). [r] S. K. Malhotra and F. Johnson, *Chem. Commun.*, 1149 (1968). See also C. W. Shoppee, F. P. Johnson, R. E. Lack, R. J. Rawson, and S. Sternhell, *J. Chem. Soc.*, 2476 (1965). [s] K. Takeda, M. Ikuta, M. Miyawaki, and K. Tori, *Tetrahedron*, **22**, 1159 (1966). See also Y. Tanahashi, Y. Ishizaki, T. Takahashi, and K. Tori, *Tetrahedron Lett.*, 3739 (1968). [t] M. Hesse, W. von Philipsborn, D. Schumann, G. Spiteller, M. Spiteller-Friedmann, W. I. Taylor, H. Schmid, and P. Karrer, *Helv. Chim. Acta*, **47**, 878 (1964). [u] L. Bauer, C. L. Bell, G. C. Brophy, W. A. Bubb, E. B. Sheinen, and S. Sternhell, *Aust. J. Chem.*, in press. [v] L. A. Paquette and G. R. Krow, *J. Amer. Chem. Soc.*, **90**, 7149 (1968). [w] Not applicable. [x] D. Gagnaire and E. Payo-Subiza, *Bull. Soc. Chim. Fr.*, 2627 (1963).

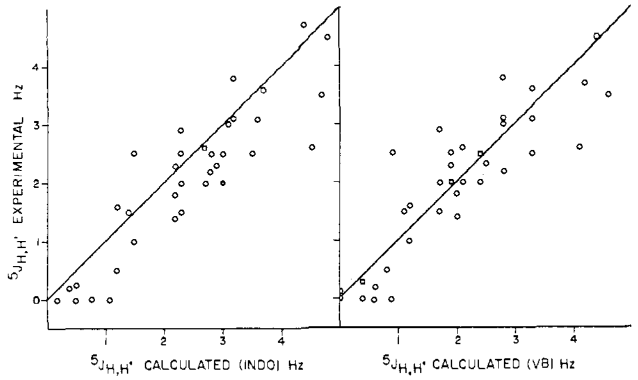
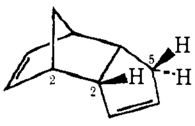


Figure 5. Comparison of experimental and calculated homoallylic coupling constants. The experimental results are taken from Table III. The theoretical INDO and VB results are taken or interpolated from Tables I–II and Figures 2–4. The squares correspond to homoallylic coupling involving a methyl group.

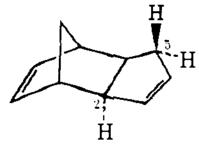
determinations. In fact, the first experimental indication of the steric dependence of homoallylic coupling constants was obtained from systems of this type.[2,29,30] Several sets of such data are entered in Table III. The results are plotted in Figure 5 and identified by squares, the circles being reserved for data on compounds where *both* dihedral angles can be measured. It can be seen that the agreement with calculated values for the two sets of points is comparable, thus providing a further justification for the use of eq 2.

Influence of Geometry. Before comparing the calculated results with experimental data for molecules of more or less rigid geometry, it is important to consider factors limiting the accuracy of the pertinent parameters. In all cases the magnitudes of dihedral angles, ϕ and ϕ', were inferred from Dreiding models. Even though the compounds which are considered here exist in predictable conformations, or have geometries which can be deduced from independent data, *e.g.*, vicinal coupling constants, the combined errors of measurement and uncertainty about the detailed conformation must amount to ±10°, which is the confidence limit adopted in previous studies of this kind.[21,25]

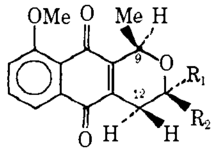
Experimental determinations of homoallylic coupling constants are complicated by difficulties associated with accurate measurements of small spacings between spectral lines,[3–6] which is sometimes further complicated because of the presence of second-order features in the nmr spectra. All experimental data are quoted (Table III) in the manner in which they were presented, but the accuracy implied in cases where no error limits have been quoted is probably unrealistic since the precautions necessary for accurate measurements of small splittings[5,6] are seldom taken in work which is not primarily concerned with nmr spectral analyses. Besides these factors, which are essentially of an experimental nature, an unambiguous comparison of theoretical and experimental results is inherently difficult. The major difficulty is that the calculations are invariably performed for unstrained and unsubstituted molecules or fragments, whereas the experimental results cannot be assumed to be insensitive to substituents and steric factors which are more complicated than a simple torsion about a C–C single bond.



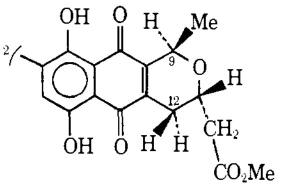
4



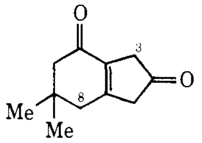
5



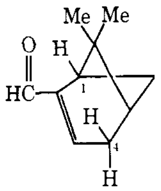
6a, $R_1 = H$; $R_2 = Me$
b, $R_1 = Me$; $R_2 = H$



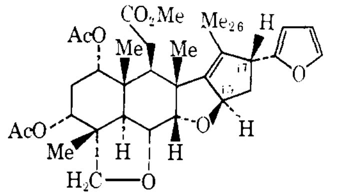
7



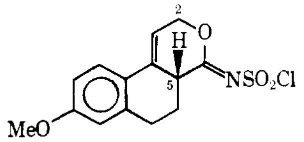
8



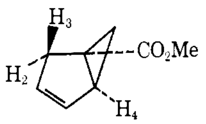
9



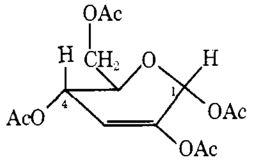
10



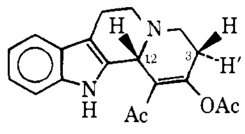
11



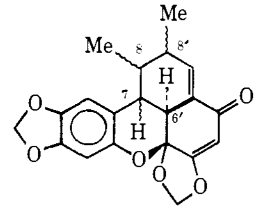
12



13



14



15a, H-7α, 8-Meα, 8′-Meβ
b, H-7β, 8-Meβ, 8′-Meα

The calculated values of homoallylic coupling constants, which are entered in Table III, were obtained by interpolation from Tables I and II and Figures 2–4. Although this procedure will certainly result in some loss of accuracy, this will be a negligible factor in comparison with the inadequacies discussed above. The calculated values, therefore, were rounded off to the nearest 0.1 Hz in most cases. Any greater significance is doubtful.

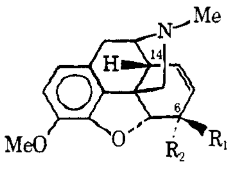
Some of the items in Table III provide additional support for the asymmetry in the coupling constant results which is predicted by the INDO–MO treatment. Thus, in the cyclopentadiene dimers, **4** and **5**, the five-membered rings must be almost perfectly planar because the vicinal ($J_{4,5}$) and allylic ($J_{3,5}$) coupling constants involving $H_{5\alpha}$ and $H_{5\beta}$ are equal.[31] However,

---

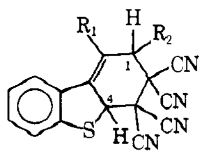
(29) J. T. Pinhey and S. Sternhell, *Aust. J. Chem.*, **18**, 543 (1965).

(30) C. R. Narayanan and N. K. Venkatasubramanian, *Indian J. Chem.*, **2**, 274 (1964).

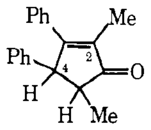
(31) K. C. Ramey and D. C. Lini, *J. Magn. Resonance*, **3**, 94 (1970).



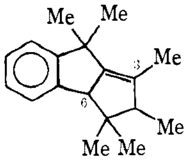
16a, R_1 = H; R_2 = OH
b, R_1 = OH; R_2 = H



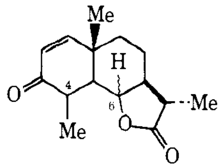
17a, R_1 = H; R_2 = Me
b, R_1 = Me; R_2 = H



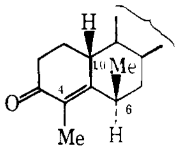
18



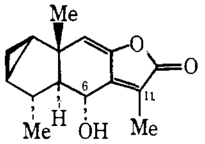
19



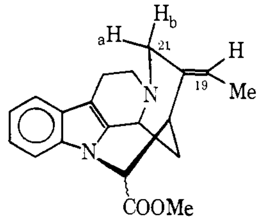
20a, H-6β
b, H-6α



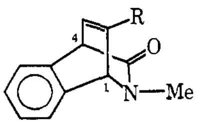
21



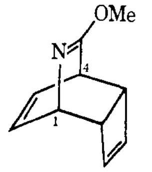
22



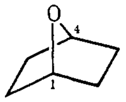
23



24, R = H, Me, Cl,



25

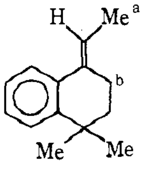


26

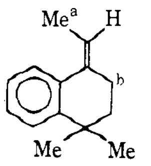
the experimentally measured homoallylic coupling constants differ significantly.[31] This difference is consistent with the INDO–MO results, but not the VB descriptions which only include π-electron mechanisms.[7-10] Similar arguments can be given for the unequal cisoid and transoid homoallylic coupling constants between axial and equatorial protons in eleutherins[32] (compounds **6** and **7** in Table III), although here the *exact* conformations are less certain.

For cyclic compounds with isopropylidene or isomeric ethylidene groups, the experimental data show that the transoid homoallylic coupling constants are almost always significantly greater than the cisoid values. The relevant INDO–MO results in Table II are in agreement with these findings and give $^{5t}J_{HH'}$ = 2.334 Hz and $^{5c}J_{HH'}$ = 2.039 Hz for perfect tetrahedral conformation, *i.e.*, ϕ = 120°. The corresponding π-electron contributions from the VB formula is 1.871 Hz for both cases.

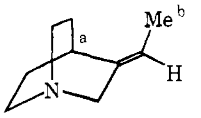
The only apparent reversal of the relationship between cisoid and transoid homoallylic coupling constants occurs for the isomeric ethylidene tetralins[33] **27** and **28**, which is clearly due to the different conformations of the two isomers, and has been discussed previously.[6] A few cases are known in which the cisoid and transoid coupling constants appear to be equal.[34] Two of these, **29**, and **30**, involve coupling constants which are predicted (Table II) to be small and which are experimentally unobservable.[34] As a consequence, the apparent equality may not be significant in these cases. However, the substantial and apparently equal cisoid and transoid homoallylic coupling constants in some ethylidenecyclopropanes[35] **31–34** may constitute genuine exceptions, which may be related to the unusual bonding associated with three-membered rings.



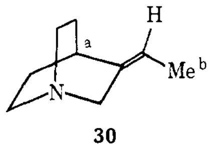
27



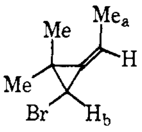
28



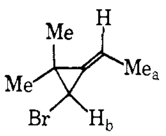
29



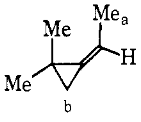
30



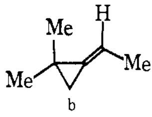
31, $J_{a,b}$ = 1.6 Hz



32, $J_{a,b}$ = 1.6 Hz



33, $J_{a,b}$ = 2.0 Hz



34, $J_{a,b}$ = 2.0 Hz

The above considerations indicate that the INDO–MO method is superior to the VB treatment in correctly predicting trends in the relative magnitudes of cisoid and transoid homoallylic coupling constants. Plots of the data from Table III as a function of the theoretical results by the two methods are given in Figure 5. Both sets of results deviate approximately equally from the experimental data; *i.e.*, most of the points in Figure 5 do not fall exactly on the line of 45° slope. In fact, some preference could be expressed for the VB results because the scatter is essentially random, whereas the INDO–MO results in Figure 5 tend to be too high.

The imperfect correlation demonstrated by the scatter of points in Figure 5 may appear to be disappointing at first sight. However, bearing in mind

---

(32) D. W. Cameron, R. I. T. Cromartie, Y. K. Hamied, P. M. Scott, N. Sheppard, and Lord Todd, *J. Chem. Soc.*, 90 (1964); D. W. Cameron and Lord Todd in "Oxidative Coupling of Phenols," W. I. Taylor and A. R. Battersby, Ed., Edward Arnold, London, 1967, p 229.

(33) G. P. Newsoroff and S. Sternhell, *Tetrahedron Lett.*, 6117 (1968), and unpublished data from these laboratories.

(34) G. van Binst, J. C. Nouls, J. Stokoe, C. Danheux, and R. H. Martin, *Bull. Soc. Chim. Belg.*, 74, 506 (1965); J. C. Nouls, P. Wollast, J. C. Braekman, G. van Binst, J. Pecher, and R. H. Martin, *Tetrahedron Lett.*, 2731 (1968).

(35) W. Rahman and H. G. Kuivila, *J. Org. Chem.*, 31, 772 (1966).

the large uncertainties in the reported values of homoallylic coupling constants, the difficulty of estimating dihedral angles and substituent effects, the agreement between the theoretical and experimental results must be considered as very satisfactory. Further, it is fortunate that the resolution of most stereochemical problems involves the choice between a "large" and a "small" coupling constant.[5,6] Thus, either set of calculated results can be of use in structural work. It must be noted, however, that experimental data for transoid homoallylic coupling constants in compounds of well-defined stereochemistry are scarce (see compound **8** and footnote *c* in Table III).

The coupling between bridgehead protons in unsaturated bicyclic systems constitutes an interesting series of apparent anomalies. In bicyclo[2.2.1]heptenes and bicyclo[2.2.1]heptadienes $J_{1,4}$ is in the range of 1–2 Hz,[36] while the analogous interactions in larger bicyclic systems[37] appear to be negligible with the exception of the rather special case of the azabicyclic system **25** (Table III). In both systems the interacting protons are essentially collinear, *i.e.*, $\phi = \phi' =$ 160–180°, which leads to the expectation of negligible homoallylic coupling constants from either the INDO or the VB treatments in variance with experiment. However, the examination of homoallylic spin–spin coupling in five-membered rings[12] showed that the presence of the additional path (across four bonds) and the nature of this path may be important. Therefore, the anomalously large homoallylic interactions in unsaturated bicyclo[2.2.1]heptane derivatives do not cast any serious doubt upon the general validity of the calculated results for other geometries of the 2-butene fragment. In confirmation, the bridgehead–bridgehead interactions in systems lacking five-membered rings, *e.g.*, in **9** and **24** (Table III), appear to be negligible, while the substantial bridgehead–bridgehead interaction in **26** (Table III) does not involve a π system.

With derivatives of 1,4-cyclohexadiene an effective double homoallylic path is possible between protons at C_3 and C_6 and very large (up to 11 Hz) coupling constants have been observed in structures of this type.[38] The steric dependence of this type of interaction appears to be the same as that involving a single homoallylic path.

Influence of Substituents. Because of the sensitivity of the homoallylic coupling constants to stereochemistry, the examination of the influence of substituents must be made with caution to ensure that the observed effect is not due to the influence of the substituent on the geometry of the molecule.

In the series of isomeric 2,3-disubstituted 2-butenes, the only results which deviate significantly from the usual values are those for the isomeric 2,3-dimethoxy derivatives[39] for which the cisoid and transoid values are 0.9 and 0.95 Hz, respectively. The conclusion that oxygen substituents at C_2 and C_3 cause a decrease in the magnitude of the homoallylic coupling constants is confirmed by the abnormally small values of 0.5 and 0.8 Hz for these respective coupling constants in the phenanthraquinone–allene adducts.[40] Qualitative rationalizations of substituent effects, based on crude molecular orbital arguments,[41] have been given for geminal coupling constants,[42] coupling over four bonds in saturated systems,[4,12,43] and homoallylic coupling with substituents at the C_1 and C_4 carbon atoms.[12] Substituents at the C_2 and C_3 carbon atoms are β to the coupled nuclei, and analogous arguments could be given for this case. Because the substituents are further removed from the orbitals with which they must interact to produce a change in the coupling constants, it seems likely that the effects will be much smaller than for substituents at the C_1 and C_4 carbon atoms. In the absence of further experimental data of the requisite degree of accuracy, the above experimental results give only an approximate idea of the nature and importance of substituents at the C_2 and C_3 carbon atoms.

Many examples[3–6] can be found in the literature for which C_2 and/or C_3 have been replaced by sp^2-hybridized nitrogen atoms. These results show that for comparable geometry, replacement of carbon by nitrogen does not result in gross changes in the magnitudes of homoallylic coupling constants. It can also be seen that the relative magnitudes of cisoid and transoid homoallylic coupling constants remain the same; the steric dependence on the two dihedral angles appears to be similar to that discussed in the previous section and large interactions are associated with a double homoallylic path.[38] Tori, *et al.*,[44] have shown that allylic and homoallylic interactions across a $C{=}N$ system decrease on protonation of the nitrogen or the conversion to the *N*-oxide. They explained this trend on the basis of a decrease in the $C{=}N$ mobile bond order. However, appreciable homoallylic interactions can still be observed.

The apparent lack of sensitivity of the homoallylic coupling constants to replacement of carbon by nitrogen can be rationalized on the basis of our previous qualitative arguments[12] regarding the effect of substituents on the homoallylic coupling constants in five-membered rings. It was shown that an inductive substituent should have the effect of *decreasing* the value of the cisoid homoallylic coupling constant for protons on the *same* side of the plane formed by the four carbon atoms (see Figure 1, for example), and it should *increase* the (cisoid) coupling constants for those cases in which the coupled protons are on *opposite* sides of the plane. Since most of the molecules which have been studied in-

(36) E. W. Garbisch, *Chem. Commun.*, 332 (1968); M. M. Martin and R. A. Koster, *J. Org. Chem.*, **33**, 3428 (1968); S. J. Cristol and G. W. Nachtigall, *ibid.*, 32, 3738 (1967); P. M. Subramanian, M. T. Emerson, and N. A. LeBel, *ibid.*, 30, 2624 (1965); R. W. King and P. E. Butler, Abstracts, 142nd National Meeting of the American Chemical Society, Atlantic City, N. J., Sept 1962, p 84Q; H. Prinzbach and J. Rivier, *Helv. Chim. Acta*, **53**, 2201 (1970); C. F. H. Allen, *Can. J. Chem.*, **45**, 1201 (1967).

(37) J. Ciabattoni, J. E. Crowley, and A. S. Kende, *J. Amer. Chem. Soc.*, **89**, 2778 (1967); S. Itô, H. Takeshita, and Y. Shoji, *Tetrahedron Lett.*, 1815 (1969); S. Itô, K. Sakan, and Y. Fujise, *ibid.*, 775 (1969); T. Mukai, H. Tsuruta, A. Takeshita, and H. Watanabe, *ibid.*, 4065 (1968); M. Oda, M. Funamizu, and Y. Kitahara, *Chem. Commun.*, 737 (1969).

(38) J. L. Marshall, K. C. Erickson, and T. K. Folsom, *J. Org. Chem.*, **35**, 2038 (1970), and references therein; M. D. Mehta, D. Miller, and E. F. Mooney, *J. Chem. Soc.*, 6695 (1965); M. Anteunis and R. de Clevn, *Bull. Soc. Chim. Belg.*, **78**, 447 (1969), and references therein.

(39) G. Benndorf, H. G. Hauthal, R. Holm, and W. Höbold, *J. Prakt. Chem.*, 311, 586 (1969).

(40) H. J. T. Bos, C. Slagt, and J. S. M. Boleij, *Recl. Trav. Chim. Pays-Bas*, **89**, 1170 (1970).

(41) J. A. Pople and D. P. Santry, *Mol. Phys.*, **8**, 1 (1964).

(42) J. A. Pople and A. A. Bothner-By, *J. Chem. Phys.*, **42**, 1339 (1965).

(43) D. J. Sardella, *J. Mol. Spectrosc.*, 31, 70 (1969).

(44) K. Tori, M. Ohtsuru, and T. Kubota, *Bull. Chem. Soc. Jap.*, **39**, 1089 (1966).

volve some type of averaging effects associated with cis and trans protons, it seems likely that the apparent lack of sensitivity of the homoallylic H–H coupling to replacement of carbon by nitrogen is due to a cancellation of two effects of opposite sign.

Acknowledgment. This work was supported in part by a grant from the National Science Foundation. Services of the University of Arizona Computer Center are gratefully acknowledged. Some valuable comments were provided by Professor F. H. A. Rummens.

Conformational Analysis. XXV. Conformational Equilibria in 5-Heterosubstituted 1,3-Dioxanes. Comparison of Calculated and Experimental Solvent Effects

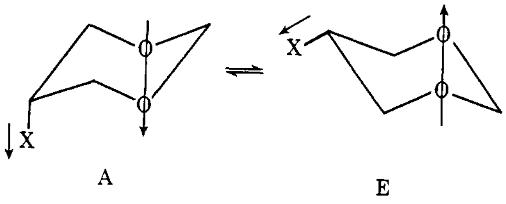
R. J. Abraham,[1] H. D. Banks,[2] E. L. Eliel,*[2] O. Hofer,[2] and M. K. Kaloustian[2,3]

Contributions from the Department of Organic Chemistry of The University of Liverpool, Liverpool, L69 3BX, United Kingdom, and the Department of Chemistry, University of Notre Dame, Notre Dame, Indiana 46556. Received July 19, 1971

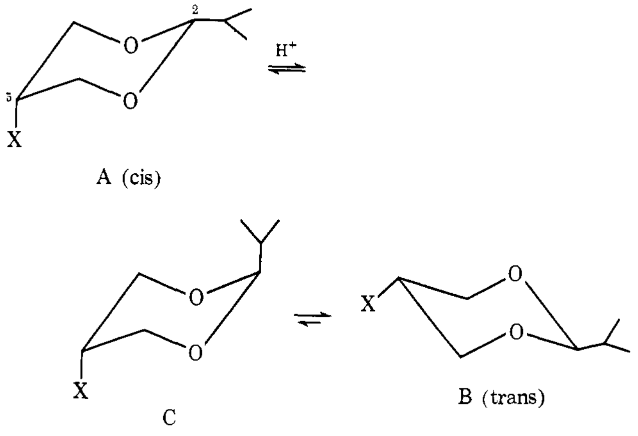
Abstract: *cis-* and *trans*-5-fluoro-, 5-chloro-, 5-bromo-, 5-cyano-, and 5-methoxy-2-isopropyl-1,3-dioxane have been equilibrated, in solvents CCl_4, diethyl ether, benzene, chloroform, and acetonitrile, by means of acid. The $\Delta G°$ values found are summarized in Table I. The preference of fluorine for the axial position in all solvents and of cyano (and, to a minor extent, methoxy) for this position in solvent acetonitrile is of note. The effect of variation of solvent dielectric in the set CCl_4, ether, chloroform, and acetonitrile is compared with predictions based on calculations by a previously published method; the agreement is good. Benzene behaves as an "anomalous" solvent in this regard.

The 1,3-dioxane system has been a fruitful framework for studying a number of conformational equilibria.[4,5] Several advantages of the system have been previously pointed out: 1,3-dioxanes with a variety of substituents in all possible positions can be easily synthesized and equilibrated; their nmr spectra are often susceptible to first-order analysis and yield information regarding configuration and conformation; interactions involving lone pairs on oxygen can be studied. To these advantages should now be added another one: the study of 5-heterosubstituted 1,3-dioxanes affords an accurate means of evaluating dipolar interactions. As seen in Scheme I the ring dipole and the substituent dipole are involved in electrostatic repulsion in the 5-axially substituted compound whereas a slightly attractive electrostatic interaction might be expected in the 5-equatorially substituted isomer. Whereas study of the equilibrium shown in Scheme I, *e.g.*, by spectral means or by measurement of dipole moment, offers no particular advantage over similar studies accomplished in the past in related systems, such as 1,2-dihaloethanes[6] or 2-halocyclohexanones,[7] the conformational equilibrium shown in Scheme I can be readily substituted by a configurational one, as shown in Scheme II; this equilibrium, in turn, can be measured very accurately by gas chromatography.[8] The diaxial intermediate C may be safely disregarded, since the $\Delta G°$ value of a 2-isopropyl group in a 1,3-dioxane is very large, 4.2 kcal/mol;[9] twist-boat forms, also, may be neglected because

Scheme I. Conformational Equilibrium in 5-Heterosubstituted 1,3-Dioxanes



Scheme II. Cis–Trans Equilibria in 5-Heterosubstituted 1,3-Dioxanes



---

[1] The Robert Robinson Laboratories, The University of Liverpool.

[2] University of Notre Dame.

[3] From the Ph.D. Dissertation of M. K. Kaloustian, University of Notre Dame, 1970.

[4] *Cf.* E. L. Eliel, *Accounts Chem. Res.*, 3, 1 (1970).

[5] See also paper XXIV in this series: E. L. Eliel and H. D. Banks, *J. Amer. Chem. Soc.*, **94**, 171 (1972).

[6] For calculations concerning such systems, see R. J. Abraham and G. Gatti, *J. Chem. Soc. B*, 961 (1969).

[7] E. L. Eliel, N. L. Allinger, S. J. Angyal, and G. A. Morrison, "Conformational Analysis," Wiley-Interscience, New York, N. Y., 1965, pp 460–469.

[8] For a preliminary report, see E. L. Eliel and M. K. Kaloustian, *Chem. Commun.*, 290 (1970).

[9] F. W. Nader and E. L. Eliel, *J. Amer. Chem. Soc.*, 92, 3050 (1970).

Abraham, et al. / Conformational Analysis