

hydride in dry diglyme was added 6.1 ml of 3.65 *M* boron trifluoride diglymate (22 moles) dropwise at 0°. After 2 hr, 2.08 g (21 mmoles) of methylcyclohexane, an internal standard, and 2.3 g (21.4 mmoles) of 2-methylenenorbornane were added. After 18 hr, 35 ml of dry propionic acid was added and the mixture refluxed for 4 hr. The acid was neutralized with sodium hydroxide pellets, and the

mixture extracted with pentane. Analysis indicated an 88% yield of 91% 2-*endo*- and 9% 2-*exo*-methylnorbornane.

Hydroboration-Protolysis of α -Fenchene with Disiamylborane. After 18 hr at room temperature, 35 ml of dry propionic acid was added and the mixture refluxed for 12 hr. Analysis indicated a 95% yield of 89% *exo*- and 11% *endo*-2,7,7-trimethylnorbornane.

Evidence for Twisted Norbornanes. X-Ray Diffraction and Valence Force-Field Calculations¹

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Abstract: A quantitative description of skeletal torsional angles of eleven norbornanes, camphanes, and norbornenes is presented. These geometrical details of the molecules from X-ray structure determinations are compared with those obtained by computer calculations (full relaxation molecular mechanics approach) of the same or of similar systems. It is shown that good quantitative agreement is achieved. Moreover, the experimental and calculated structures demonstrate unequivocally that substituted norbornanes and camphanes may adapt themselves to strain induced by certain substituents by two possible modes of twist in which the entire skeleton takes part. "synchro" twist occurs readily in the presence of substituents on C(2), C(3), C(5), or C(6). "contra" twist is mainly limited to molecules carrying a bulky group on C(1), and to camphanes. The synchro twisting of the norbornane skeleton may attain surprising magnitudes in suitable cases, depending on size, position, and orientation of substituent groups. For example, the difference between the torsional angles defined by carbon atoms 7,1,2,3 and 2,3,4,7, respectively, is zero in a structure possessing C_{2v} symmetry. In contrast, differences of 5–10° commonly occur in the molecules investigated. In 2-*endo*-3-*exo*-disubstituted norbornane, a difference as large as 14° was recorded. The twisting effect caused by substituents seems to be a more or less additive property. The important role of β atoms (not directly bound to the ring) is discussed.

Derivatives of norbornane have been used extensively as a testing ground for theories concerning chemical reactivity, nmr spin coupling phenomena, and numerous others. One of the main attractions of the norbornane system is its supposed rigidity. We wish to report our observations and calculations concerning the torsional angles of substituted norbornanes and camphanes that show conclusively that these bridged systems can subtly adapt themselves to strain induced by certain substituents, by demonstrating two different modes of twist.

An illustrative way to describe the results of the X-ray determinations and of the force-field calculations of structures is to consider the norbornane skeleton as being assembled from two cyclopentane rings, R and L, to give a boat-shaped six-membered ring, B (these basic rings are notoriously flexible). The designation of torsional angles is shown in Figure 1.

Methods

The requisite experimental torsional angles have been obtained by standard methods from available atomic coordinates of norbornanes,^{4,5} camphanes⁶ and nor-

bornenes⁷ as determined by X-ray crystallography or electron-diffraction methods. Thus far, no author has reported these interesting geometrical parameters. The published X-ray analyses⁸ vary widely with respect to the accuracy attained and customary significance criteria were applied.⁹ The torsional angles in a structure are said to differ significantly when their difference exceeds 2.6 σ .

and S. H. Bauer, *J. Amer. Chem. Soc.*, **90**, 3149 (1968); (c) G. Dallinga and L. H. Toneman, *Rec. Trav. Chim.*, **87**, 795 (1968); 1,4-dichloronorbornane (2); (d) ref 4b.

(5) (a) 2-*exo*-Norbornanol *p*-toluenesulfonate (3), C. Altona and M. Sundaralingam, *Acta Crystallogr.*, to be published; (b) 3-*exo*-(*N*-benzyl-*N*-methylaminomethyl)-2-*endo*-norbornanol (4), A. V. Fratini, K. Britts, and I. L. Karle, *J. Phys. Chem.*, **71**, 2482 (1967).

(6) (a) 1,1'-Biapocamphane (8), R. A. Alden, J. Kraut, and T. G. Traylor, *J. Amer. Chem. Soc.*, **90**, 74 (1968); (b) (+)-10-bromo-2-*exo*-chloro-2-nitrosocamphane (9), G. Ferguson, C. J. Fritchie, J. M. Robertson, and G. A. Sim, *J. Chem. Soc.*, 1976 (1961); (c) (-)-2-*exo*-bromo-2-nitrosocamphane (10), D. A. Brueckner, R. A. Hamor, J. M. Robertson, and G. A. Sim, *ibid.*, 799 (1962); (d) 1-retusamine as α '-bromo-D-camphor-*trans*- π -sulfonate (11), J. A. Wunderlich, *Acta Crystallogr.*, **23**, 846 (1967).

(7) (a) *anti*-7-Norbornenyl *p*-bromobenzoate (12), A. C. MacDonald and J. Trotter, *ibid.*, **19**, 456 (1965); (b) *syn*-7-benzonorbornenyl *p*-bromobenzenesulfonate (13), T. Sato, M. Shiro, and H. Koyama, *J. Chem. Soc., B*, 935 (1968); (c) *anti*-8-tricyclooctyl *p*-bromobenzenesulfonate (14), A. C. MacDonald and J. Trotter, *Acta Crystallogr.*, **18**, 243 (1965); this compound does not possess a double bond but its geometrical properties, due to the presence of the three-membered ring, are related to those in the norbornenes rather than in the norbornanes; (d) norbornide, S. Abrahamsson and B. Nilsson, *J. Org. Chem.*, **31**, 3631 (1966); not used in the present work.

(8) A number of interesting structures reported in the literature unfortunately had to be ignored in the present work because the necessary atomic coordinates were withheld from publication.

(9) D. W. J. Cruickshank and A. P. Robertson, *Acta Crystallogr.*, **6**, 698 (1953).

(1) Communicated in part at the Eighth International Congress of Crystallography, Stony Brook, N. Y., Aug 13–23, 1969, Abstract XIII-43; *Acta Crystallogr. Suppl.*, **A25**, 141 (1969).

(2) To whom correspondence should be addressed at the Chemical Laboratories of the University, Leiden, The Netherlands. Work carried out during a leave of absence from the University of Leiden.

(3) A Fulbright-Hays Travel Grant from the U. S. Educational Foundation in The Netherlands is gratefully acknowledged.

(4) Norbornane (1): (a) Y. Morino, K. Kuchitsu, and A. Yokozeki, *Bull. Soc. Chem. Jap.*, **40**, 1552 (1967); (b) J. F. Chiang, C. F. Wilcox,

Table I. Experimental and Calculated Torsional Angles of Norbornane and of Some Substituted Norbornanes

Subst ^a	Exptl or calcd	Twist ^b	Torsional angles, ^c deg													$\sigma(\phi)$, deg		
			Ring R					Ring L					Ring B					
			a	b	c	d	e	a'	b'	c'	d'	e'	f	g	f'	g'		
1	ED ^f		35	0	35	55	55	35	0	35	55	55	72	72	72	72	± 1	
1	Calcd		36	0	36	56	56	36	0	36	56	56	71	71	71	71		
2	1-Cl 4-Cl	ED	35	0	35	54	54	35	0	35	54	54	73	73	73	73	± 1	
3	2-x-OR ^d	X-ray ^g	C(-, +)	31	3	37	55	53	34	1	36	57	56	73	70	71	71	± 1
4	2-n-OH 3-x-CH ₂ R ^e	X-ray ^h	S(+, +)	44	9	30	56	61	31	5	39	57	53	64	78	74	68	± 1
5	2-n-OH 3-x-Me	Calcd	S(+, +)	40	5	31	54	57	33	4	39	59	56	67	74	73	68	

^a n = *endo*, x = *exo*. ^b See Figure 3. ^c See Figure 1. ^d R = tosyl. ^e R = NMePh. ^f See ref 4c. ^g See ref 5a. ^h See ref 5b.

The force field used in the energy minimization procedure¹⁰ was based on that developed by Allinger, *et al.*,¹¹ but incorporated a number of innovations.¹²⁻¹⁵ The total energy, E_t , of the molecule was minimized, allowing full relaxation of internal coordinates, with respect to the following terms: $E_t = E_{\text{stretch}} + E_{\text{bend}} + E_{\text{torsion}} + E_{\text{nonbonded}} + E_{1,3} (+ E_{\text{Coulomb}})$. Coulombic terms were only included when heteroatoms were present. Symmetry constraints were not imposed; however, some structures containing symmetrically placed substituents (*viz.*, **1**, **6**, **7**, **20**) yielded the expected symmetry to a high degree of precision ($<0.01^\circ$) at the termination of the iterative procedure (root mean square coordinate shift $\leq 0.001 \text{ \AA}$). A symmetrical structure was calculated even when the starting coordinates were purposely made nonsymmetric.

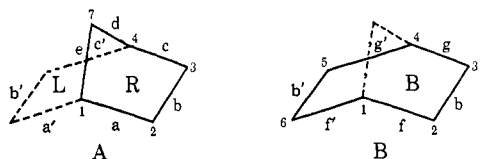


Figure 1. Torsional angles in the norbornane skeleton: a-e in five-membered ring R, a'-e' in ring L, f, g, f', g' in boat ring B.

Our force field gave highly satisfactory results in calculations of substituted cyclohexanes,¹³ aliphatic open-chain compounds,¹⁴ and steroids.¹⁵ In the great majority of cases, the calculated structures agreed with the observations to within the limits of error of the latter. A presentation and thorough discussion of the calculated strain energies are not relevant for our present purposes and will be postponed for a later publication.¹⁴

Table I contains the (meager) experimental data available for norbornane and substituted norbornanes (**1-4**) and two calculated structures (**1** and **5**; the latter is analogous to **4**). Torsional angles, mainly experimental values, of camphanes and norbornenes are shown in Table II. Finally, Table III gives the calculated results of a selected series of norbornanols, methyl-substituted norbornanes, and norbornanols. The orientation of the

atoms β to the norbornane skeleton was found to be of paramount importance (β effect and see below) and is denoted by Y, Y', and Y'' (Figure 2 and Table III). In order to avoid confusion when speaking of increasing or decreasing torsional angles, only the absolute magnitudes and not the signs of the angles are shown.

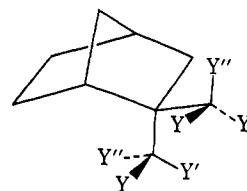


Figure 2. Position of *endo*- and *exo*- β -substituents (Y) as used in Table III.

Discussion

There is no doubt that the symmetry of the parent compound **1** is truly C_{2v} .⁴ Unfortunately, several important details of the structure are less clear. Three recent electron-diffraction studies⁴ disagree considerably regarding the exact carbon-carbon bond distances and some bond angles as well, *e.g.*, the bond angle C(6)-C(1)-C(2) is given as 103.5° ,^{4b} 107.2° ,^{4a} and 107.1° .^{4c} In X-ray diffraction determinations of substituted norbornanes, this angle is generally found in the range $108-110^\circ$. Whatever the true geometry may turn out to be, for the present it is sufficient to note that our calculated structure agrees well with the results of Dallinga and Toneman^{4c} (Table I). 1,4-Dichloronorbornane^{4b} (**2**) also has a C_{2v} structure; the torsional angles of this compound are practically equal to those in **1**.

The situation is completely different, however, in the case of the 2- and 2,3-substituted norbornanes, **3** and **4**. The torsional angles a and c (a' and c') are exactly equal in C_{2v} symmetry, but they are found to display surprising differences: 6° in ring R of **3**, 14 and 7° in rings R and L of **4**, respectively. These findings are significant and in fact led us to undertake the computer calculations in order to gain an insight into the geometrical and energetical factors involved, the experimental data being rather meager at the present time. It is satisfying to note that calculated structure **5**, compared with the closely analogous experimental structure **4**, displays the same trend in all torsional angles (Table I). In fact, **4** seems more distorted than **5**, possibly reflecting the effect of the larger 3β substituent in the former (NMePh *vs.* H).

- (10) R. H. Boyd, *J. Chem. Phys.*, **49**, 2574 (1968).
 (11) N. L. Allinger, J. A. Hirsch, M. A. Miller, I. J. Tyminski, and F. A. Van-Catledge, *J. Amer. Chem. Soc.*, **90**, 1199 (1968); N. L. Allinger, J. A. Hirsch, M. A. Miller, and J. Tyminski, *ibid.*, **90**, 5773 (1968); **91**, 337 (1969), and further references therein.
 (12) C. Altona, to be published.
 (13) C. Altona and M. Sundaralingam, *Tetrahedron*, in press.
 (14) C. Altona, unpublished results.
 (15) C. Altona and H. Hirschmann, *Tetrahedron*, in press; C. Altona, to be published.

Table II. Experimental Torsional Angles of Some Camphanes and Norbornenes

Subst ^a	Exptl or calcd	Twist ^b	Torsional angles, ^c deg												$\sigma_{(\phi)}$, deg		
			Ring R					Ring L					Ring B				
			a	b	c	d	e	a'	b'	c'	d'	e'	f	g	f'	g'	
Norbornane																	
6 1-Me ^d	Calcd	C(-, +)	35	0	36	56	56	35	0	36	56	56	71	71	71	71	
Camphanes																	
7 Camphane	Calcd	C(-, +)	35	0	36	55	54	35	0	36	55	54	72	72	72	72	
8 1,1'-Biapocamphane	X-ray ⁱ	C(-, +)	33	1	37	56	53	33	2	37	56	53	70	72	71	71	±0.3
9 2-n-NO ^e 2-x-Cl	X-ray ⁱ	C(-, +)	31	5	40	57	53	37	1	37	60	57	71	67	69	72	±4
10 2-n-NO ₂ 2-x-Br	X-ray ^k	C(-, +)	29	7	40	56	50	36	2	39	62	58	73	70	68	71	±4
11 2-keto 3-n-Br	X-ray ^l	C(-, +)	35	3	41	60	58	30	3	36	52	49	79	69	73	69	±3
Norbornenes																	
12 7-a-OR ^o	X-ray ^m		36	2	34	57	57	36	4	30	50	52	66	69	67	75	±3
13 7-s-OR ^o	X-ray ⁿ		35	2	36	59	59	33	1	31	49	49	69	66	70	70	±2.5
14 7-a-OR ^h	X-ray ^o		33	1	36	58	55	33	1	34	53	53	73	70	71	72	±3

^a n = *endo*, x = *exo*. ^b See Figure 3. ^c See Figure 1. ^d Norbornane. ^e Also 10-Br. The angles shown represent the mean of the two independent molecules occurring in the unit cell. ^f In retusamine. ^o Double bond in ring L. ^h Three-membered ring at C₅-C₆. ⁱ See ref 6a. ^j See ref 6b. ^k See ref 6c. ^l See ref 6d. ^m See ref 7a. ⁿ See ref 7b. ^o See ref 7c.

Table III. Calculated Torsional Angles in Some Norbornanols, Methylnorbornanes, and Methylnorbornanols

Subst ^a	β -Proton orientation ^d	Twist ^b	Torsional angles, ^c deg														
			Ring R					Ring L					Ring B				
			a	b	c	d	e	a'	b'	c'	d'	e'	f	g	f'	g'	
15	2-n-OH	Y	S(+, +)	37	1	35	56	57	36	0	36	57	56	70	71	71	70
	2-n-OH	Y'	S(+, +)	37	1	35	56	57	35	0	36	57	56	70	71	71	70
	2-n-OH	Y''	S(-, -)	35	1	37	57	56	38	3	34	56	58	71	69	68	72
16	2-x-OH	Y	S(+, +)	37	1	35	56	57	36	0	36	57	56	69	72	70	70
	2-x-OH	Y'	S(-, -)	36	0	36	57	57	37	1	35	56	57	70	70	70	71
	2-x-OH	Y''	S(-, -)	33	3	38	57	55	38	3	34	56	58	73	68	68	72
17	2-n-Me		S(-, -)	34	2	37	57	56	39	3	33	56	58	71	69	68	73
18	2-x-Me		S(-, -)	32	4	39	57	55	39	4	33	56	58	73	68	68	73
19	2-x-Me 3-n-Me		S(-, -)	33	3	38	57	55	38	1	35	57	58	72	67	70	70
20	2-x-Me 5-x-Me		S(-, -)	31	6	41	58	55	41	6	31	55	58	74	66	66	74
21	2-n-OH 2-x-Me	Y	S(-, -)	32	4	39	56	55	39	4	33	57	58	73	67	68	72
22	2-n-Me	Y	S(-, -)	36	1	37	57	57	39	4	33	56	58	71	70	68	73
	2-x-OH																
	2-n-M 2-x-OH	Y''	S(-, -)	31	5	40	57	55	41	6	32	56	60	74	66	66	74

^a n = *endo*, x = *exo*. ^b See Figure 3. ^c See Figure 1. ^d See Figure 2.

The observed and calculated distortions can be visualized as a *partial pseudorotation*¹⁶ of the five-membered rings R and L, and of the six-membered ring B away from the symmetrical forms. Although indications are strong that this process is a concerted one to a certain extent (a twist of ring R causing a twist in ring L, e.g., compound **16**, Table III), the distribution of strain and the corresponding pseudorotation in nonsymmetrically substituted norbornanes may be quite different for the two rings. This point is clear from Tables I-III; see also Table IV.

The geometry of the pseudorotational pathway of a five-membered ring close to the envelope form is such

(16) A quantitative description of puckering and conformation of five-membered rings (ring D in steroids) in terms of a *phase angle* Δ of *pseudorotation* has been presented elsewhere.¹⁷ Suffice it to say that in a general pseudorotating five-membered ring a rotation over 720° restores the original ring. Envelope forms occur at intervals of 72°, interspaced with half-chair conformations. The $\Delta = 0$ reference point usually refers to a half-chair form. However, in the present case the undistorted reference structure is an envelope form, and we now take $\Delta = 0$ for this form. Then half-chair conformations occur at +36° and at -36°.

Table IV. Phase Angles, Δ , of Pseudorotation of Rings R and L in Some Norbornanes and Camphanes

Compd	Δ , deg	
	S Ring R	Ring L
Norbornanes	3	-6
	4	+16
2-Substituted camphanes	9	-10
	10	+1
		+4

that a twisting of the ring (\equiv shift in phase angle Δ ¹⁷) is reflected foremost in the values of the torsional angles *a*, *b*, and *c*; much less affected are *d* and *e* (Figure 1, Tables I-III). From the five torsional angles in each ring, R and L, the shift in Δ was obtained with the aid of known equations.¹⁷ A few representative examples are shown in Table IV. It can be seen that the twist

(17) H. J. Geise, C. Altona, and C. Romers, *Tetrahedron Letters*, 1383 (1967); C. Altona, H. J. Geise, and C. Romers, *Tetrahedron*, **24**, 13 (1968).

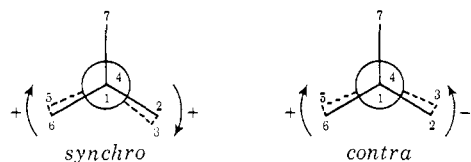


Figure 3. Projections of substituted norbornanes along C(1)...C(4), showing examples of the two possible modes of twist, *synchro* (S) and *contra* (C).

in ring R of 4 ($\Delta = 16^\circ$) takes the conformation of this ring *almost halfway toward the half-chair form* ($\Delta = 36^\circ$). It now seems likely that norbornanes can be found that come considerably closer to the half-chair, even if it is only in one ring. The limit of this process is a matter of conjecture.¹⁸

A convenient shorthand description of the pseudorotation of the entire system is shown in Figure 3.

If, in projection along the C(1)...C(4) vector, the rear atoms C(3) and C(5) have *both* moved in a clockwise (+) or anticlockwise (-) direction, the phenomenon is termed a *synchro* twist,¹⁹ indicated by $S(+,+)$ or $S(-,-)$ in Tables I-III. The combinations $(+,-)$ and $(-,+)$ define the *contra* twist ($C(+,-)$ and $C(-,+)$, respectively). Inspection of Tables I-III leads us to present the following tentative generalizations.

(i) Substituents on C(2), C(3), C(5), and C(6) cause a *synchro* twist of the norbornane skeleton.²⁰

(ii) Substituents on C(1) have a very weak effect, if any. They will give rise to a *contra* twist.

(iii) Camphanes similarly display a (weak) *contra* twist, unless substituents are present on C(2) or C(3). For example, **9**, **10**, and **11** seem to show a considerable distortion, as expected, of ring R and a much smaller one of L.²¹

(iv) Most 2-*endo* and 2-*exo* substituents carrying a hydrogen β to ring R cause a (-) rotation of this ring. Particularly strong effects are noted for the "inner" positions Y". Hydrogens at positions Y seem to cause a small (+) effect. Most instructive in this respect are the two calculated conformations Y and Y" of the 2-*endo*-methylnorbornan-2-ol (**22**), Table III.²² Of course, the methylnorbornanes **17-20** carry hydrogens in all three positions and it is interesting to see that again the Y" hydrogens have a dominant effect.

(v) The calculations tend to show that the twisting effect of substituents is a more or less *additive property*.

(vi) The norbornenes **12-14** do not seem to be twisted within the limits of error of the X-ray determinations.²³ Unfortunately, the errors are quite large in all three structures.

(18) A series of calculations of obvious candidates, e.g., 2-*endo*-5-*endo*-substituted norbornanes, is currently being planned.

(19) We have the following relations between sign of twist (*synchro* and *contra*) and relative magnitude of torsional angles a and c (a' and c'): $S(+,+)$ $a > c$, $a' < c'$; $C(+,-)$ $a > c$, $a' > c'$; $C(-,-)$ $a < c$, $a' > c'$; $C(-,+)$ $a < c$, $a' < c'$.

(20) The one exception seems to be the tosylate **3**, which cannot be compared to the corresponding alcohol **16** because the conformation about the C(2)-O bond in the former is such that the O-S bond almost eclipses the C(2)-H_{endo} bond²⁴ (distorted form Y, Figure 2). Furthermore, the bulky tosyl group is folded in the direction of the cage, giving rise to some nonbonded interactions that confuse the picture.

(21) The standard deviations of the angles in these three X-ray determinations are large and, without the support of our calculations, no conclusions would have been possible.

(22) The calculated order of strain energies in the norbornanols is rather surprising, viz., $endo E(Y) \leq E(Y') < E(Y'')$, $exo (E(Y'')) < E(Y') E(Y)$, but in **22**, $E(Y) \ll E(Y'')$.

(23) From the foregoing, one may predict that 2-*endo*-substituted

In conclusion, the analysis of torsional angles of substituted norbornane systems, obtained from experiment as well as from force-field calculations of molecular structures, has shown conclusively that the norbornane skeleton may undergo a limited pseudorotation (or twist). These findings suggest various interesting possibilities for further experimental and theoretical research that are now being pursued.

Force-Field Parameters Used in the Calculations

The basic ideas and principles of the molecular mechanics approach have been thoroughly discussed in the recent literature (cf. ref 11, 24-26). The force field currently employed was taken from Allinger, *et al.*¹¹ (AFF), but several modifications were introduced for the following reasons (see also ref 13).

(i) We wished to reproduce more accurately the known variation in carbon-carbon bond lengths of sterically crowded aliphatic molecules²⁵ and of steroids.¹⁵

(ii) AFF does not seem to reproduce in a satisfactory way the observed increase (decrease) of the carbon-carbon bond distances A-B and B-C in cases where the bond angle A-B-C is constrained to be much smaller (larger) than the normal value. Norbornane is a case in point.¹¹

(iii) At the same time we wished to reproduce as closely as possible previously calculated strain energies of relatively nonstrained molecules such as substituted cyclohexanes and simple aliphatic compounds. For reasons of convenience we preferred to stick to the well-tested AFF bond energy scheme.¹¹ It should be realized that a choice of this kind is rather arbitrary and that selection of a different force field could well lead to an entirely different (but equally valid) bond energy scheme. For example, some calculations utilizing the force field recently proposed by Lifson and Warshel²⁶ (LWFF) yielded reasonable geometries and conformational energies, although the calculated "strain energies"²⁷ were found to be much higher. The AFF "strain" in cyclohexane is of the order of 1 kcal/mol whereas the LWFF "strain" in this molecule runs to about 10 kcal/mol.

Our modification of AFF involves the treatment of the E_{stretch} and $E_{1,3}$ functions.

E_{stretch} . A linear term was added to the usual harmonic stretching equation²⁸ which allows a rather smaller quadratic force constant than used in AFF, while the stretching energy is kept within the required limits. The first derivatives with respect to distance of our carbon-carbon stretching functions (which determine the carbon-carbon bond distance) are roughly parallel to that of LWFF and to the first derivative of the function selected by Bartell, *et al.*²⁵ (BFF).²⁹ Fol-

5,6-norbornenes will display only a small distortion, if any. On the other hand, 2-*exo* derivatives with a bulky Y" group might well show an appreciable twist.

(24) K. B. Wiberg, *J. Amer. Chem. Soc.*, **87**, 1070 (1965).

(25) E. J. Jacob, H. B. Thompson, and L. S. Bartell, *J. Chem. Phys.*, **47**, 3736 (1967).

(26) S. Lifson and A. Warshel, *ibid.*, **49**, 5116 (1968).

(27) "Strain energy (enthalpy)" here, as in AFF, is defined as the sum total of all calculated interactions in the molecule, and is a function of the force field used. Of course *differences* in calculated strain energies, for example in the form of conformational enthalpies,¹¹ barriers to ring inversion, excess enthalpies in homologous series,²⁶ and heats of formation,¹¹ are experimentally verifiable.

(28) At present for carbon-carbon bonds only.

(29) Note that both LWFF and BFF utilize some form of 1,3 interactions whereas AFF does not.

Table V. Some Force-Field Parameters Used in the Calculations

Carbon-carbon stretching
 $E = \frac{1}{2}k_s(l - l_0)^2 + k'(l - l_0)$. All C-C bonds $K_s = 1.56$ mdyn/Å, $l_0 = 1.424$ Å, k' (mdyn) for various combinations of primary, secondary, tertiary, and quaternary carbon: -0.077 (pp, ps, ss), -0.069 (pt, pq, st, or Csp² on one end), -0.055 (tt), -0.049 (sq, tq, qq).

Bond bending
 As in ref 11, k_b increased by 15%
 HCO $k_b = 0.855$ mdyn Å/radian², $\theta_0 = 107.2^\circ$
 CCCI $k_b = 1.10$ mdyn Å/radian², $\theta_0 = 107.0^\circ$

Nonbonded parameters for use in the Hill equation
 As in ref 11, except
 H...Cl $r^* = 1.67$ Å, $\epsilon = 0.153$ kcal/mol (6/12 function)
 H...O $r^* = 1.59$ Å, $\epsilon = 0.053$ kcal/mol

1,3-Interactions
 Parameters for use in the Hill (6/12) equation

	r^*	ϵ
H...H	1.00	0.015
H...C	1.215	0.09
H...Cl	1.27	0.12
H...O	1.18	0.05
C...C	1.39	0.22
C...Cl	1.50	0.16

Charges (electrons)

-CH ₃	H +0.025e, C -0.075e	
-CH ₂ -	H +0.014e, C -0.028e	
>CH-	H +0.005e, C -0.005e	
	Cl -0.220e	neighboring atom
ketones	=O -0.470e	charges matched to
ethers	-O- -0.300e	produce neutral molecule
alcohols	-O- -0.470e	

lowing Allinger, *et al.*,¹¹ we found it necessary to distinguish between various combinations of primary, secondary, tertiary, and quaternary carbon bonds. In contrast to AFF, however, the quadratic force constants k_s and the equilibrium distance l_0 were kept the same for all combinations (Table V) and the value of the linear constant k_s' was adapted to fit observed bond lengths.³⁰ To our knowledge, linear terms in bond stretching have not been utilized previously in molecular mechanics calculations but several authors^{11,25,26} did introduce linear terms in angle deformations and Urey-Bradley field equations for essentially the same purpose, *viz.* to obtain correct geometries as well as acceptable relative strain energies.

$E_{1,3}$. Our treatment of interactions between atoms bound to a common atom also deviates from previous usage. The prime motivation for including 1,3-interactions in the force field lies of course in their power to give rise to a bond-stretching effect on closure of the bond angle. Similarly, a 1,3-attraction has a bond con-

(30) A listing of observed carbon-carbon bond distances in aliphatic and cycloaliphatic compounds is given in ref 11 and 25.

tractive component. Simple goniometry shows in what fashion the stretching force depends on the angle between the two bonds and on the relative lengths of the bonds. There seems to be no *a priori* reason to cling to a harmonic 1,3-function of the usual Urey-Bradley type in energy-minimization calculations; the original UB field³¹ was in fact based on the assumption of an inverse power function of the distance between 1,3-atoms. We carried out a series of empirical calculations utilizing several possible 1,3-interaction potentials^{25,26} and finally settled on a van der Waals (2-parameter Hill type) function using a 15–20% smaller radius than employed in normal nonbonded interactions. The exact values (in conjunction with and dependent on the remaining force-field parameters) were established by calculation of small molecules of accurately known geometry (alkanes, chloroalkanes, alcohols, ketones, ethers).

The actual force-field parameters employed in the present work, insofar different from AFF, are shown in Table V. The calculated carbon-carbon bond distances match those observed by electron diffraction in simple alkanes²⁵ to within ± 0.002 Å but a detailed comparison of observed and calculated bond lengths in cyclohexanoid systems,¹³ including some steroids,¹⁵ has convinced us that the force field in the present form yields values that are systematically too high by about 0.005 Å. Pending further work, we prefer to accept this deficiency for the time being.

It is realized that the physical model used is necessarily crude in the present stage of our knowledge. Nevertheless, the molecular mechanics approach as it stands might be justified by the surprisingly good results so obtained. However, there is room for improvement and several possible fundamental changes in the force-field equations and parameters are now being investigated.

The calculations were carried out on a Univac 1108 computer. A typical problem, 2-*exo*-methylnorbornan-2-*endo*-ol, for example (23 atoms, 386 interactions), required five cycles of iteration and 30 sec of computer time.

Acknowledgments. This research was supported by Grant GP-15977 of the National Science Foundation and by Grant GM-14828 from the National Institutes of Health of the U. S. Public Health Service. We wish to thank Professor Richard H. Boyd for making his energy minimization program available to us, and Dr. S. T. Rao for valuable suggestions on computer programming.

(31) H. C. Urey and C. A. Bradley, *Phys. Rev.*, **38**, 1969 (1931).