ORGANIC
LETTERS

2003
Vol. 5, No. 1
23−26

σ-Antiaromaticity in Cyclobutane, Cubane, and Other Molecules with Saturated Four-Membered Rings[†]

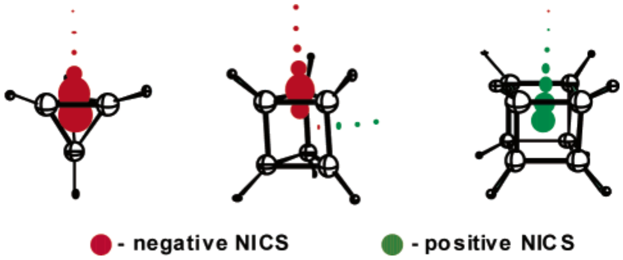
Damian Moran,[‡,§] Mariappan Manoharan,[‡] Thomas Heine,[||] and Paul von Ragué Schleyer*,[‡,§]

Computational Chemistry Annex, University of Georgia, Athens, Georgia 30602, Computational Chemistry Center, Institute of Organic Chemistry, University of Erlangen−Nuremberg, Henkestr. 42, D-91054 Erlangen, Germany, and Institut für Physikalische Chemie, TU Dresden, D-01062 Dresden, Germany

schleyer@chem.uga.edu

Received October 23, 2002

ABSTRACT



Dissected nucleus-independent chemical shift (NICS) analyses of cycloalkanes and cage hydrocarbons reveal contrasting ring current effects, diatropic in three- and five-membered and paratropic in four-membered ring systems. The large shielding effects of the C–C bonds of the archetypal *σ*-aromatic, cyclopropane, are magnified in tetrahedrane and related structures. The remarkable deshielding effect of the cyclobutane C–C(*σ*) bonds is general: cubane and cages with four-membered rings are strongly deshielding (i.e., *σ*-antiaromatic).

Cyclopropane is stabilized both by σ-aromaticity[1−3] involving the six electrons in its strained (40.4 kcal/mol)[4] C−C bonds and by C−H bond strengthening, due to the sp^2-like carbon hybridization.[4] Strong evidence for σ-aromaticity exists:[5,6] large diamagnetic susceptibility and anisotropy, upfield cyclopropane ^{1}H NMR shifts, shielding of protons, and negative NICS located above cyclopropane rings. The stabilization of cyclopropane due to σ-aromaticity (11.3 kcal/mol)[4] is a significant fraction of benzene's 33.2 kcal/mol aromatic stabilization.[7]

While von Baeyer's angle deformation theory[8] explains the much larger strain energies of cyclosilapropane (38.3 kcal/mol)[9] than cyclosilabutane (17.0 kcal/mol),[9] the remarkably similar cyclopropane (27.5 kcal/mol)[10] and cyclobutane (26.5 kcal/mol)[10] values are in clear violation. We now present evidence that cyclobutane and related molecules with four-membered rings (4MR) are destabilized by σ-antiaromaticity involving the eight electrons in the strained (30.3 kcal/mol)[4] C−C bonds. The cyclobutane (D_{4h}) HOMOs, a

---

[†] This paper is dedicated with warmth to George Olah on his 75th birthday and in recognition of forty years of friendship.

[‡] University of Georgia.

[§] University of Erlangen−Nuremberg.

[||] TU Dresden.

(1) Minkin, V. I.; Glukhovtsev, M. N.; Simkin, B. Y. *J. Mol. Struct. (THEOCHEM)* **1988**, *181*, 93.

(2) Dewar, M. J. S. *J. Am. Chem. Soc.* **1984**, *106*, 669.

(3) Cremer, D.; Gauss, J. *J. Am. Chem. Soc.* **1986**, *108*, 7467.

(4) Exner, K.; Schleyer, P. v. R. *J. Phys. Chem. A* **2001**, *105*, 3407.

(5) Jackman, L. M.; Sternhell, S. *Application of Nuclear Magnetic Resonance Spectroscopy in Organic Chemistry*, 2nd ed.; Pergamon Press: Braunschweig, Germany, 1969.

(6) Dauben, H. J.; Wilson, J. D.; Laity, J. L. In *Nonbenzenoid Aromatics*; Snyder, J. P., Ed.; Academic Press: New York, 1971.

(7) Schleyer, P. v. R.; Puhlhofer, F. *Org. Lett.* **2002**, *4*, 2873.

(8) Baeyer, A. *Chem. Ber.* **1885**, *18*, 2269.

(9) Zhoa, M.; Gimarc, B. M. *Inorg. Chem.* **1996**, *35*, 5378.

(10) Greenberg, A.; Liebman, J. F. *Strained Organic Molecules*; Academic Press: New York, 1978.

10.1021/ol027159w CCC: $25.00

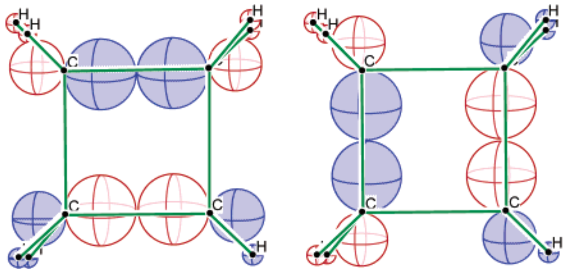


Figure 1. Degenerate E_u HOMO of cyclobutane; although the combination of parallel C−C bond orbitals help C−H bonding, they preclude cyclic delocalization.

degenerate pair of σ-orbitals of e_u symmetry (Figure 1),[11] are 1−2 and 3−4 σ bonding but 1−3 and 2−4 antibonding.[12] These MOs resemble the π-orbitals of the antiaromatic cyclobutadiene. Similarly, "repulsion of parallel bonds" has been invoked to explain the unexpected instability of cubic P_8.[13]

There have been indications of $4n + 2$ π-electron-like behavior of the σ-systems of small ring hydrocarbons.

A review by Dauben et al.[6] points to the abnormally high magnetic susceptibility of cyclopropane and cyclopentane and the abnormally low value of cyclobutane. Also, ^{13}C and ^{1}H chemical shifts are shielded in C_3H_6 but deshielded in C_4H_8.[5] Sauers[14] and our group[4,15] have observed the diatropic NICS of three-membered rings (3MRs) and analyzed the paratropic effects of the C−C bonds of 4MRs in detail.[16]

All structures were optimized at the B3LYP/6-311+G** DFT level using Gaussian 98.[17] While planar ring symmetries were imposed for interpretative simplicity, e.g., to enforce $\sigma-\pi$ separation, NICS[16,18,19] for the fully relaxed systems show no fundamental differences.[16] Localized molecular orbital NICS ("dissected NICS", LMO−NICS)[16,19] points were computed (PW91/IGLO−III) at ring centers (see data plotted in Figure 2) and as grids of points 0.5 Å apart (see Figure 3) using the deMon NMR program.[20]

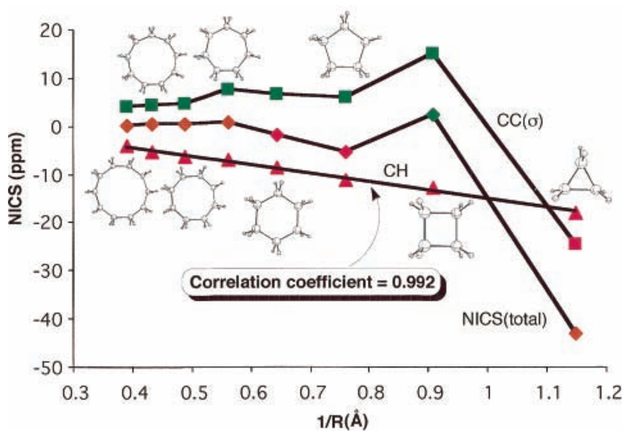


Figure 2. NICS at cycloalkane centers versus 1/R (where R is the distance between the ring center and the carbons). NICS(0) total and CC(σ) and CH contributions to NICS(0) shown.

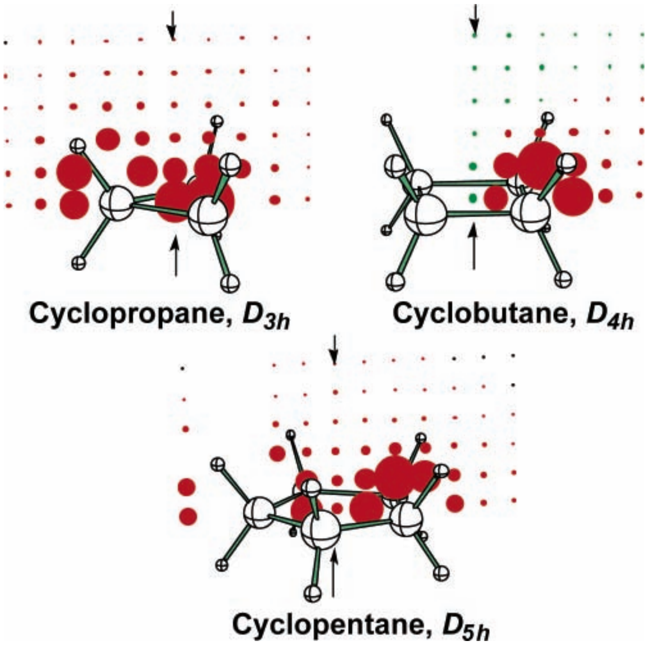


Figure 3. Planar cyclopropane, cyclobutane, and cyclopentane NICS(total) grids. Red and green points denote positive and negative NICS values, respectively, and the arrows point to the ring centers and above.

The C_nH_{n+2} (n = 3−10) cycloalkane total NICS(0) (at ring centers) are dissected into CC(σ) and CH contributions (Figure 2). The CH line is monotonic, and there is no evidence of any aromatic or antiaromatic contributions. In contrast, the NICS(total) and CC(σ) data show zigzag behavior; this becomes more regular for the larger rings. The

---

(11) Degeneracies and orbital shapes are retained for puckered D_{2d} cyclobutane. The D_{2d} equilibrium structure is 1.05 kcal/mol + ZPE more stable than D_{4h} cyclobutane.

(12) Hoffmann, R.; Davidson, R. B. *J. Am. Chem. Soc.* **1971**, *93*, 5699.

(13) Ahlrichs, R.; Brode, S.; Ehrhardt, C. *J. Am. Chem. Soc.* **1985**, *107*, 7260.

(14) Sauers, R. R. *Tetrahedron* **1998**, *54*, 337.

(15) Bettinger, H. F.; Pak, C. H.; Xie, Y. M.; Schleyer, P. v. R.; Schaefer, H. F. *J. Chem. Soc., Perkin Trans. 2* **1999**, 2377.

(16) Schleyer, P. v. R.; Manoharan, M.; Wang, Z.-X.; Kiran, B.; Jiao, H.; Puchta, R.; Hommes, N. J. R. v. E. *Org. Lett.* **2001**, *3*, 2465.

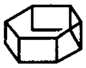
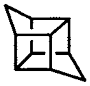
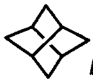
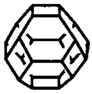
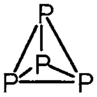
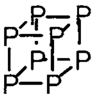
(17) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Zakrzewski, V. G.; Montgomery, J. A., Jr.; Stratmann, R. E.; Burant, J. C.; Dapprich, S.; Millam, J. M.; Daniels, A. D.; Kudin, K. N.; Strain, M. C.; Farkas, O.; Tomasi, J.; Barone, V.; Cossi, M.; Cammi, R.; Mennucci, B.; Pomelli, C.; Adamo, C.; Clifford, S.; Ochterski, J.; Petersson, G. A.; Ayala, P. Y.; Cui, Q.; Morokuma, K.; Malick, D. K.; Rabuck, A. D.; Raghavachari, K.; Foresman, J. B.; Cioslowski, J.; Ortiz, J. V.; Stefanov, B. B.; Liu, G.; Liashenko, A.; Piskorz, P.; Komaromi, I.; Gomperts, R.; Martin, R. L.; Fox, D. J.; Keith, T.; Al-Laham, M. A.; Peng, C. Y.; Nanayakkara, A.; Gonzalez, C.; Challacombe, M.; Gill, P. M. W.; Johnson, B. G.; Chen, W.; Wong, M. W.; Andres, J. L.; Head-Gordon, M.; Replogle, E. S.; Pople, J. A. *Gaussian 98*, revision A.5; Gaussian, Inc.: Pittsburgh, PA, 1998.

(18) Schleyer, P. v. R.; Maerker, C.; Dransfeld, A.; Jiao, H. J.; Hommes, N. J. r. V. E. *J. Am. Chem. Soc.* **1996**, *118*, 6317.

(19) Schleyer, P. v. R.; Jiao, H.; Hommes, N. J. R. v. E.; Malkin, V. G.; Malkina, O. L. *J. Am. Chem. Soc.* **1997**, *119*, 12669.

(20) Malkin, V. G.; Malkina, O. L.; Eriksson, L. A.; Salahub, D. R. *J. Am. Chem. Soc.* **1994**, *116*, 5898.

Table 1. PW91/IGLO-III//B3LYP/6-311+G** Dissected NICS (in ppm) at Cage and Ring Centers[a]

#	Cage		NICS	CC(σ)	CH
1	 T_d	Cage	-48.3	-37.2	-10.4
		3MR	-46.1	-33.6	-11.9
2	 C_{2v}	Cage	-14.3	-9.9	-4.2
		3MR	-41.4	-32.1	-8.7
		4MR	-13.2	-8.3	-4.5
3	 D_{3h}	Cage	-0.1	+1.2	-1.2
		3MR	-33.0	-24.0	-8.7
		4MR	-0.8	+2.9	-3.4
4	 O_h	Cage	+23.1	+21.6	+1.6
		4MR	+13.1	+18.0	-4.8
5	 D_{5h}	Cage	+6.4	+8.0	-1.0
		4MR	+2.8	+9.5	-6.6
		5MR	+0.7	+5.6	-4.5
6	 D_{6h}	Cage	+7.4	+10.8	-3.6
		4MR	+5.2	+12.2	-6.8
		6MR	+0.4	+2.6	-2.8
7	 D_{7h}	Cage	-11.1	+14.0	-3.6
		4MR	-7.8	+12.0	-4.2
		7MR	-7.1	+15.0	-7.4
8	 T_d	Cage	-15.2	-9.0	-7.2
		3MR	-43.8	-32.7	-10.5
		6MR	-13.2	-5.9	-7.5
9	 C_{2v}	Cage[b]	+3.0	+5.6	-2.5
		4MR*	+2.9	+0.9	-6.7
		4MR	+5.9	+12.1	-5.5
		5MR	-3.1	+2.8	-5.7
10	 D_{2h}	Cage	-5.9	-1.2	-4.4
		4MR	-5.4	+2.8	-7.2
		5MR	-6.9	-0.5	-6.2
11	 T_d	Cage	-0.3	+3.6	-4.0
		6MR	-1.1	+2.8	-4.1
12	 I_h	Cage	+0.7	+6.0	-4.0
		5MR	-2.2	+5.0	-7.6
13	 D_{3h}	Cage	-8.1	-2.4	-5.4
		4MR	-10.9	-6.8	-3.8
14	 D_{3h}	Cage	-4.1	+2.7	-6.4
		6-MR	-3.2	+2.6	-6.8
15	 D_2	Cage	-5.4	+1.3	-6.4
		6-MR	-4.1	+2.5	-6.3
16	 D_{2d}	Cage	-9.1	-2.7	-7.1
		5-MR	-8.8	-1.7	-7.1
17	 D_3	Cage	-11.7	-6.3	-5.2
		5-MR	-10.2	-3.4	-6.8
18	 O_h	Cage	+0.7	+10.8	-9.6
		4-MR	+3.3	+13.1	-9.6
		6-MR	-2.3	+6.3	-8.4
19	 T_d	Cage	-59.7	-36.0	-15.6
		3MR	-57.4	-37.1	-14.1
20	 O_h	Cage	+43.4	+42.2	+0.8
		4-MR	+26.6	+26.0	0.0

[a] Cages are minima in the symmetries. [b] At the cubane cage unit center: +7.0 (NICS), +8.9 (CC(σ)), and −1.8 (CH).

extremely diatropic NICS(total) (−42.8 ppm) of cyclopropane, the archetypal σ-aromatic, is due to the combined CC(σ) (−24.3 ppm) and CH (−18.0 ppm) shielding effects.[21] In contrast, the cyclobutane CC(σ) is large and paratropic (+15.2 ppm), but this is nearly balanced by CH shielding contributions (−12.8 ppm). NICS(total) is still paratropic by 2.6 ppm. The CC(σ) framework of cyclobutane is σ-antiaromatic.

Recently, a new refinement, MO−NICS analysis, has been developed.[22] This separates total NICS into contributions from individual canonical (rather than localized) molecular orbitals. The MO−NICS (see Figure 4) and LMO−NICS (Figure 2) refinement schemes are complementary and lead to the same conclusions regarding the NICS shielding contributions. The Walsh orbitals[12,23] of cyclopropane are shielding, but those of cyclobutane are deshielding. The

---

(21) NICS points close to ethane also are deshielded, but to a much smaller extent. At the cyclopropane (0.871 Å) and cyclobutane (1.101 Å) carbon to ring center distances from the ethane C−C bond, the shielding is only −2.3 ppm and −0.2 ppm, respectively.

(22) Heine, T.; Schleyer, P. v. R.; Corminboeuf, C.; Seifert, G.; Reviakine, R.; Weber, J. *J. Am. Chem. Soc.* **2002**, submitted. For a related method, see: Corminboeuf, C.; Heine, T.; Weber, J. *Phys. Chem. Chem. Phys.* **2002**, accepted. MO-NICS analysis gives the contributions of all the single canonical MOs; their total is the shielding tensor. In the GIAO method, the MO contribution of the shielding tensor can be taken directly from the orbital-based formulation given by eqs 27 and 28 in: Schreckenbach, G.; Ziegler, T. *J. Phys. Chem.* **1995**, *99*, 606.

(23) Walsh, A. D. *J. Chem. Soc.* **1953**, 2260.

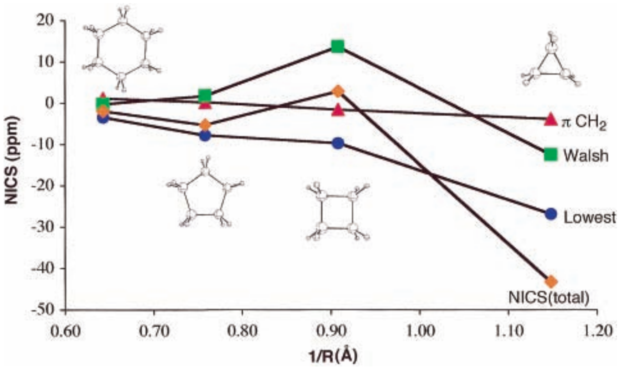


Figure 4. Cycloalkane MO-NICS showing π CH_2, Walsh, and lowest energy MO contributions to NICS(total).

cyclopentane NICS may have a slight diatropic enhancement (see Figure 2), but this is not pronounced.

Grids of total NICS points bisecting 3-, 4-, and 5MR planes (Figure 3) provide more details. Magnitudes are shown by the sizes of the dots. The cyclopropane NICS grid is filled with large red (negative, shielding) points reflecting the known diatropic effect of 3MRs.[16] The cyclopentane NICS grid is similar except that the points at and above the center (indicated by the arrows) are much smaller. The cyclobutane NICS grid, in contrast, shows a deshielding cone in the central region. Consistent with Figure 2, NICS(0) and points above the 4MR plane are paratropic (green) and radiate outward.

The large diatropic and paratropic CC(σ) effects shown in Figures 2 are strongly magnified in certain cyclopropane and cyclobutane hydrocarbon cages (Table 1). With four fused cyclopropane rings, tetrahedrane (**1**) has very large NICS(0) (at the cage center) and CC(σ) (−48.3 and −37.2, respectively). Remarkably, the tetrahedrane cage is "super σ-aromatic". P_4 (T_d) behaves similarly (Table 1).[24]

The six 4MR faces of cubane (**4**) have the opposite effect. The large, positive (+23.1, deshielded) NICS(0) at the cage center is due almost entirely to CC(σ) contributions (+21.6 ppm). The 4MR face center of **4** also has a large diatropic CC(σ) (+18.0), but the CH contributions (−4.8 ppm) reduce the total NICS somewhat to +13.1. Remarkably, the cubane cage appears to be "super σ-antiaromatic". Cubic P_8 (O_h) exhibits similar behavior (Table 1).

The abstract illustration contrasts the magnetic characteristics of **1** and **4**. Also shown is a "mixed" system, prismane (**3**), which has competing diatropic 3MRs and paratropic 4MRs. The other cage systems collected in Table 1 show similar 3MR and 4MR effects. The cages comprised of 5MRs and 6MRs have NICS(0) near zero. The three-membered ring faces in homotetrahedrane (**2**) and truncated tetrahedrane (**8**)[15] behave similarly to **1**, with large (≤−33 ppm) diatropic NICS(total). For example, **8** cage center NICS is −15.2 ppm, while NICS(total) 3MR is a considerable −43.8 ppm.

The cages possessing four-membered rings, pentaprismane (**5**), hexaprismane (**6**), heptaprismane (**7**), homocubane (**9**), and cuboctahedrane (**18**) also have 4MR faces with significant (>9.5 ppm) paratropic CC(σ) ring currents, but they are equalized by the CH contribution. Hence, NICS at both the cage and 4MR face centers are only moderately deshielding (≤7.4 ppm), if at all.

Bicyclo[1.1.1]pentane (**13**) is a special case. Although composed entirely of 4MRs, NICS at the cage (−10.9) and 4MR centers (CC(σ) −6.8) are significantly diatropic. Hence, in contrast with other 4MR species in Table 1, **13** is σ-aromatic. This may be responsible for the anomalously low experimental heat of formation of **13** compared with the much higher molecular mechanics (MM4) prediction.[25] MO-NICS shows the negative NICS to be due to the many small diatropic contributions of the lower-lying MOs.

In conclusion, LMO- and MO-NICS analyses of hydrocarbon ring and cage systems have demonstrated the contrasting diatropic (3MR and perhaps 5MR) and paratropic (4MR) ring current effects. The archetypal σ-aromatic, cyclopropane, has a shielding σ-framework, as does tetrahedrane and other 3MR-containing cages. Remarkably, the C−C(σ) bonds of cyclobutane and related 4MR structures (e.g., cyclobutane, cubane, etc.) are strongly deshielding (i.e., σ-antiaromatic). These electronic effects influence the strain energies.

Acknowledgment. We thank the University of Georgia and NSF (Grant CHEM-0209857) for support.

Supporting Information Available: Data plotted in Figures 2 and 4. This material is available free of charge via the Internet at http://pubs.acs.org.

OL027159W

---

(24) Hirsch, A.; Chen, Z.; Jiao, H. *Angew. Chem., Int. Ed.* **2001**, *40*, 2834.

(25) Chen, K. H.; Allinger, N. L. *J. Mol. Struct. (THEOCHEM)* **2002**, *581*, 215.