Journal of Theoretical and Computational Chemistry, Vol. 2, No. 2 (2003) 171–177

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AROMATICITY IN SUBSTITUTED [2,2]PARACYCLOPHANE: A DENSITY FUNCTIONAL STUDY

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Received 11 January 2003
Accepted 12 February 2003

Inductive effect in the aromatic moieties of [2,2]paracyclophane is theoretically analyzed with the density functional theory. The inclusion of different substituents in one of the moieties seems to affect the behaviour of the other. The nature of activating or deactivating groups as substituents reflect known facts on electrophilic aromatic substitutions derived from the inductive effects. The interesting feature in this case is that the phenomenon is transfered from the substituted deck to the other via transannular effects. The strain suffered by the cyclophane molecule is also analyzed.

Keywords: Cyclophane; DFT study; aromaticity; transannular effect.

1. Introduction

The chemistry of cyclophanes has reached 100 years since the [2,2]metacyclophane was prepared from the first time by Pellegrin[1] in 1899. Modern systematic studies started with the Cram and co-workers,[2] but since then, this topic has diversified into many interesting works and now the research on this matter has generated a lot of reports that can be found in excellent reviews on experimental and structural features[3,4] as well as on theoretical work.[5]

[2,2]Paracyclophane (see Fig. 1) has been used as a model in many of the studies indicated above.[5] This substance is the most simple species in this family of compounds, but it retains many of the characteristics that make the study of cyclophanes a popular topic of investigation. One of these characteristics is their behaviour with respect to aromaticity. There are a lot of theoretical and experimental studies in which the aromaticity of cyclophanes has been examined.[2c,6] The general conclusion is that the strain has little influence on the aromaticity and on the electronic behaviour of the rings. Another characteristic of these

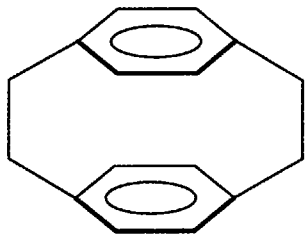


Fig. 1. [2,2]paracyclophane.

compounds that plays a role in their reactivity is the transannular electronic flow,[7] or simply transannular effect. The transannular effect is the electronic communication between the aromatic moieties. This communication can be divided in two contributions. As was suggested by Gleiter, Heilbroner and Hoffmann[8]: the contribution through space (π/π) and the contribution through bonding (σ/π). This effect could be important for the reactivity of these molecules. Indeed Sheehan and Cram[7b] reported experimental studies on the influence of substituents at one aromatic ring on the other unsubstituted ring. Cram and

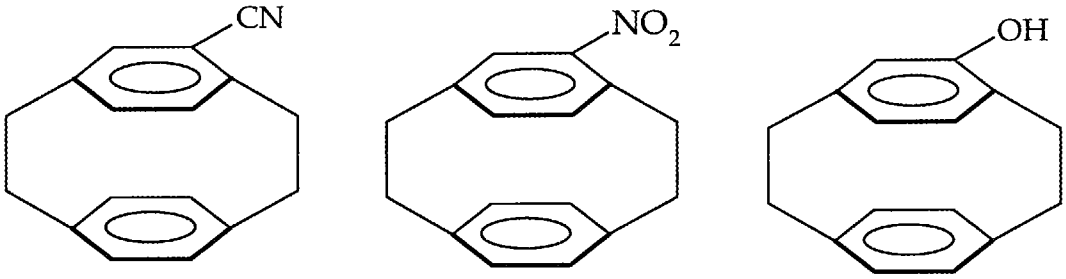


Fig. 2. Molecules under study.

Cram[2c] pointed out that the inclusion of an activating substituent on one aromatic ring activates in a normal way that ring, but may also activate the second aromatic ring.

The aim of this work was to study this possibility by comparing several substituted cyclophane molecules with different substituents which could be activating or deactivating, in order to find out the source of the proposed activation or deactivation. The results can help to clarify the experimental fact found by Cram and Cram[2c] and also can contribute to explain the source of strain suffered by this kind of molecules. The study was carried out using a DFT scheme at B3LYP/6-31G** level. NICS values (Nuclear Independent Chemical Shift) were calculated using the technique developed by Schleyer[9] in order to evaluate the changes in aromaticity. Analysis of the molecular orbitals was used to elucidate the possible pathways that the electrons follow in order to establish the transannular effect.

2. Computational Procedure

All calculations were performed using the hybrid B3LYP method[10] which combines the exact Hartree–Fock exchange with a local exchange operator[11] and uses the Lee–Yang–Parr correlation function[12] in order to include the most important correlation effects. The version used was that included in the Gaussian98 package,[13] in all cases the chosen basis was 6-31G**. This method was chosen because recent investigations have demonstrated that the DFT-B3LYP leads to excellent results for geometries and energies[14] and it has been recommended for calculations in which magnetic properties are involved.[15] Initial geometries were obtained by molecular mechanics methods included in the Cerius[2] software.[16]

3. Results and Discussion

The chosen molecules are shown in Fig. 2. The substituent groups were $-CN$, $-NO_2$, and $-OH$. The first analysis was made on monosubstituted compounds. The study was later extended to disubstituted species because the molecule suffers a strain that will be discussed hereafter, and the substitution plays an important role in the source of this strain.

[2,2]Paracyclophane presents a slightly twisted structure as has been demonstrated by a very sophisticated X-ray study.[17] Walden and Glatzhofer (WG),[18] carried out an interesting theoretical study on this molecule by means of a Hartree–Fock/B3LYP method and they got the distorted geometry, although their energy results are less accurate. Hensler and Hohlneicher (HH)[19] performed a similar study but in this case they used the MP2 method obtaining similar results to WG with respect to the geometry. They obtained more reliable values of the energy related to the distortion. HH studied other cyclophanes in another work,[20] and they proposed that one possibility for the source of the distortion could be the preference of the aromatic rings to twist, following a boat-like distortion instead of a chair-like distortion. Anyway the distortion has been difficult to study in a theoretical fashion, due maybe to the very small energy difference associated with the twist process. Several theoretical studies before the work of WG and HH reported the totally eclipsed structure by geometry optimization processes.[21]

The interesting feature is that we found spontaneously the strained structure for our substituted

molecules but not for the unsubstituted molecules. The reason for this behaviour is discussed in the next analysis.

The energy barrier between the strain and the completely symmetric structures is very small, indeed WG claim that the value is so small that the obtained numerical result is within the precision of the method (1×10^{-3} kcal/mol). HH obtained a value of 0.65 kcal/mol and in the present work the corresponding difference between the symmetric unsubstituted molecule and the strained is 0.017 kcal/mol favouring the asymmetric one. It is possible to think that the problem of these differences should not be ascribed to the method but to the fact that the barrier is very small, so it should be a very fast dynamical equilibrium between both isomers (the Boltzmann population computed with the energy results for both structures is 51.46% of symmetric isomer versus 48.54 of the twisted one). Therefore both isomers should coexist in gas or solution phase. The process of this interconversion was studied and the plot of the energy barrier against the β angle defined by WG is shown in Fig. 3.

However, the source of the strain deserves some discusion. Andrews and Westrum[22] performed thermodynamic measurements on [2,2]paracyclophane and found out that there is a transition at 50°K; and they attribute this transition to the characteristic twisting of the molecule. Boyd suggested[23] that the close distance between the rings precludes the hydrogen atoms from being so near in a way that causes some repulsion to produce the distortion. However, it is as though that there is some additional influence from the aromatic rings. The distance between the rings is 3.0 Å, less than the van der Waals distance of about 3.4 Å. This characteristic has been pointed out as the source of the transannular effect.[5] The influence of both aromatic clouds is important and the results of this paper emphasize it. The effect can be appreciated through the analysis of the substituted cyclophanes in which the breaking of the symmetry intrinsically cause the distortion, this result can help to solve the controversy between the Walden/Glatzhoffer[18] and Hensler/Hohlneicher[19] groups.

The twist angle β vary from one substituted molecule to another, the results are shown in Table 1. It is possible to see that the largest deviation is present in the electron withdrawing substituents case, i.e. when the electronic flow through space diminishes. On the other hand, the corresponding angle β of the molecule with electron release substituent is almost the same as that of the unsubstituted molecule.

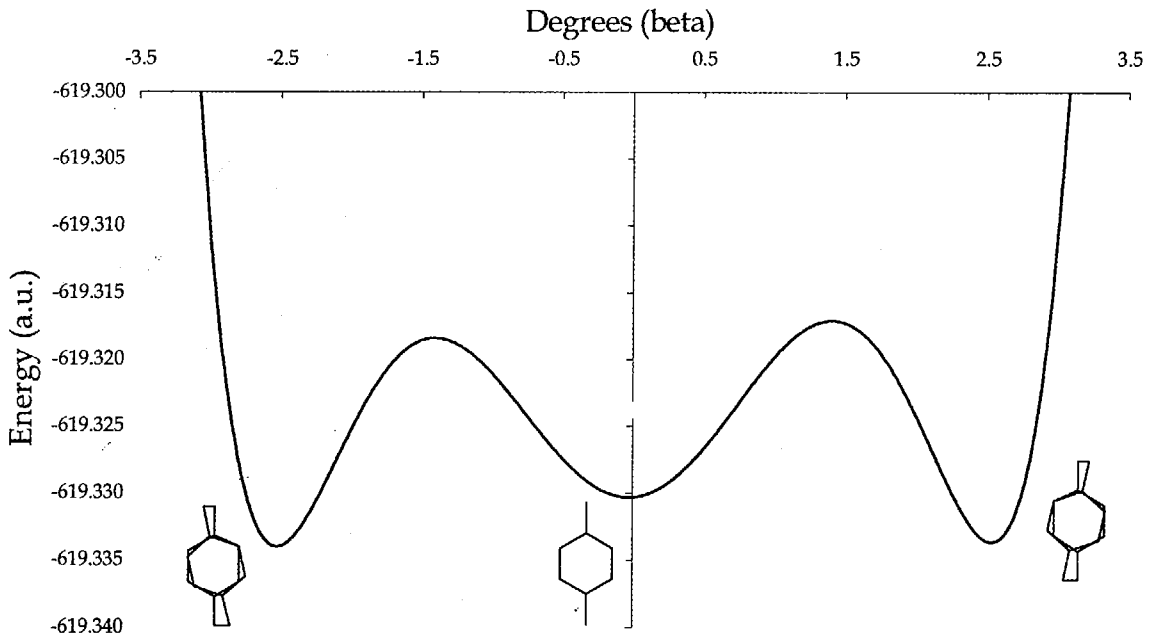
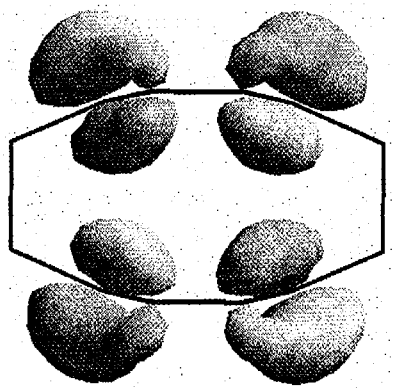


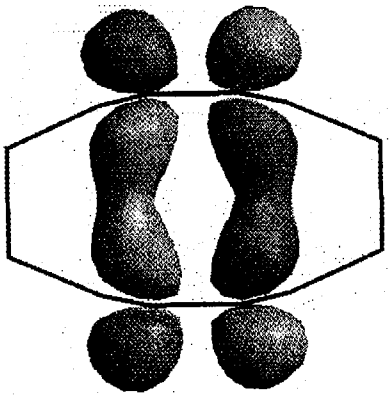
Fig. 3. Plot of the energy barrier for [2,2]paracyclophane.

Table 1. Deviation angle of molecules understudy.

Compound (substituent)	β
None (symmetric)	0.0
None (strain)	3.0
$-CN$	5.1
$-NO_2$	5.5
$-OH$	3.7



HOMO



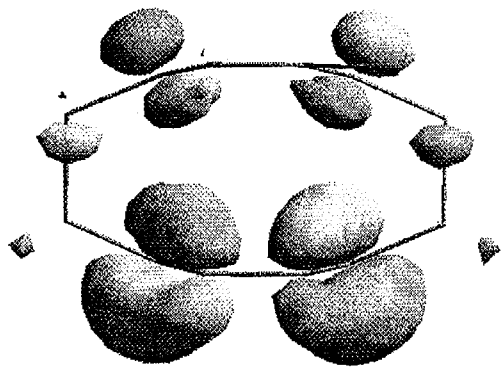
LUMO

Fig. 4. Frontier orbitals of [2.2]paracyclophane.

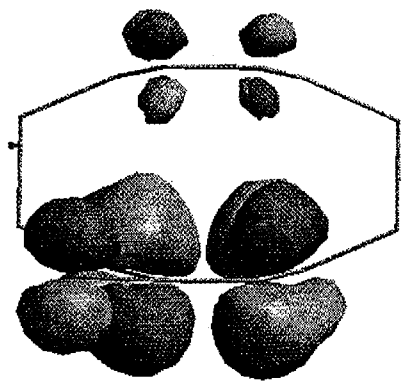
Therefore, the decrease of aromaticity favours the strain. In this case the rings show some tendency to "aliphatization" because in a minimal degree the aromatic framework suffers some weakness, then the molecule suffer distortion. On the other hand an electron release substituent reinforces this aromatic framework and it is expected the phenomenon of distortion would be less important in this case.

The shape of the molecular orbitals is useful to analyze this effect. The corresponding molecular orbitals are shown for the unsubstituted molecule in Fig. 4. The same functions of the nitrile substituted molecule as an example of an electron withdrawing group are found in Fig. 5 and finally in the case of the hidroxyl-substituted molecule as an example of an electron releasing case can be sight in Fig. 6. The HOMOs of all molecules have the most interesting behaviour. The HOMO of the unsubstituted molecule belongs to the b_{2g} irreducible representation as was characterized by Heilbroner and coworkers.[8c,d,e] However, the substituted molecules lose their symmetry due to the substitution and they are already deformed in different ways depending on the nature of the substituent.

Almost all the corresponding orbital of the molecule with CN substituent is localized on the ring that is unsubstituted. On the other hand, in the

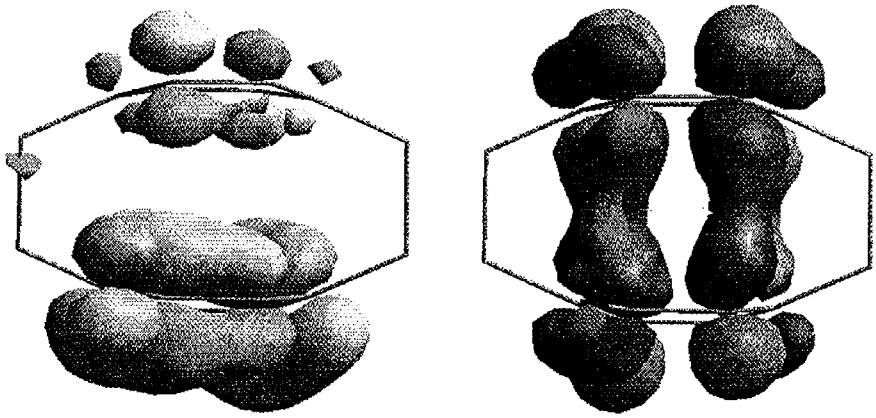


HOMO



LUMO

Fig. 5. Frontier orbitals of [2.2]paracyclophane-nitrile.



HOMO LUMO

Fig. 6. Frontier orbitals of [2.2]paracyclophane-hidroxyl.

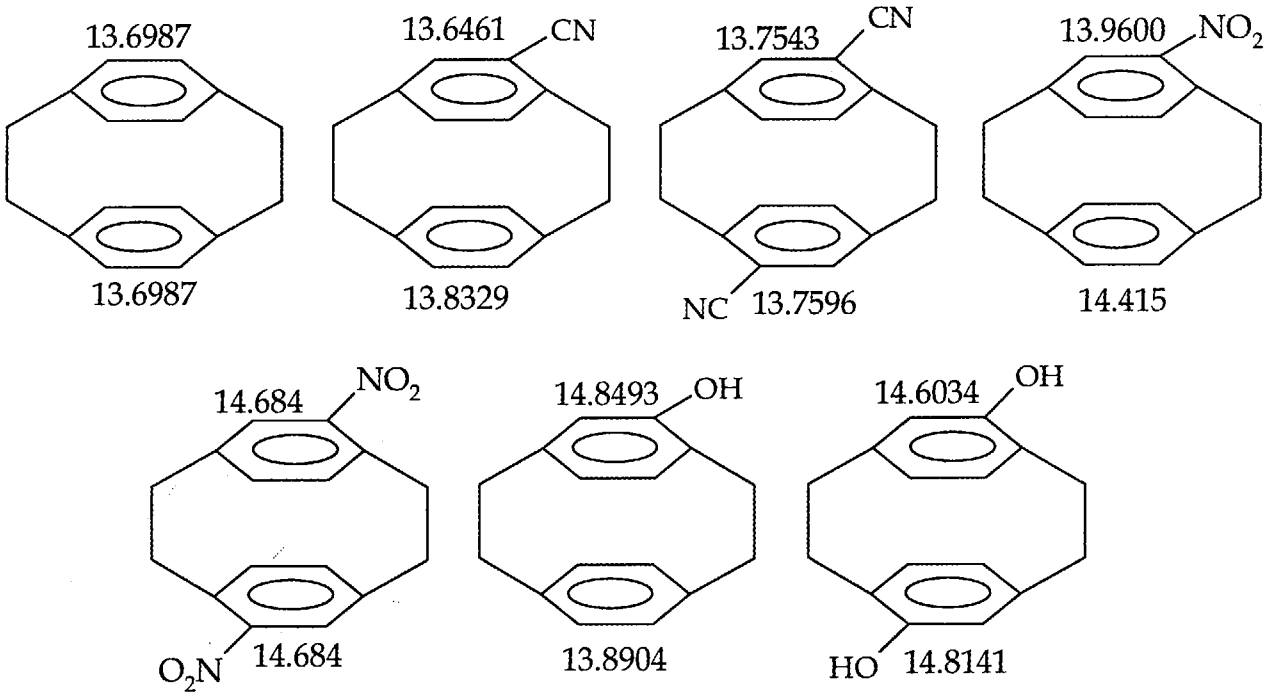


Fig. 7. NICS values of molecules under study.

case of the molecule with $-OH$ substituent almost all the orbital is localized on the ring that has the substituent.

The inductive effect plays an important role in this context, the $-CN$ group withdraws electrons from the aromatic ring and it is a deactivating substituent; indeed, high reactivity is not expected at the substituted ring position. The molecule containing the $-OH$ fragment in its own way is an electron-release substituent and is activating the aromatic ring, therefore this behaviour is reflected on the HOMO of this molecule. All the analysis of the molecule containing the $-NO_2$ radical is practically the same as the $-CN$ analogue.

The behaviour described above is confirmed by analyzing the aromaticity of the molecules. NICS

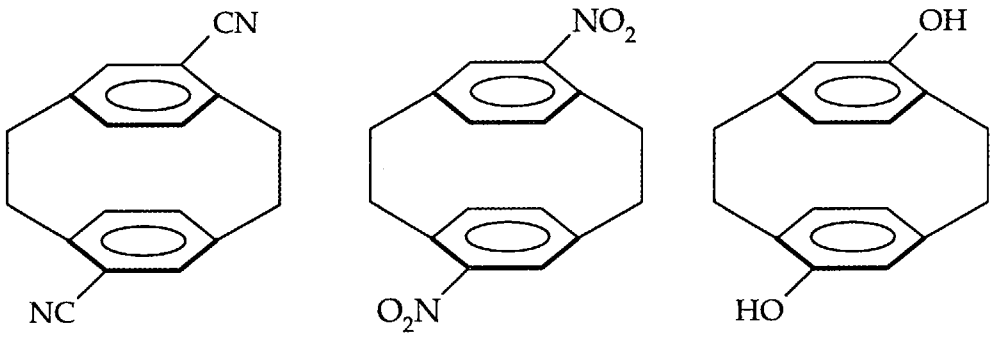


Fig. 8. Double substituted molecules.

values calculated at the centre of each ring are shown in Fig. 7. The reference is the value obtained by Schleyer for benzene at the same level of theory[9] (−11.5). The NICS for the unsubstituted molecule is −13.7 for both decks. The values are more negative for the −OH substituted molecule, with −14.85 for the substituted ring and −13.9 for the unsubstituted ring, whereas in the −CN analogue corresponding values are −13.64 for the substituted ring and −13.83 for the unsubstituted one. In the case of $-NO_2$ the values are −13.96 and −14.41 respectively.

These results are interesting since there is a change in the inductive effect on the counterpart ring but is not the same at all. For activating substituents there is an activation of the unsubstituted ring as was suggested by Cram and Cram,[2c] but the effect is very small. However in deactivating substituents, the substitution does not deactivate the other deck, moreover it provides some activation. This phenomenon is a consequence of the electron richness in the first case and the lack of electrons in the second case.

The doubly substituted molecules are shown in Fig. 8. It is a curious feature that the new symmetry reached by these molecules allows them to avoid much of the behaviour of the mono-substituted cases. Both rings are activated on the double −OH substituted molecule and have a NICS value of −14.8, whereas as it was expected, both rings of the double substituted −CN molecule are deactivated with −13.75 NICS value.

4. Conclusions

The twist distortion of [2,2]paracyclophane depend on the electron population of the aromatic rings and on the breaking of the intrinsic symmetry in the case of substituted molecules, besides the hydrogen repulsion suggested by Boyd.[23] The variation of the electron flow reached by substituted [2,2]paracyclophane confirms this, the process of distortion has a very little energy barrier, indeed only the rupture of the symmetry caused for the inclusion of different substituents can enhance the distortion. The inductive effect has normal behaviour on the ring that supports the substitution, but it changes completely the behaviour of the counterpart ring confirming the proposition of Cram and Cram.[2c] Both D2 and D2h forms can be reached because the energy between them is so small.

Acknowledgment

The authors are indebted to Ms. Patricia Islas, Ms. Teresa Vasquez, Ms. Sara Jimenez and Mr. Roberto Perez for technical help. We thank DGAPA-UNAM (grant IN107399) for the financial support.

References

1. M. Pellegrin, *Rec. Trav. Chim. Pays. Bas.* **18**, 558 (1899).
2. (a) D.J. Cram and H.J. Steinberg, *J. Am. Chem. Soc.* **73**, 5691 (1951); (b) D.J. Cram, *Rec. Chem. Prog.* **20**, 71 (1959); (c) D.J. Cram and J.M. Cram, *Acc. Chem. Res.* **4**, 204 (1971); (d) D.J. Cram, R.B. Hornby, E.A. Truesdale, H.J. Reich, M.H. Delton and J.M. Cram, *Tetrahedron* **30**, 1757 (1974).
3. H.R. Christen and F. Vögtle, *Organische Chemie. Van der Grundlagen zur Forschung* (Salle-Sauerlnder, Frankfurt a. M/Aarau, 1989), Vols. I and II.
4. (a) F. Vögtle, *Cyclophane Chemistry* (John-Wiley & Sons, West Sussex, 1993); (b) L. Rossa and F. Vogtle, *Top. Curr. Chem.* **113**, 1 (1983); (c) F. Vögtle and G. Hohner, *Top. Curr. Chem.* **74**, 1 (1974).

5. R. Salcedo, A. Martínez, L.E. Sansores and N. Mireles, *Research Developments in Molecular Structure*, in press.
6. (a) P.J. Dyson, D.G. Humphrey, J.E. McGrady, M.P. Mingos and D.J. Wilson, *J. Chem. Soc. Dalton Trans.* 4039 (1995); (b) M.K. Cyranski, K.D. Krygowski and C.W. Bird, *Tetrahedron* **54**, 9711 (1998); (c) F. Bickelhaupt, *Pure Appl. Chem.* **62**, 373 (1990); (d) B.H. Hong, J.Y. Lee, S.J. Cho, S. Yun, and K.S. Kim, *J. Org. Chem.* **64**, 5661 (1999).
7. (a) L. Czhuchajowski and W. Pietrzycki, *J. Mol. Struct.* **47**, 423 (1978); (b) M. Sheehan and D.J. Cram, *J. Am. Chem. Soc.* **91**, 3553 (1969); (c) S. Pignataro, V. Manzini, J.N.A. Rydiard and H.J. Lempka, *Chem. Comm.* 142 (1971); (d) R. Boschi and W. Schmidt, *Angew. Chem. Int. Ed. Engl.* **12**, 402 (1973); (e) M. Tuttle and R.A. Wielesek, *Tetrahedron Lett.* **29**, 2537 (1974); (f) T. Koenig, R.A. Wielesek, W. Snell and T. Balle, *J. Am. Chem. Soc.* **97**, 3225 (1975).
8. (a) R. Gleiter, *Tetrahedron Lett.* **51**, 4453 (1969); (b) R. Gleiter, W. Schafer, G. Krennrich and H. Sakurai, *J. Am. Chem. Soc.* **110**, 4117 (1988); (c) E. Heilbronner and J.P. Maier, *Helv. Chim. Acta* **57**, 151 (1974); (d) B. Kovac, M. Mohraz, E. Heilbronner, V. Boeckelheide and H. Hopf, *J. Am. Chem. Soc.* **102**, 4314 (1980); (e) E. Heilbronner and Z.-Z. Yang, *Top. Curr. Chem.* **115**, 1 (1983); (f) R. Hoffmann, *Acc. Chem. Res.* **4**, 1 (1979).
9. (a) P.V.R. Schleyer, C. Maerker, A. Dransfeld, H. Jiao, N.J.V.E. Hommes, *J. Am. Chem. Soc.* **118**, 6317 (1996); (b) G. Subramanian, P.V.R. Schleyer and H. Jiao, *Angew. Chem. Int. Ed. Engl.* **35**, 2638 (1996); (c) H. Jiao, P.V.R. Schleyer, Y. Mo, M.A. McAllister and T.T. Tidwell, *J. Am. Chem. Soc.* **119**, 7075 (1997).
10. A.D. Becke, *J. Chem. Phys.* **98**, 5648 (1993).
11. A.D. Becke, *Phys. Rev.* **A38**, 3098 (1988).
12. C. Lee, W. Yang and R.G. Parr, *Phys. Rev.* **B37**, 785 (1988).
13. M.J. Frisch, G.W. Trucks, H.P. Schlegel, G.E. Scuseira, M.A. Robb, J.R. Cheeseman, V.G. Zakrzewski, J.A. Montgomery, Jr., R.E. Stratmann, J.C. Burant, S. Dapprich, J.M. Millam, A.D. Daniels, K.N. Kudin, M.C. Strain, O. Farkas, J. Tomasi, V. Barone, M. Cossi, R. Cammi, B. Menucci, C. Pomelli, C. Adamo, S. Clifford, J. Ochterski, G.A. Petersson, P.Y. Ayala, K. Morokuma, D.K. Malick, A.D. Rabuck, K. Raghavachari, J.B. Foresman, J. Cioslowski, J.V. Ortiz, B.B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. Gomperts, L.R. Martin, D.J. Fox, T. Keith, M.A. Al-Laham, C.Y. Peng, A. Nanayakkara, C. Gonzalez, M. Challacombe, P.M.W. Gill, B.G. Johnson, W. Chen, M.W. Wong, J.L. Andres, M. Head-Gordon, E.S. Replogle and J.A. Pople, *Gaussian98* (Gaussian Inc., Pittsburgh, PA, 1998).
14. (a) A.A. El-Azhary and H.U. Sutter, *J. Phys. Chem.* **100**, 15056 (1996); (b) F. Turecek, *J. Phys. Chem.* **102**, 4703 (1998).
15. J.B, Foresman and E. Frisch, *Exploring Chemistry with Electronic Structure Methods*, 2nd edn. (Gaussian Inc., Pittsburgh, PA, 1996).
16. Cerius^2 forcefield-based simulations (Molecular Simulations Inc., San Diego, April, 1997).
17. H. Hope, J. Bernstein and K.N. Trueblood, *Acta Crystallogr.* **B28**, 1733 (1972).
18. S. Walden and D.T. Glatzhofer, *J. Phys. Chem.* **A101**, 8233 (1997).
19. D. Hensler and G. Hohlneicher, *J. Phys. Chem.* **A102**, 10828 (1998).
20. D. Hensler and G. Hohlneicher, *J. Mol. Struct. THEOCHEM* **497**, 145 (2000).
21. (a) S. Canuto and M.C. Zerner, *J. Am. Chem. Soc.* **112**, 2114 (1990); (b) T.-L. Shen, J.E. Jackson, J.-H. Yeh, D.G. Nocera and G.E. Leroi, *Chem. Phys. Lett.* **191**, 149 (1992); (c) S. Canuto and M.C. Zerner, *Chem. Phys. Lett.* **157**, 353 (1989).
22. J.T.S. Andrews and E.F. Westrum Jr., *J. Phys. Chem.* **74**, 2170 (1970).
23. R.H. Boyd, *Tetrahedron* **22**, 119 (1966).