Barriers to Internal Rotation in 1,3,5-Trineopentylbenzenes. 8.[1] Molecular Mechanics Calculations. Theoretical Evidence for Attractive Steric Effects

Robert E. Carter[*2a] **and Peter Stilbs**[2b]

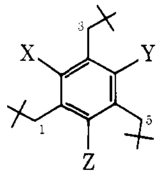
Contribution from Organic Chemistry 2 and Physical Chemistry 2, Chemical Center, University of Lund, 220 07 Lund, Sweden. *Received January 16, 1976*

Abstract: Molecular mechanics calculations on the conformational energies of the various rotamers in 1,3,5-trineopentylbenzene (TNB) and its 2,4-di- and 2,4,6-trimethyl derivatives provide firm theoretical support for the operation of attractive steric effects among the neopentyl groups, leading to the predominance of a rotamer with all three neopentyls on the same side of the aromatic ring. An attempt is made to calculate barriers to internal rotation of a neopentyl group past a proton (in TNB itself) and past a methyl group (in $(CH_3)_2$TNB). Reasonable agreement with available experimental estimates of these barriers is obtained in both cases.

During the 30 years since the publication of the original work by Hill[3a] and by Westheimer[4] on the molecular mechanics approach to the study of steric effects, the method has been considerably developed and refined.[5-12] The total conformational energy of a molecular system is partitioned according to the equation

$$E_{\text{total}} = \sum E_{\text{stretch}} + \sum E_{\text{bend}} + \sum E_{\text{torsion}} + \sum E_{\text{nonbonded}} + \sum E_{\text{out-of-plane}} + \sum E_{\text{stretch-bend}} + \sum E_{\text{torsion-bend}} + \sum E_{\text{dipole}} \quad (1)$$

and this energy is subsequently minimized by a more or less efficient minimization routine.[12] (Each form of energy is described by an appropriate potential function and the summations are taken over all interactions of a given type in the molecule.) The first four terms in eq 1 arise from bond stretching and compression, angle bending, torsion, and nonbonded interactions. The "out-of-plane" term refers to the energy due to deviation from planarity of an sp^2-hybridized group of atoms, while the stretch–bend and torsion–bend terms refer to a coupling between stretching and bending and between torsional and bending degrees of freedom, respectively. Finally, the dipole term accounts for the contribution of dipole–dipole interactions. In the calculations to be described in this paper, the last two terms in eq 1 are neglected and furthermore, effects due to p–π conjugation are ignored.[9a] These limitations are, however, not expected to pose serious problems for the molecules considered here (see below). The force field used in this work has been described by Andose and Mislow.[9a]



The 1,3,5-trineopentylbenzene (TNB) system has recently[1] shown itself to be extremely suitable for studies of *attractive* steric effects, since it has been found that the ^{1}H and ^{13}C NMR spectra of symmetrically trisubstituted derivatives (X = Y = Z = Cl, Br, or CH_3) may be consistently interpreted in terms of the predominance of a rotamer (D in Figure 1) with all three neopentyl groups on the same side of the benzene ring. This rotamer is apparently stabilized relative to rotamers A, B, and C (Figure 1) by attractive nonbonded interactions. Having thus obtained experimental evidence[1] interpretable in terms of the operation of attractive steric effects in a hydrocarbon system, it became of interest to perform empirical force field molecular mechanics calculations on the TNB system to attempt to gain theoretical support for the postulation of attractive steric effects as the source of the stabilization energy of rotamer D. A judicious interpretation of the results of such calculations might lead to insight into the origin of the attractive nonbonded interactions involved. The parametrization of the available molecular mechanics computer program[8,9a] (STRAIN[13]) was most thoroughly tested for calculations on pure hydrocarbon systems. Consequently, the calculations described in this paper are on the conformational energetics of TNB itself and of 2,6-di- and 2,4,6-trimethyl TNB. *Differences* in rotamer energies due to p–π conjugation are certainly expected to be negligible and thus, as mentioned above, omission of these effects will not be a serious limitation. We have also attempted to calculate barriers to internal rotation of a neopentyl group in TNB and in the 2,6-dimethyl derivative for comparison with experimental data[14] and to (hopefully) provide information about the details of the rotational process.

A simple plot routine for the generation of skeletal stereoviews was added to the auxiliary program TRANSF in the STRAIN program package.[13] This routine generates plots of the projections of the molecule on the *xy*, *yz*, and/or *zx* planes by drawing lines between coordinates for connected atoms. The left picture in the stereoview is based on the direct projection, while the right picture is based on a new set of coordinates obtained by rotating the molecule 3° around the second axis (e.g. the *z* axis for the *yz* projection).

All calculations were performed on a UNIVAC 1108 computer.

Conformational Energies. In any detailed analysis of results from molecular mechanics calculations of conformational energies, the derived partitioning of energy in various forms is of course a reflection of the empirical force field chosen.[7,12] The finer points of this partitioning must therefore be taken cum grano salis, but with this stipulation in mind, we may nonetheless attempt to use the molecular mechanics method to gain a deeper understanding of the conformational energetics of the rotamer distributions in trineopentylbenzenes. It should be emphasized at this point that no parameter fitting was undertaken in connection with this work. Thus, as mentioned above, we have used the force field described by Andose and Mislow[9a] without alteration.

The results summarized in Table I clearly demonstrate the operation of attractive steric effects *as the dominant factor* in the determination of rotamer energies in all three TNB's studied. This is especially true in the case of TNB itself (dis-

Table I. Calculated Strain Energy Contributions

	Strain energy, kcal/mol						
Molecule (rotamer)	Bond	Angle	Torsional	Nonbonded	Out-of-plane	Stretch-bend	Total
TNB (A/B/C)	3.00	5.77	0.18	−8.40	0.02	−0.72	−0.14
TNB (D)	3.01	5.82	0.20	−9.38	0.03	−0.72	−1.05
$(CH_3)_2$TNB (A/C)[a]	5.10	12.70	0.93	−5.34	0.39	−1.25	12.52
$(CH_3)_2$TNB (B)[a]	5.25	13.79	0.42	−4.76	0.08	−1.32	13.46
$(CH_3)_2$TNB (D)[a]	5.12	13.54	0.60	−5.83	0.29	−1.26	12.46
$(CH_3)_3$TNB (A/B/C)[b]	6.60	17.87	2.82	−2.60	1.26	−1.67	≤24.28
$(CH_3)_3$TNB (D)[b]	6.42	17.86	2.53	−3.75	1.45	−1.59	≤22.92

[a] See Figure 1; $X = Y = CH_3$, Z = H. [b] Not completely minimized; see text.

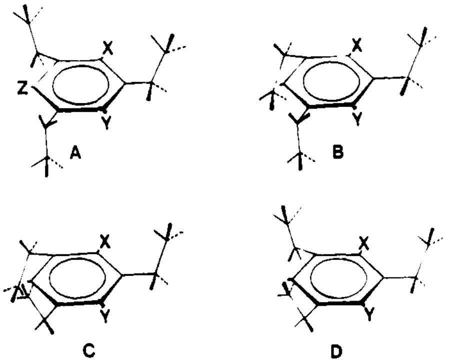


Figure 1. The four rotamers in a trisubstituted 1,3,5-trineopentylbenzene. Note that the wedges and the full or dashed lines denote methylene protons or *tert*-butyl methyl groups, as appropriate. The Z substituent is omitted from rotamers B, C, and D for the sake of clarity.

cussed in detail below), for which almost all other forms of strain energy except that due to nonbonded interactions are calculated to be more positive for rotamer D than for rotamer A, B, or C. (The energies due to the stretch-bend term are identical in the two cases.) In other words, the final balance of "effects" is determined almost entirely by the attractive part of the van der Waals potential function, which in the presently employed force field is the two-parameter Hill equation:[3b,7,9a]

$$E_{\text{nonbonded}} = 8.28 \times 10^5 \epsilon_{ab} \exp(-d/(0.0736 d_{ab}^*)) - 2.25\, \epsilon_{ab}(d_{ab}^*/d)^6$$

In this expression, $\epsilon_{ab} = (\epsilon_{aa}\epsilon_{bb})^{1/2}$ and $d_{ab}^* = (d_{aa}^* + d_{bb}^*)/2$, where the ϵ's are "hardness parameters" for the pertinent atom-atom interactions, and d_{ab}^* is a function of the van der Waals radii of atoms a and b.

Stereoviews of the calculated conformations are shown in Figures 2-4 for TNB, $(CH_3)_2$TNB, and $(CH_3)_3$TNB, respectively. In all cases, two methyl groups of each neopentyl face toward the benzene ring, perhaps due in part to attractive $C_{sp^3}\cdots C_{Ar}$ interactions between the two methyl carbons and the ortho, ortho′ aromatic carbons. For example, a contribution of −0.78 kcal/mol to the energy of rotamer D in TNB is calculated to arise from this source. The corresponding value for rotamer A, B, or C in TNB (the "up"-neopentyl group) is −0.91 kcal/mol. However, as pointed out by one of the referees, these attractive forces are probably not the main factors determining the molecular geometry here, since this geometry is required to prevent eclipsing at the methylene group. Preliminary data from an x-ray structure determination on Br_3TNB[16] reveal the same preferred conformation of the neopentyl methyls and, interestingly enough, the coexistence of equal amounts of rotamers of types A, B, C and D in the crystal.

Table II. Nonbonded Components of Strain Energy for Rotamers D and A/B/C in Trineopentylbenzene

Nonbonded interaction	Number	Strain energy, kcal/mol D	A/B/C
$H\cdots H$	600	−0.715	−0.457
$C_{sp^3}\cdots H$	474	−6.759	−6.257
$C_{sp^3}\cdots C_{sp^3}$	75	−0.353	−0.252
$C_{Ar}\cdots H$	201	1.777	1.889
$C_{Ar}\cdots C_{sp^3}$	78	−3.329	−3.320
Total	1428	−9.38	−8.40

Table III. Average C-C Bond Lengths and C-C-C Bond Angles in Neopentane and the Neopentyl Groups in Rotamers A, B, C and D in Trineopentylbenzene

Average C-C bond distance, Å	Average C-C-C bond angle, deg	Ref
	Neopentane	
1.54 ± 0.01	109.5 ± 1	17
1.540	109.6	18
1.545		19
1.533	109.47	STRAIN calcn (present work)
Neopentyl groups in A,B,C,D as calculated by STRAIN		
C-C bond distances, Å	C-C-C bond angles, deg	
1.534-1.541	108.1-111.5	

A further dissection of the nonbonded strain energy components for TNB itself is presented in Table II. Obviously the 474 $C_{sp^3}\cdots H$ interactions are the dominant contributors to the attractive part of this energy, for the individual rotamers as well as for the difference between them, taken per interaction. The only other comparably important contribution to the energy difference arises from the $C_{sp^3}\cdots C_{sp^3}$ interactions. The results in this table reflect the choice of the "hardness parameters" ϵ_H and ϵ_{Csp^3} as 0.06 and 0.116 kcal/mol, respectively, with equal van der Waals radii of 1.50 Å for both H and C_{sp^3}.[9a] The total energy difference of −0.91 kcal/mol is of interest in comparison with a corrected $\Delta G°$ value of −1.04 kcal/mol estimated for Br_3TNB by taking into account a symmetry factor of $R \ln 3$, in conjunction with a measured $\Delta G°$ value of −0.49 kcal/mol at −19 °C. The experimental value was obtained in deuteriochloroform solution in connection with a complete band shape analysis of the methylene proton spectrum.[1]

The calculated C-C bond distances and C-C-C angles in the neopentyl groups in both types of rotamer are not unduly

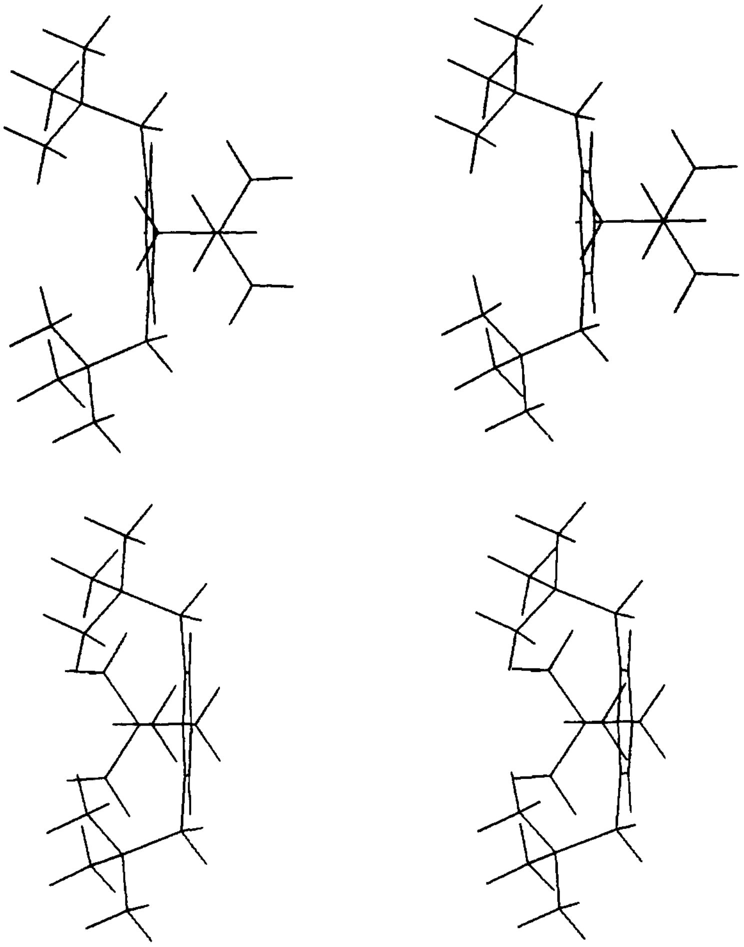


Figure 2. Stereoviews of calculated conformations for rotamers A, B, C (above) and D (below) in TNB. The conformations are shown in *yz* projections. (The *z* direction is perpendicular to the plane of the aromatic ring.)

distorted in comparison with corresponding experimental distances and angles estimated by electron diffraction studies on neopentane.[17-19] (See Table III, which also includes the results of a STRAIN calculation on neopentane.) Changes in the geometry of the neopentyl groups themselves may consequently be eliminated as potentially important contributions to the total calculated attractive van der Waals energy.

In the case of $(CH_3)_2$TNB, due to the symmetry properties of the molecule, the conformational energies of three different rotamers must be taken into account, viz. a chiral pair A and C related by mirror-image symmetry and the achiral rotamers B and D (see Figure 1, $X = Y = CH_3$, $Z = H$). This is true for all mono- and identically disubstituted TNB's and for all trisubstituted TNB's with two identical substituents. (In disubstituted TNB's with different substituents, A and C are not enantiomerically related.) In $(CH_3)_2$TNB, rotamer B is calculated to lie 1.0 kcal/mol higher in energy than D, while the A,C pair is (unexpectedly) only 0.06 kcal/mol above rotamer D (see Table I).

The calculations on $(CH_3)_3$TNB were discontinued after a total of ca. 1.5 h of CPU time on the UNIVAC 1108 had been expended (on rotamers D and A/B/C together) without achieving complete minimization. This was obviously due to the presence of a very shallow minimum in the potential surface, since the conformational strain energy began to change very slowly just prior to the discontinuation of the calculations. For example, the energy of rotamer D decreased only 0.5 kcal/mol (from 23.64 to 23.15 kcal/mol) during 13 min of CPU time, and further calculations were judged to be economically unfeasible. With these limitations in mind, a comparison can nonetheless be made between the calculated energy difference between rotamers A/B/C and D (of the order of 1.4 kcal/mol, cf. Table I) and experimentally determined energy differences based on population ratios at −50 and −40 °C in carbon disulfide and deuteriochloroform solutions,[1] respectively. The ratio D/(A/B/C) was found to be 1.4 in the former solvent and 3.1–3.2 in the latter. The value in deuteriochloroform corresponds to a $\Delta G°$ of −0.54 kcal/mol, while that in carbon disulfide corresponds to $\Delta G° = 0.16$ kcal/mol. Taking into account a symmetry factor of $R \ln 3$, as described above for TNB itself, yields corrected $\Delta G°$ values of −1.04 kcal/mol in deuteriochloroform solution and −0.64 kcal/mol in carbon disulfide solution.

A point of interest which should be borne in mind in connection with molecular mechanics results is that the calculations refer of course to the gas phase and, as noted by Ford and Allinger,[21] when conformational free energies have been determined in both the gas phase and in solution, it is observed that in solution the equilibrium is shifted toward the conformer with smallest molecular volume. The calculated energy differences are consequently not expected to apply exactly in solution. Errors from this source would hopefully be no more than a few tenths of a kilocalorie per mole,[21] but in the cases considered in this paper, this approaches the observed energy differences. The experimental observations[1] are, however, consistently interpretable in the same direction as the molecular mechanics results, i.e., in terms of the preponderance of type D rotamers.

Barriers to Internal Rotation. An experimental value of $\Delta G^{\ddagger}_{118K} = 5.4 \pm 0.2$ kcal/mol for the barrier to rotation of

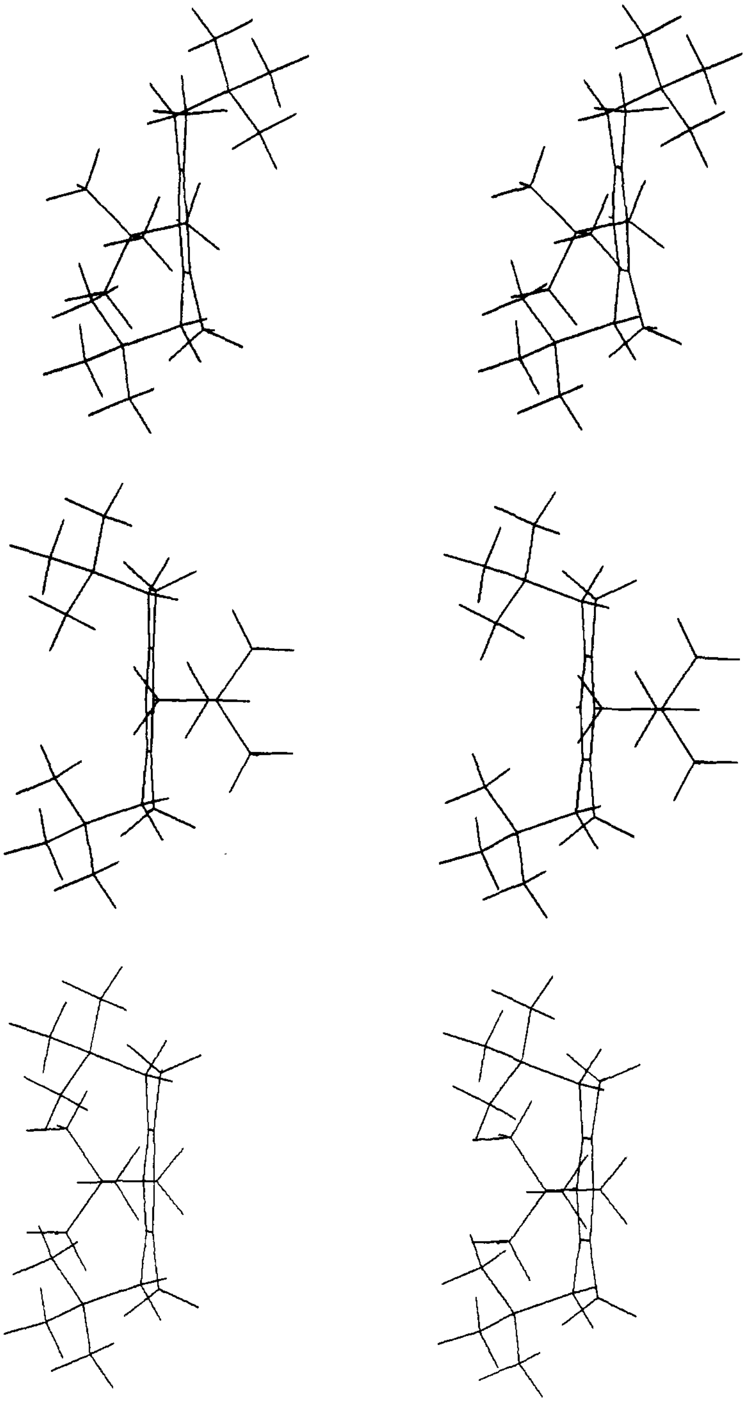


Figure 3. Stereoviews of calculated conformations for rotamers A, C (top), B (middle), and D (bottom) in $(CH_3)_2$TNB. (See caption for Figure 2.)

a neopentyl group past a proton was estimated[14] by band shape simulation near the collapse temperature, using 2-bromo-3,5-di-*tert*-butylneopentylbenzene as a model compound. We have previously[15] concluded that the barrier to rotation is primarily determined by the effect of the smaller of the two different substituents in unsymmetrically disubstituted compounds. Assuming that this conclusion is transferable to the model compound, the observed barrier of 5.4 kcal/mol may be taken as a good "order-of-magnitude" value for the barrier in 1,3,5-trineopentylbenzene itself, which will now be compared with the barrier calculated with the aid of the STRAIN program.

In transition-state geometry and energy calculations with an energy minimization procedure, it is usually necessary to resort to the artifice of restricting the motion of certain atoms in order to prevent the relaxation of the molecular geometry back toward that of the initial state.[20] The starting geometry for the transition-state calculations was obtained by simply rotating the "up" neopentyl group in an A/B/C rotamer 90° by means of a program auxiliary to STRAIN for performing coordinate transformations (TRANSF). The potential energy surface describing the internal rotation is of course unsymmetrical, since the initial and final states are not identical. However, the transition state(s) must be the same independent of the direction of approach, and as computer time was at a premium we decided to concentrate on a reasonable transition-state energy and geometry rather than attempting to map out a complete reaction coordinate as a function of the torsional angle of the rotating neopentyl group.

Initially, no restricted motion was applied, and apparently

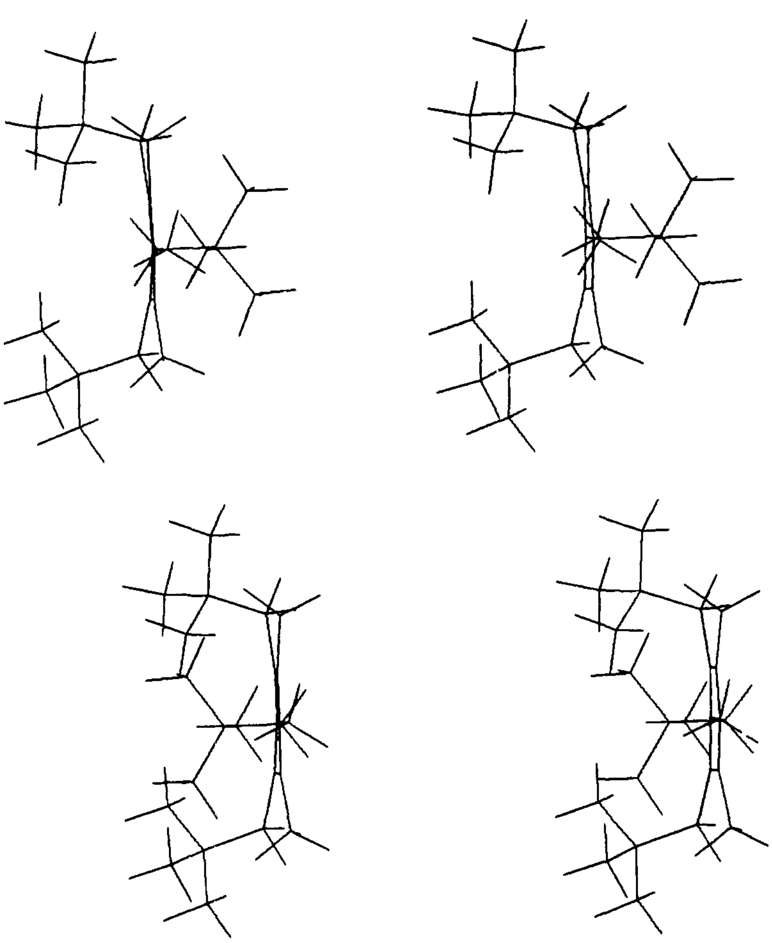


Figure 4. Stereoviews of calculated conformations for rotamers A, B, C (above), and D (below) in $(CH_3)_3$TNB. (See caption for Figure 2.)

the "scissoring" of the ring by the rotated $>C(CH_3)_2$ fragment prevented a return to the initial state energy. Nonetheless, the quaternary and methylene carbons of the rotated neopentyl group and the aromatic carbon to which this group was attached were subsequently "frozen" in the *z* direction (perpendicular to the ring plane). Furthermore, in order to save computer time, all of the atoms in the "nontwisted" neopentyl groups, as well as the remaining aromatic ring carbons, were "frozen" in all directions until the energy minimization was ostensibly complete. (The value of the energy at this point was 4.63 kcal/mol.) All of the restricted atoms, except for those directly involved in the rotation (cf. above) were then "unfrozen" and a new energy minimization was performed to reach a final value of 4.48 kcal/mol. The most important contributions to this total energy are bond strain (3.65 kcal/mol), angle strain (8.71 kcal/mol), and nonbonded interaction (−7.29 kcal/mol). The largest increases compared to the initial state (cf. Table I) are due to angle strain and nonbonded interactions, as might be intuitively expected. (The $C_{Ar}CH_2C<$ angle is opened from 116.2° in A/B/C to 126.7° in the "transition state".)

Presumably, the reaction coordinate is primarily a combination of twisting about the C_{Ar}–CH_2 and $CH_2C<$ bonds. The energy calculated as described above should represent a local minimum in the potential surface rather than a "true" saddle point, since we have not specifically taken into account the possibility that twisting about the $CH_2C<$ bond *after* a 90° twist about the C_{Ar}–CH_2 bond might be involved in the approach to the transition state. (In a real molecule, of course, these two twisting modes would be expected to occur more or less simultaneously and continuously along the rotational pathway.) In order to test this possibility, the passing *tert*-butyl group was twisted about the CH_2–$C<$ bond, first by 8°, then by an additional 5°, and finally by a further 7°. After each twist, the geometry was allowed to completely relax. We reasoned that if the energy increased beyond the value of 4.63 kcal/mol obtained previously (for the "frozen" system), this would indeed indicate a local minimum, and the increased energy would more closely approximate that of the "transition state". Each twist increment led to an initial increase of the energy, which was then relaxed to the same value (within 0.01 kcal/mol) of 4.68 kcal/mol, only 0.05 kcal/mol above the original value. The completely "unfrozen" system at this point relaxed from 4.68 to 4.51 kcal/mol, and thus we finally find the "transition state" to lie ca. 5.5 kcal/mol above rotamer D. The agreement between this value and the experimental estimate cited above is probably at least partly fortuitous, but it is nonetheless extremely encouraging. A stereoview of this "transition state" structure is shown in Figure 5.

Similar calculations were performed on $(CH_3)_2$TNB, starting from rotamer D or B, and leading to a "transition state" energy of 26.09 kcal/mol, i.e., 13.63 kcal/mol above rotamer D or 12.63 kcal/mol above rotamer B. The experimental $\Delta G^{\ddagger}_{298K}$, corrected for the symmetry factor due to the two possible identical paths for rotation past a methyl group in this molecule, is 15.4 kcal/mol.[14] The $C_{Ar}CH_2C<$ angle of the rotated neopentyl group opens from 118.3° in rotamer D (or 119.8° in B) to 135.3° in the corresponding "transition state", and is thus the dominant source of strain energy in this structure. A twisting/relaxation procedure analogous to that

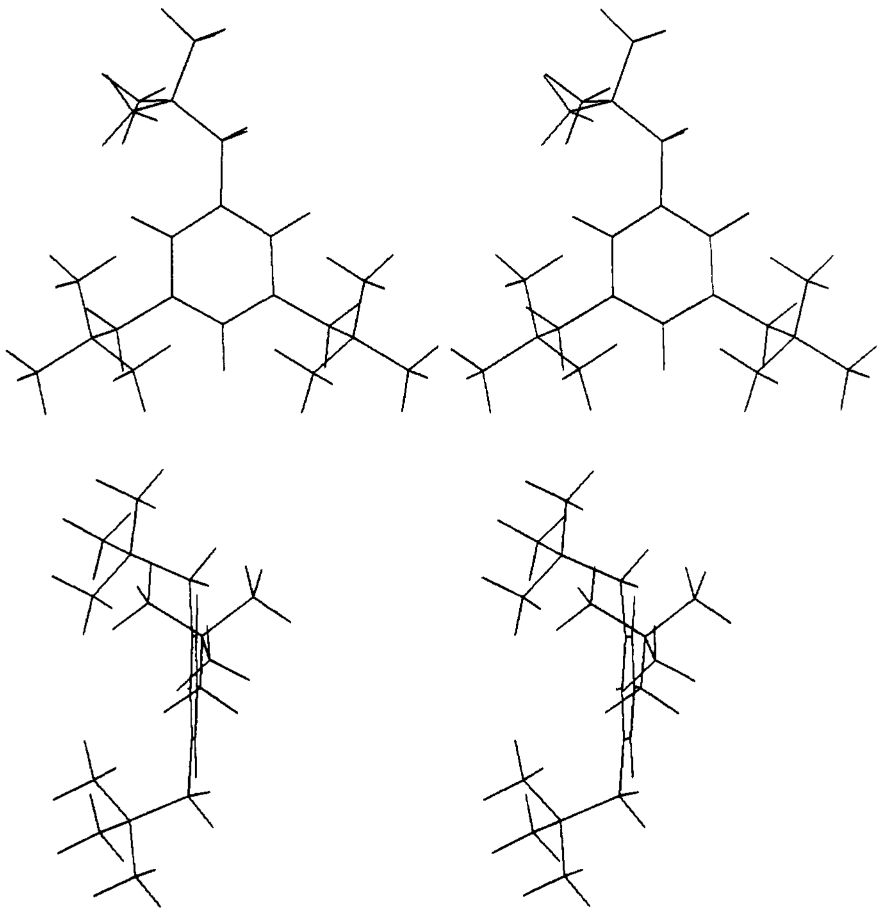


Figure 5. Stereoviews of calculated "transition-state" structure for the internal rotation of a neopentyl group in TNB. The structure is shown in *xy* (above) and *yz* (below) projections.

described for TNB, with a twist angle of 20°, led to a *lower* energy after relaxation than the 26.22 kcal/mol originally obtained.

Conclusions.

This work has provided firm theoretical support for the operation of attractive steric effects as the determining factor in conformational equilibria in a pure hydrocarbon system. The existence of such effects has of course long been known, but examples of experimental evidence[1] corroborated by theoretical calculation are scarce in the literature. A possible example is the apparent preference for a conformer containing gauche *tert*-butyl groups in the meso isomer of 3,4-dichloro-2,2,5,5-tetramethylhexane,[22] but this case is complicated by the presence of the chlorine atoms, which are also gauche in the preferred conformer. In any event, attractive steric effects are certainly more important than has generally been recognized for pure hydrocarbon systems.

The attractive effects discussed in this work trace their origin to long-range London dispersion forces, the resulting energy of which is given (in principle, at least) by a second-order pertubation treatment of an appropriate wave function. They should be carefully distinguished (conceptually) from the attractive steric effects discussed in the framework of *ab initio* SCF molecular orbital calculations,[23] from which attractive steric effects may emerge by consideration of the balance between electron-electron and nuclear-nuclear repulsion on the one hand, and nuclear-electron attraction on the other.[23,24]

Acknowledgment. We are grateful to Dr. Tommy Liljefors, University of Lund, for comments on the manuscript during the course of preparation, and to Mr. Bo Nilsson for assistance with some of the STRAIN calculations. We are deeply indebted to Professor Kurt Mislow, Princeton, for his kindness and generosity in placing the STRAIN program package at our disposal. This work was supported in part by a grant from the Swedish Natural Science Research Council.

References and Notes

(1) Part 7: R. E. Carter, B. Nilsson, and K. Olsson, *J. Am. Chem. Soc.*, **97**, 6155 (1975).

(2) (a) Organic Chemistry 2; (b) Physical Chemistry 2.

(3) (a) T. L. Hill, *J. Chem. Phys.*, **14**, 465 (1946); (b) *ibid.*, **16**, 399 (1948).

(4) (a) F. H. Westheimer and J. E. Mayer, *J. Chem. Phys.*, **14**, 733 (1946); (b) F. H. Westheimer, *ibid.*, **15**, 252 (1947); F. H. Westheimer in "Steric Effects in Organic Chemistry", M. S. Newman, Ed., Wiley, New York, N.Y., 1956, Chapter 12.

(5) J. B. Hendrickson, *J. Am. Chem. Soc.*, **89**, 7047 (1967), and previous papers in the same series.

(6) K. B. Wiberg, *J. Am. Chem. Soc.*, **87**, 1070 (1965).

(7) D. H. Wertz and N. L. Allinger, *Tetrahedron*, **30**, 1579 (1975), and other papers in the same series by Allinger and his coworkers.

(8) E. M. Engler, J. D. Andose, and P. v. R. Schleyer, *J. Am. Chem. Soc.*, **95**, 8005 (1973).

(9) (a) J. D. Andose and K. Mislow, *J. Am. Chem. Soc.*, **96**, 2168 (1974); (b) M. G. Hutchings, J. D. Andose, and K. Mislow, *ibid.*, **97**, 4553, 4562 (1975).

(10) R. H. Boyd, *J. Chem. Phys.*, **49**, 2574 (1968).

(11) (a) M. Bixon and S. Lifson, *Tetrahedron*, **23**, 769 (1967); (b) S. Lifson and A. Warshel, *J. Chem. Phys.*, **49**, 5116 (1968); (c) A. Warshel and S. Lifson, *ibid.*, **53**, 582 (1970); (d) O. Ermer and S. Lifson, *J. Am. Chem. Soc.*, **95**, 4121 (1973).

(12) For reviews and discussions of the empirical force field molecular mechanics method, see (a) J. E. Williams, P. J. Stang, and P. v. R. Schleyer, *Annu. Rev. Phys. Chem.*, **19**, 531 (1968); (b) A. I. Kitaygorodsky, "Molecular Crystals and Molecules", Academic Press, New York, N.Y., 1973, Chapter 7; (c) C. Altona and D. H. Faber, *Fortschr. Chem. Forsch.*, **45**, 1 (1974).

(13) The STRAIN program was generously placed at our disposal by Professor Kurt Mislow, Princeton University.

(14) B. Nilsson, P. Martinson, K. Olsson, and R. E. Carter, *J. Am. Chem. Soc.*, **96**, 3190 (1974).

(15) (a) B. Nilsson, R. E. Carter, K.-I. Dahlqvist, and J. Márton, *Org. Magn. Reson.*, **4**, 95 (1972); (b) P. Martinson, *Acta Chem. Scand.*, **26**, 3568 (1972).

(16) B. Aurivillius, unpublished results.
(17) R. L. Livingstone, C. Lurie, and C. N. R. Rao, *Nature (London)*, **185**, 458 (1960).
(18) W. Zeil, J. Haase, and M. Dakkouri, *Z. Naturforsch.*, **22**, 1644 (1967).
(19) L. D. Ray, Thesis, University of Texas at Austin, 1971.
(20) See, however, O. Ermer, *Tetrahedron*, **31**, 1849 (1975).
(21) W. Ford and N. L. Allinger, *J. Org. Chem.*, **35**, 3178 (1970).
(22) D. C. Best, G. Underwood, and C. A. Kingsbury, *Chem. Commun.*, 627 (1969).
(23) See, for example, J. E. Eilers and A. Liberles, *J. Am. Chem. Soc.*, **97**, 4183 (1975); S. Wolfe, *Acc. Chem. Res.*, **5**, 102 (1972); R. B. Davidson and L. C. Allen, *J. Chem. Phys.*, **54**, 2828 (1971).
(24) L. C. Allen, *Chem. Phys. Lett.*, **2**, 597 (1968); W. H. Fink and L. C. Allen, *J. Chem. Phys.*, **46**, 2261 (1967).

On the Ability of the CNDO/2 and INDO MO Methods to Cope with Nonbonded Interactions

Allan R. Gregory and Michael N. Paddon-Row*[1]

Contribution from the Department of Chemistry, The Australian National University, Canberra, Australia 2600. *Received September 18, 1975*

Abstract: Results are presented which show that the popular CNDO/2 and INDO closed-shell restricted Hartree-Fock MO methods are unable to account properly for nonbonded interactions. Potential energy curves which should be strongly repulsive are predicted to be either weakly repulsive or attractive. The more sophisticated of the two methods, the INDO method, gives significantly worse results. In contrast, the extended Hückel method, the simplest full-overlap all-valence electron MO method, predicts the correct nature of the curves.

The ready availability of computer programs for calculating electronic wave functions and energies by single determinantal molecular orbital (MO) methods has resulted in a large increase in the number of applications of these methods to problems in organic chemistry and biology. One only has to look through recent issues of this journal to see how important and popular a tool they have become in these fields for rationalizing the results of experiments and for guiding new ones.

The methods currently enjoying the greatest popularity amongst experimentalists are the approximate, all-valence electron, neglect of differential overlap (NDO) variants of the Hartree-Fock (HF) model. The complete (C) NDO/2 and intermediate (I) NDO schemes that were introduced by Pople and his co-workers[2] are the two most often used. Most specialists in MO calculations are aware, however, that these two schemes overemphasize bonding effects in molecules. Thus they tend, for example, to favor more highly connected structures.[3,4] However, this particular defect is one that is shared in many systems by minimal basis ab initio HF theory.[3] Hence it is not always wholly due to the NDO approximations or to the choice of parameters, but is sometimes due in part to the use of a minimal basis.

Other failures of the CNDO/2 and INDO methods which have the same origin, but are not shared by minimal basis ab initio HF theory, have been reported.[2,3a,4] There is, however, one such failure that has not yet been properly documented. The purpose of this paper is to correct that situation by presenting the results of some simple test calculations, which show unequivocally that the CNDO/2 and INDO methods are unable to account properly for nonbonded lone pair/lone pair and lone pair/π-bond interactions. Applications of these methods to conformational problems where such interactions play a nonnegligible role are therefore of uncertain value.

Our work stems from a CNDO/2 and INDO closed shell (CS) restricted (R) HF investigation of intramolecular hydrogen bonding between alcohols and unsaturated linkages.[3a,5] Calculations on a model system consisting of a methanol molecule suitably oriented with respect to an ethylene molecule correctly predicted the existence of weak OH. . . π bonds, but also implied that alcohols can interact with double bonds so as to form "oxygen-π" bonds. We argued that the latter bonds could derive their stability from the mixing of the nonbonding atomic orbitals (AO's) of the oxygen and the π MO's of the double bond and turned to a simpler and more convenient system to test this hypothesis. Our results are reported in the next section.

Water/Ethylene System

Potential energy curves were calculated by the CNDO/2 and INDO CS RHF methods for the four approaches of a water molecule to an ethylene molecule, shown in Figure 1.[6]

The geometries of both molecules were held fixed. The CC and CH bond lengths in the ethylene molecule were set at 1.339 and 1.086 Å, respectively, and the HCH bond angles at 117.5°. The OH bond lengths in water were set at 0.98 Å, the HOH angle at 104.2°.

Orbital interaction diagrams for the lone pair orbitals, n_1 and n_2, of the oxygen and the π and π^* MO's of the double bond are also shown schematically in Figure 1. The symmetry classifications S (symmetric) and A (antisymmetric) refer to the symmetry planes indicated at the bottom of each diagram. The symmetry inherent in approaches 2–4 was not available to us in the methanol/ethylene system because of the presence of the methyl group. Case 1 corresponds to the methanol/ethylene approach which led to the most stable symmetrical "oxygen-π" bond. Cases 2 and 4 are the most interesting because, at the level of approximation implied by the diagrams, there can be little doubt as to the outcome of orbital mixing: destabilization and a repulsive potential energy curve.

The CNDO/2 and INDO calculations led, however, to attractive potential curves for all four approaches. The approximate distances between the oxygen atom and the midpoint of the CC bond of the ethylene at the minima and the corresponding stabilization energies are shown in Table I. Approach 1 leads to the deepest minimum, but approach 2, which one expects to be repulsive from simple orbital interaction considerations, is also associated with strong stabilization at distances not too far removed from ordinary bonding distances. The other two approaches are associated with potential curves with very shallow minima at much larger distances; here rising electronic stability is nearly offset by the internuclear repulsion