Synthesis and Conformational Study of 1,1'-Ethano-9,9'-bifluorenyl. *Anti* and Gauche Conformers of a 9,9'-Bifluorenyl Derivative and Chair and Twist Conformers of a Dibenzo-1,5-cyclooctadiene Derivative

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Abstract: A Hofmann-type elimination of the sulphonium salt (18) under basic conditions led to the formation of a novel o-xylylene derivative (11) which dimerized regioselectively to give the bifluorenyl/dibenzo-1,5-cyclooctadiene derivative (3). The reaction is shown to be kinetically controlled and non-concerted. The two rigid conformers (3a) and (3b) were characterised by their ¹H NMR spectra and they represent respectively the first observed examples of an anti bifluorenyl derivative and a twist dibenzo-1,5-cyclooctadiene derivative. A semiempirical molecular orbital PM3 calculation supported the observed results. Dynamic ¹H NMR studies indicated an interconversion process (3a) \neq (3b) at higher temperatures involving a conformational barrier estimated at 65.2 kJ mol¹.

Whereas 1,1,2,2-tetraphenylethane¹⁻³ prefers to adopt the anti conformation, its "clamped" derivative bifluorenyl (1) has been shown to exist in the gauche conformation (1a) from theoretical calculation⁴, n.m.r. spectroscopic study in solution^{5,6} and X-ray crystallography study in solid state.⁵ The conformational behavior of dibenzo-1,5-cyclooctadiene (2) seems more complex and has received extensive investigation. An early report⁷ indicated that (2) adopts the anti conformation (2a) in the solid state. Another study⁸ by dipole moment measurement suggested a boat conformation (2b) for the molecule in solution. A twist-boat conformer (2c) was however found to be the most stable from force-field calculations.⁹ Dynamic n.m.r.



spectroscopic studies¹⁰⁻¹² reported by different workers claimed evidence for the existence of equilibria between boat-boat conformers, chair-boat conformers and chair-twist boat conformers respectively.

Our semiempirical molecular orbital PM3¹³ calculations show that in isolation, the relative stability of (2a) : (2c) : (2d) is 0 : 12.4 : 11.7 kJ mol⁻¹, whereas (2b) is not a stable conformer. (2c) is the nearest stable conformer to (2b). The conformer (2d) is less stable than (2a), because in (2d) one pair each of the C3-C7 and C4-C8 methylene protons are in close proximity (1.845Å) whereas the methylene protons in (2a) are farther apart — the closest H-H distance being 2.258Å. The conformer (2c) is less stable than (2a) due to π - π repulsion between the benzene rings in the former, which is not accounted for in force field calculations.⁹ Moreover, the C3-C7 hydrogens are separated by only 1.770Å in (2c). A model compound which possesses structural features of both (1) and (2) would be 1,1'-ethylene-9,9'-bifluorenyl (3) which is however expected to be conformationally more rigid than either (1) or (2). We wish to report on the synthesis of (3), the study of its conformational behavior experimentally using dynamic ¹H n.m.r. spectroscopy, and the theoretical study using the semiempirical MO PM3¹³



Thermal elimination of dimethylamine from the ammonium salt (4) is known to form *p*-xylylene (5) which dimerizes to form [2.2]paracyclophane.¹⁴ Pyrolysis of (6) on the other hand results in elimination of HCl leading to the formation of *o*-xylylene (7), which could yield benzocyclobutene¹⁵ or dimerize to give dibenzo-1,5-cyclooctadiene.¹⁶ Based on the above observation and taking advantage of the moderate acidities of the methylene protons in fluorene and its derivatives,¹⁷ a sulfonium salt such as (9) would be expected to eliminate dimethylsulfide under basic conditions to afford the *o*-xylylene derivative (11). Depending on the

degree of regioselectivity in the dimerization of (11), one or both of the dimers, namely (3) and (12), could then be synthesized.

Synthesis of (3).— Rearrangement of the sulfonium bromide (17) was reported¹⁸ to give only a moderate yield (*ca.* 45%) of (10). Reaction of 1-methyl-9-bromofluorene (14) with dimethylsulfide took 5-7 days to afford (17) in *ca.* 65% yield. An alternative route to the desired compound (8) was thus investigated in our work. Reaction of (13) with thiourea followed by base-hydrolysis of the initially formed thiouronium salt gave the mercaptan (15), mp 95-96°C, in 85% yield. Treatment of (15) with NaOH followed by quenching with iodomethane afforded a 91% yield of the methyl sulfide (16). Methylation of (16) was achieved readily with dimethoxycarbonium tetrafluoroborate¹⁷ yielding the sulfonium tetrafluoroborate (18) which is expected to be more stable than the corresponding sulfonium bromide similar to (17). Thus treatment of (18) with base afforded the rearranged product (8) in *ca.* 90% yield. The synthetic route from (13) to (8) involved a number of steps but the latter was obtained in an overall yield of *ca.* 57%.



Remethylation of (8) with dimethoxycarbonium tetrafluoroborate¹⁹ gave the desired sulfonium salt (9). Stirring a suspension of (9) in ethanol in the presence of NaOH led to the isolation of seemingly only one component after column chromatography. The mass spectrum of the product showed a molecular ion at m/z 356 as the base peak consistent with the structure of (3) or (12), and a strong peak at m/z 178 suggesting a facile symmetrical cleavage of the molecule. Although t.l.c. studies using various solvent systems did not indicate the presence of isomers of (3) or (12), the ¹H n.m.r. spectral data (Table 1; Figure 1) clearly support the presence of two conformers of (3). The methine protons were observed (in CDCl₃) as two singlets at δ 4.65 and 3.85 respectively. This obviously rules out the presence of any conformer of (12) the methine protons of which are expected to show a splitting pattern based on couplings with the methylene protons. In addition, the two AB quartets observed (Table 1; Figure 1) are also consistent only with ethylene bridges

present in conformers of (3).

Our results from PM3 calculations show that (12) is in fact thermodynamically more stable than (3a) (most stable conformer of (3); see later discussion) by 25.95 kJ mol-1. The fact that (12) was not formed experimentally however suggests that the regioselective dimerization of (11) to form (3) is kinetically controlled. The coefficients obtained for the HOMO and LUMO of (11) indicate that concerted overlap of the HOMO of one molecule of (11) with the LUMO of another does not lead to bonding because orbitals of opposite signs overlap between one pair of carbon atoms. This is consistent with the general rule that [4+4] cycloaddition reactions are thermally forbidden based on the conservation of orbital symmetry.²⁰ A stepwise mechanism has been forwarded to rationalize the formation of the [4+4] dimer.²¹ Based on the phase and magnitude of the lobes of the corresponding frontier orbitals, an initial overlap of the HOMO methylene carbon orbital on one molecule of (11) with the LUMO methylene or methine carbon orbital on another molecule of (11) is almost equally likely. Qualitatively however a steric consideration would suggest an initial bond formation between the two methylene terminals followed by the ring closure via the two methine carbons. This could be further encouraged by the formation of the relatively more stabe intermediate diradical (I) compared to the route affording diradical (II). Reported results on the relative rates of radical formation²² indicated that diphenylmethyl radical could be formed >65 times faster than the phenylmethyl radical. The resonance stabilization of the diradical (I) and the steric inhibition favouring the formation of (3) must be very significant kinetically to discourage the formation of the thermodynamically more stable (12).



Rigid Conformers of (3).— All three integration ratios (in CDCl₃) of the two doublets for H-8/H-8', the two singlets for the methine protons and the two AB quartets for the methylene protons indicated a 1.2:1.0 mixture of two conformers of (3). Based on the known conformational behavior of (1) and (2), there are four possible conformers of (3), namely the *anti/chair* (3a), the gauche/twist (3b), the *syn/boat* (3c) and the gauche/twist-boat (3d). The higher conformational rigidity in (3) however does not allow the following interconversion

processes: (3a) = (3c), (3a) = (3d), (3b) = (3c) and (3b) = (3d). Steric interactions in (3c) and (3d) are also expected to be more severe than those in (3a) and (3b). In addition, immediately apparent on examination of the proton chemical shifts of the ring protons for the isolated product is the presence of shielded H-8/H-8' (\$6.33, 6.07). The other aromatic protons were observed as complex multiplets in the range of $\delta 6.9-7.8$. With reference to the respective chemical shifts of H-8/H-16 for [2.2]metacyclophanes anti-(19)²³ and svn-(19).24 our observed data are clearly consistent with conformers (3a) and (3b) which have H-8/H-8' located near the shielding zones of the respective opposite benzene rings similar to H-8/H-16 in anti-(19). The presence of the conformer (3c) would have shown an upfield shift of the external protons (H-2, 2', 3, 3', 4, 4', 5, 5', 6, 6', 7, 7') similar to those in syn-(19) as a consequence of one aromatic ring shielding the other. Going from the [2.2]metacyclophane anti-(19) to the anti-[2.2]orthocyclophane (dibenzo-1,5-cyclooctadiene) system in (3a) involves a significant outward sliding of rings A and C, and thus rings B and D, similar to phenomena reported for related cyclophane systems.²⁵ This would account for the much less significant shielding experience of H-8/H-8' (δ6.33) in (3a) compared with that of H-8/H-16 (δ4.25) in anti-(19). The chemical shift of the methine protons (δ 4.65) in (3a) is similar to that (δ 4.71) in (1). The PM3 calculations showed that when the ethano bridge in anti/chair (3a) undergoes pseudo-rotation to give gauche/twist (3b) (going from (III) to (IV)), there is an inward sliding of rings B and D thus placing H-8/H-8' (δ 6.07) in (3b) more directly over the respective shielding zones of rings B and D compared to (3a) where H-8/H-8' appears at δ6.33 although these rings are slightly further apart in (IV). The rigid guache/twist conformation of (3b) also places the methine protons (δ 3.85) slightly above rings A and C respectively thus resulting in the appreciable shielding of these protons.



The PM3 calculations showed that in isolation, the relative stability of (3a) : (3b) : (3d) is 0 : 0.083 : 18.08 kJ mol⁻¹, whereas (3c) is not a stable conformer. Therefore, relative to (3a), conformer (3b) is thermodynamically possible but (3d) is less likely. There is also a kinetic reason for (3d) not being formed, due to the steric hindrance of having to place (11) face to face to form (3d). The calculations showed that converting (3a) to (3b) entailed a loss of entropy by 1.277 J K⁻¹ mol⁻¹, which at 298K contributes 0.380 kJ mol⁻¹ to the equilibrium free energy ΔG° . Adding on the enthalpy gives the total $\Delta G^{\circ} = 0.463$ kJ mol⁻¹, and using the usual thermodynamic expression $\Delta G = -RT$ In K we obtain for the equilibrium ratio (3a) : (3b) = 1.20 : 1 which agrees very well with the ¹H NMR experiment in CDCl₃. The calculations also showed that (3a) is an entropy favoured conformation due to its greater vibrational degrees of freedom.

	H8, H8'	Methine	Methylene
3a ^{e,b}	6.33,° d, <i>J</i> 7.6 Hz	4.65, s	3.70, 3.44; AB, J 15.7 Hz
3b ^{a,b}	6.07, ^e d, J 7.4 Hz	3.85, s	3.24, 3.07; AB, J 13.3 Hz
3a ^{b,c}	6.27, ¹ d, <i>J</i> 7.6 Hz	4.45, s	3.63, 3.41; AB, J 15.9 Hz
3b ^{b,c}	6.06, ^f d, <i>J</i> 7.5 Hz	3.56, s	3.23, 2.98; AB, J 13.1 Hz
3a ≠ 3b ^{c,d}	6.17, d, <i>J</i> 7.6 Hz	4.05, s	3.42, 3.19; AB, J 14.6 Hz
Τ _c (K)	324	340	329
Δv (Hz)	65.9	268.4	118.8, ⁹ 129.9 ^h
ΔG_{c}^{+} (kJ mor ¹)	65.6	65.1	65.1, ⁹ 64.9 ^h

Table 1. ¹H NMR spectral data (300 MHz) of selected protons of 3a and 3b, and the observed free energy of activation for 3a - 3b based on dynamic ¹H NMR spectroscopic studies.

9n C₆D₅NO₂. dAt 383K. ^bAt 298K. ^aIn CDCI₃. Other aromatic protons of 3a and 3b appear as complex multiplets at \$6.89-7.82. Other aromatic protons of 3a and 3b appear as complex multiplets at δ6.93-8.12. PReferring to the two low-field doublets of the respective AB quartets.

^hReferring to the two high-field doublets of the respective AB quartets.



Figure 1. ¹H NMR spectra of the methylene and methine protons of (3a) and (3B) at 30°C and 110°C ($C_6D_5NO_2$; 300 MHz)

Dynamic n.m.r. study of (3).— The above results evidently confirm the existence of rigid conformers (3a) and (3b) at room temperature. An estimate of the conformational barrier for the interconversion process (3a) **#** (3b) would then require a high-temperature dynamic ¹H n.m.r. study. The ¹H n.m.r. spectrum of the product mixture in $C_6D_5NO_2$ at 25°C indicated a 1:1 ratio of (3a) and (3b) based on integrations of H-8/H-8', the methine protons and the methylene protons. The frequency separations (Δv) of the peaks concerned (Table 1) are very large in comparison with the line width of the signals. Thus the coalescence temperature method^{26,27} would allow a good estimate of ΔG^+_c (the transition state free energy at coalescence) as a measure of the energy barrier for the process (3a) **#** (3b). An interesting feature in the ¹H NMR spectrum of (3a) and (3b) taken in $C_6D_5NO_2$ is the appreciable upfield shifts of the methine protons (Table 1) compared with the spectrum taken in CDCl₃. The solute-solvent interactions would be expected to involve the stacking of nitrobenzene molecules over and below the planar fluorene moietles in (3a) and (3b) thus further shielding the methine protons.

As a sample of (3a) and (3b) in C₆D₅NO2 was warmed from 25°C, all signals seemed to broaden although to different extents. The complete coalescence of the two doublets corresponding to H-8/H-8' of the two conformers could be observed precisely at 51°C. Due to partial overlap of signals, the coalescence temperature of the two AB quartets corresponding to the methylene protons could only be estimated at ca. 56°C. The two singlets corresponding to the methine protons however could again be correctly observed to coalesce at 67°C. At 110°C a doublet (δ), a sharp singlet (δ) and an AB quartet (δ_A , δ_B) were observed, within experimental error, at the averaged positions of the initial pairs of doublets, singlets and AB quartets respectively (Table 1; Figure 1). This is consistent with the conformational process involving a rapid interconversion (3a) # (3b). An examination of molecular models indicates that the CH-CH bridge is more rigid but pseudo-rotation of the CH2-CH2 bridge alone would bring about the interconversion (3a) = (3b). Based on the spectra taken at several temperatures near 25°C at which the rate of exchange was slow, there was no significant dependence of the frequency separation (Δv) on temperature. Thus the chemical shift differences (Δv ; Table 1) at the respective coalescence temperatures (T_c ; Table 1) of H8/H8', methine protons and methylene protons in the dynamic n.m.r. study of (3) were assumed to be very similar to those at 25°C. Within experimental error, values of the transition state free energy at coalescence, ΔG_{s}^{\dagger} , estimated from the equation: ${}^{26,27} \Delta G_{c}^{\dagger} = 0.019 T_{c}(9.972 + \log T_{c}/\Delta v)$ kJ mol⁻¹, based on the coalescence of H8/H8', methine protons and methylene protons in (3) agree satisfactorily (Table 1). The conformational energy barrier for the interconversion process (3a) = (3b) was thus estimated at ca. 65.2 kJ mol⁻¹.

Conclusion.— Before this work, derivatives of bifluorenyl (1) were all reported⁶ to adopt the gauche conformation. The conformer (3a) should be the first observed rigid *anti* bifluorenyl derivative. On the other hand, derivatives of dibenzo-1,5-cyclooctadiene (2) seem to exhibit different conformational preference among the chair, boat and twist boat conformers.^{11,12,28} The conformer (3b) described in our work should however be the first twist dibenzo-1,5-cyclooctadiene derivative reported. A semiempirical molecular orbital PM3 calculation clearly supported the observed results. In addition, the relatively high rigidity in conformers of (3)

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is evident from the energy barrier found for the interconversion process (3a) \neq (3b) (65.2 kJ mol⁻¹) which is significantly higher than the barriers observed for gauche-gauche interconversion in bifluorenyls (40-55 kJ mol⁻¹).⁶ The free energy of activation observed for chair-boat, boat-boat, or boat-twist boat interconversions in dibenzo-1,5-cyclooctadiene derivatives however varies largely (35-90 kJ mol⁻¹)^{11,12} depending on the nature of the substituent(s).

Experimental Section

All melting points were determined on a Synbron/Thermolyne MP-12615 melting apparatus and are uncorrected. ¹H n.m.r. spectra were determined in CDCl_3 (at room temperature) or $\text{C}_6\text{D}_5\text{NO}_2$ (for high-temperature studies) on a Bruker ACF-300 (300 MHz) or a JEOL FX90Q (90 MHz) Fourier transform spectrometer. All chemical shifts are reported in ppm downfield from tetramethylsilane as the internal standard. I.r. spectra were recorded on a Perkin-Elmer 1310 infrared spectrometer. Mass spectra were determined on a VG Micromass 7305 mass spectrometer at 70 eV using electron impact. Relative intensities are given in parentheses. Microanalyses were performed by the Microanalytical Laboratory, Department of Chemistry, National University of Singapore.

Fluoren-9-thiol (15). 9-Bromofluorene (5.00 g, 20.4 mmol) and thoiurea (1.56 g, 20.4 mmol) in THF were heated at solvent refluxing temperature for 3 h. The bulk of the solvent was removed under reduced pressure and the thiouronium salt precipitated was filtered. The salt was redissolved in an aqueous solution of KOH (17.17 g, 0.31 mole) and the mixture was heated at reflux for 4 h. The mixture was then cooled and acidified carefully with conc H_2SO_4/H_2O (1:1). Chloroform was added to extract the product. The organic layer was washed with water, dried and evaporated to give (15), 3.46 g (85%). Recrystallization from hexane gave pale yellow crystals of (15), m.p. 95-96°C. MS (M⁺⁺⁾ m/z 198 (8%), 197 (10), 196 (35), 166 (15), 165 (100), 152 (13); ¹H NMR (90 MHz) δ 7.2-7.5, 7.6-7.8 (m, 8H, ArH), 4.75 (br s, 1H, H9), 1.54 (br s, 1H, SH); IR (KBr) 1475, 1440, 1400, 1229, 1180, 1020, 1000, 950, 925, 880, 765., 735, 680, 625 cm ⁻¹. Calcd for C₁₃H₁₀S: C, 78.77; H, 5.09%. Found: C, 78.65; H, 4.99%.

9-Mercaptomethylfluorene (16). A solution of (15) (3.26 g, 15.4 mmol) in degassed THF (10 ml) was cooled in ice-bath and 10% aqueous NaOH solution (1.25 ml, 31 mmol) was added. The mixture was stirred for 5 min followed by addition of iodomethane (1.1 ml, 18.4 mmol). The mixture was further stirred for 30 min and extracted with dichloromethane. The organic phase was washed with 1N HCl followed by water, dried and evaporated. The product was chromatographed on silica gel using hexane as eluent to yield (16) as a thick yellow oil, 2.98 g (91%). MS (M⁺⁺) m/z 212 (18%), 166 (15), 165 (100), 91 (14); ¹H NMR (90 MHz) δ 7.2-7.4, 7.6-7.7 (m, 8H, ArH), 4.84 (s, 1H, H9), 1.37 (s, 3H, CH₃); IR (neat) 1480, 1445, 1295, 1190, 1150, 1065, 1020, 1000, 970, 940, 915, 795, 740, 680, 645 cm ⁻¹. M_r calcd for C₁₄H₁₂S 212.0660), found (MS) 212.0660.

1-Methylmercaptomethylfluorene (8). The salt (18). A solution of (16) (10.00 g) in dichloromethane (5 ml) was added dropwise via a syringe to a suspension of dimethoxycarbonium tetrafluoroborate (11.43 g, 70.6 mmol) in dichloromethane (6 ml) maintained at -30°C under nitrogen. The mixture was then stirred without further cooling for 3 h followed by addition of ethyl acetate (35 ml). The mixture was further stirred for 4 h and colorless crystals of (18), 18.13 g (82%) were filtered.

Rearrangement of **(18)**. NaOH (3.82 g, 95.5 mmol) was added to a suspension of **(18)** (10.00 g, 31.8 mmol) in 95% ethanol and the mixture was stirred at room temperature for 3 h. The solvent was removed under reduced pressure and the product extracted into dichloromethane. The organic phase was washed with water, dried and evaporated. The product was chromatographed on silica gel with hexane as eluent to yield **(8)**, 6.51 g (90%). Recrystallization from hexane gave orange crystals of **(8)**, m.p. 77-78°C. MS (M⁺) *m/z* 226 (14%), 179 (80), 178 (100), 176 (15), 165 (12), 89 (12); ¹H NMR (90 MHz) δ 7.1-7.8 (m 7H, ArH), 3.76 (s, 2H, H9), 3.88 (s, 2H, CH₂S), 1.98 (s, 3H, CH₃); IR (KBr) 1475, 1445, 1300, 1185, 1155, 1105, 1095, 1025, 1005, 975, 940, 920, 870, 830, 785, 750, 735, 680, 650, 625 cm ⁻¹. Calcd for C₁₅H₁₄S: C, 79.60; H, 6.23%. Found: C, 79.25; H, 6.29%.

1,1-Ethano-9,9'-bifluorenyl (3a) and (3b). The salt (9). Methylation of (8) (2.00 g, 8.84 mmol) with dimethylcarbonium tetrafluoroborate (2.86 g, 17.7 mmol) similar to that described for preparation of (18) gave colorless crystals of (9), 2.10 g (75%).

Reaction of (9). This was carried out with (9) (0.50 g, 1.53 mmol) and NaOH (0.18 g, 4.6 mmol) under similar conditions described for the rearrangement of (18). After chromatography on silica gel using hexane as eluent, a mixture of (3a) and (3b) was obtained, 0.35 g (64%). Recrystallization from benzene/ethanol gave colorless crystals of (3a) and (3b), mp >240°C (subl.). MS (M⁺) *m/z* 356 (100%), 355 (18), 341 (13), 178 (81); ¹H NMR (300 MHz), see Table 1; IR (KBr) 1450, 1420, 1100, 950, 810, 760, 630, 625 cm ⁻¹. Calcd for $C_{28}H_{20}$: C, 94.34; H, 5.66%. Found: C, 94.19; H, 5.59%.

Computational Details. The initial geometries were generated using the MMX²⁹ force field with the PCMODEL v4.0³⁰ implemented on the PC/AT 386. All the semiempirical PM3¹³ calculations were carried out with the MOPAC system (v6.0)³¹ on a personal IRIS computer. The eigenvector following (EF) procedure,³² which was found to be faster and more robust³³ than the standard BFGS optimizer,³¹ was used together with the keywords DMAX=0.1 and PRECISE for geometry optimizations. This combination is rather efficient in minimizing the gradient norms $\sqrt{[\Sigma\partial E/\partial r]^2}]$, which are below 0.003 kcal/Å for all these systems. All the structures were ensured to be minimum with non-negative force constants. The optimized structures were inspected with the PCMODEL system. The post-SCF facility VECTORS was used to obtain the orbital coefficients and the keywords FORCE THERMO(298,298) ROT=1 were used to calculate the entropy.

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References

- 1. Finocchiaro, P.; Gust, D.; Hounshell, W. D.; Hummel, J. P.; Maravigna, P.; Mislow, K. J. Am. Chem. Soc. 1976, 98, 4945.
- Finocchiaro, P.; Gust, D.; Hounshell, W. D.; Hummel, J. P.; Maravigna, P.; Mislow, K. J. Am. Chem. Soc. 1976, 98, 4952.
- 3. Dougherty, D. A.; Mislow, K.; Blount, J. F.; Wooten J. B.; Jacobus, J. J. Am. Chem. Soc. 1977, 99, 6149.
- 4. Hounshell, W. D.; Dougherty, D. A.; Hummel J. P.; Mislow, K. J. Am. Chem. Soc. 1977, 99, 1916.
- 5. Dougherty, D. A.; Llort, F. M.; Mislow, K. Tetrahedron 1978, 34, 1301.
- 6. Olah, G. A.; Field, L. D.; Watkins, M. I.; Malhotra, P. J. Org. Chem. 1981, 46, 1761.
- 7. Baker, W.; Banks, R.; Lyon, D. R.; Mann, F. G. J. Chem. Soc. 1945, 27.
- 8. Randali, E. W.; Sutton, L. E. J. Chem. Soc. 1958, 1266.
- 9. Allinger, N. L.; Spraque, J. T. Tetrahedron 1975, 31, 21.
- 10. Montecalvo, D.; St-Jacques, M.; Wasylishen, R. J. Am. Chem. Soc. 1973, 95, 2023.
- 11. Crossley, R.; Downing, A. P.; Nógrádi, M.; Braga de Oliveira, A.; Ollis, W. D.; Sutherland, I. O. J. Chem. Soc. Perkin Trans. 2 1973, 205.
- 12. Sauriol-Lord, F.; St-Jacques, M. Can. J. Chem. 1975, 53, 3768.
- 13. (a) Stewart, J. J. P. J. Comput. Chem. 1989, 10, 209; (b) Stewart, J. J. P. J. Comp. Aided Mol. Design 1990, 4, 1.
- (a) Winberg, H. E.; Fawcett, F. S.; Mochel, W. E.; Theobald, C. W. J. Am. Chem. Soc. 1960, 82, 1428;
 (b) Winberg, H. E.; Fawcett, F. S. Org. Synth. Collect. Vol. 5 1973, 883.
- 15. See, for example: Thummel, R. P. Acc. Chem. Res. 1980, 13, 70.
- 16. (a) Errede, L. A. J. Am. Chem. Soc. 1961, 83, 949; (b) Han, B.-H. and Boudjouk, P. J. Org. Chem. 1962, 42, 751.
- (a) Streitwieser, Jr., A.; Murdoch, J. R.; Häfelinger G.; Chang, C. J. J. Am. Chem. Soc. 1973, 95, 4248;
 (b) Streitwieser, Jr., A.; Ciuffarin, E.; Hammons, J. H. J. Am. Chem. Soc. 1967, 89, 63.
- 18. Nishida, A.; Yoshimoto, Y.; Fukuda, H.; Fujisaki, S.; Kajigaeshi, S. Kagaku Kaishu 1984, 1409.
- 19. Borch, R. F. J. Org. Chem. 1969, 34, 627.

- 20. Woodward, R. B. and Hoffman, R. The Conversation of Orbital Symmetry, Verlag Chemie, GmbH, Weinheim, Bergstr., Germany, 1971.
- 21. Chou, C.-H. and Trahanovsky, W. S. J. Am. Chem. Soc. 1986, 108, 4138.
- 22. Barlett, R. D. and Hiatt, R. R. J. Am. Chem. Soc. 1958, 80, 1398.
- 23. Wilson, D. J.; Boekelheide, V.; Griffin, Jr., R. W. J. Am. Chem. Soc. 1960, 82, 6302.
- 24. Mitchell, R. H.; Vinod, T. K.; Bushnell, G. W. J. Am. Chem. Soc. 1990, 112, 3487.
- 25. Mitchell, R. H.; Yan, J. S. H.; Dingle, T. W. J. Am. Chem. Soc. 1982, 104, 2551.
- 26. I. C. Calder and P. J. Garratt, J. Chem. Soc. (B) 1967, 660.
- 27. Dixon, K. R.; Mitchell, R. H. Can. J. Chem. 1983, 61, 1598.
- (a) Marquardt, F.-H. Tetrahedron Lett. 1967, 4989; (b) Blomquist, A. T.; Meinwald, Y. C.; Bottomley, C. G.; Martin, P. W. Tetrahedron Lett. 1960, 13; (c) Cava, M. P.; Pohlak, R.; Erickson, B. W.; Rose, J. C.; Fraenkel, G. Tetrahedron 1962, 18, 1005.
- 29. Based on the MM2(87) force field with expanded parameter sets. See Bays, J. P. J. Chem. Educ. 1992, 69, 209.
- 30. Serena Software, Box 3076, Bloomington, IN 47402-3076, USA.
- 31. Stewart, J. J. P., MOPAC v6.0, Program 455, QCPE, University of Indiana, Bloomington, USA.
- (a) Baker, J. J. Comput. Chem. 1986, 7, 385; (b) Lehd, M. and Jensen, F. J. Org. Chem. 1990, 55, 1034; (c) Baker, J., Jenson, F., Rzepa, H. S. and Stebbings, A. QCPE 1990, 10, 76.
- Yi, M. Y., Investigation of Solvation and Hydrogen Bonding Using Molecular Orbital Theories, PhD Thesis, Department of Chemistry, Imperial College, London, 1991.