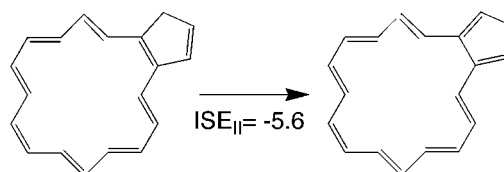# On the Stability of Large [4*n*]Annulenes

Chaitanya S. Wannere,[†] Damian Moran,[†] Norman L. Allinger,[†]
B. Andes Hess, Jr.,[‡] Lawrence J. Schaad,[‡] and Paul von Ragué Schleyer*,[†]

*Computational Chemistry Annex, Department of Chemistry, University of Georgia,
Athens, Georgia 30602, and Department of Chemistry, Vanderbilt University,
Nashville, Tennessee 37235*

schleyer@chem.uga.edu

ABSTRACT

The stabilization energies (B3LYP/6-31G*) of planar [4*n*]annulenes, evaluated by a new indene-isoindene isomerization method (see Abstract graphic), reveal that all 4*n* π-electron rings larger than the energetically unfavorable cyclobutadiene are only slightly destabilized by the π-electron interactions. Cyclooctatetraene prefers the "tub" conformation because of strain effects. Generally, the antiaromatic character of the larger systems with 4*n* π-electrons is revealed best by their magnetic properties rather than by their energies.

Originally, [4*n*]annulenes, the unfavorable counterparts of the stabilized [4*n* + 2]π-electron aromatics, were described as being pseudoaromatic,[1] i.e., they were expected to lack special conjugative stabilization and to resemble polyenes. In a pioneering series of investigations, Breslow provided convincing evidence that π-electron interactions destabilize small 4π-electron systems such as the cyclopropenyl anion, cyclobutadiene (CBD), and the cyclopentadienyl cation. He coined the term "antiaromatic" to describe [4*n*] systems generally.[2] However, in his 1973 account,[3] Breslow conceded that "there is no strong evidence yet for conjugative destabilization in the [larger] 4*n* systems relative to normal compounds", although [4*n*] systems are clearly less stable than [4*n* + 2] systems. Wiberg's authoritative review of antiaromaticity in 2001 concluded that "when the ring size becomes larger, the antiaromatic character is decreased and is smaller even with cyclooctatetraene".[4] Due to the ring strain complications associated with the larger [4*n*]annulenes,

Wiberg was unable to evaluate their π energy contributions. We have overcome this problem in the present paper and show that except for CBD, the larger [4*n*] π-electron systems are only slightly destabilized.

The first uniform evaluations of the energies of [*n*]-annulenes of increasing size were carried out in the early days of organic electronic structure theory using Hückel theory and its subsequent refinements.[5] The "resonance energy per electron" (REPE) of Dewar,[5b] employed extensively by Hess and Schaad (HS),[5c] is representative. Their results indicate the aromaticity of benzene to be very high, while that of the larger [4*n* + 2]annulenes decreases steadily. Conversely, the antiaromatic character of the larger [4*n*]-annulenes is predicted by their REPEs to become less and less negative from the high cyclobutadiene value. This work contributed to the firmly embedded popular view that planar antiaromatic systems are destabilized.

However, evidence[6] to the contrary, particularly dealing with cyclooctatetraene (COT), has existed for a long time.

[†] University of Georgia.

[‡] Vanderbilt University.

(1) Streitwieser, A., Jr. *Molecular Orbital Theory for Organic Chemists*; John Wiley: New York, 1961.

(2) (a) Breslow, R. *Chem. Eng. News* **1965**, *43*, 90. (b) Dewar, M. J. S. *Adv. Chem. Phys.* **1965**, *8*, 65.

(3) Breslow, R. *Acc. Chem. Res.* **1973**, *6*, 393.

(4) Wiberg, K. B. *Chem. Rev.* **2001**, *101*, 1317.

(5) (a) Minkin, V. I.; Glukhovtsev, M. N.; Simkin, B. Y. *Aromaticity and Antiaromaticity. Electronic and Structural Aspects*; John Wiley & Sons: New York, 1994. (b) Dewar, M. J. S.; de Llano, C. *J. Am. Chem. Soc.* **1969**, *91*, 789. (c) Schaad, L. J.; Hess, B. A., Jr. *Chem. Rev.* **2001**, *101*, 1465. (d) Hess, B. A., Jr.; Schaad, L. J. *J. Am. Chem. Soc.* **1971**, *93*, 305.

(6) Klärner, F.-G. *Angew. Chem., Int. Ed.* **2001**, *40*, 3977.

The strongly twisted double-bond conformations of the most stable tub form (D_{2d}) preclude π interactions. Planar COT is known to prefer D_{4h} symmetry with alternating single and double bonds. Since the D_{4h} form is expected to be antiaromatic, the D_{2d}–D_{4h} energy difference gives an upper bound to the antiaromatic destabilization energy. This is known from NMR measurements on COT derivatives to be about 10 kcal/mol,[7] a value that can be reproduced very well by DFT computations on C_8H_8 itself.[8] However, at least part of this ca. 10 kcal/mol difference is due to the increase in the strain energy in going from tub to the planar form.

The COT strain energy has been computed by molecular mechanics, which do not take the electronic repulsions inherent in the antiaromaticity concepts into account. On the basis of MM2, MM3, and MM4 results, Allinger and co-workers concluded that the ca. 10 kcal/mol COT inversion barrier is due almost completely to strain rather than to electronic effects.[9] Our present MM4 re-examination gives a 0.9 kcal/mol D_{4h} COT destabilization energy.
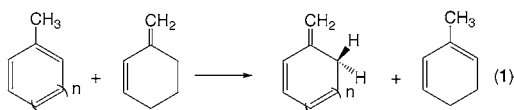
We have applied the recently introduced Schleyer and Pühlhofer (SP) isomerization stabilization energy (ISE)[10] method, but with the appropriate corrections, to investigate the REs of [4n]annulenes. The data, computed at B3LYP/6-31G*+ZPE on assumed planar structures, indicate destabilizations of less than 1 kcal/mol for COT and small destabilizations also for [12]-, [16]-, and [20]annulenes. The small destabilization of planar COT is in complete agreement with the existing thermodynamic conclusions.[6,9]
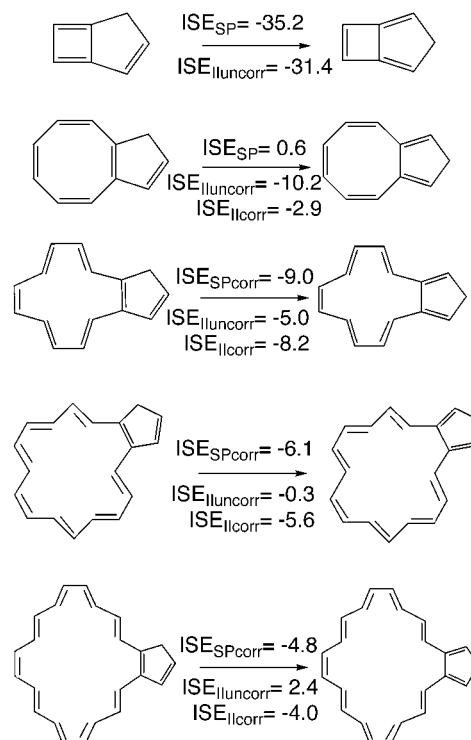
28.8 kcal/mol; Calc from ΔH_f (see ref 15)
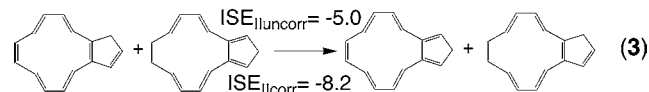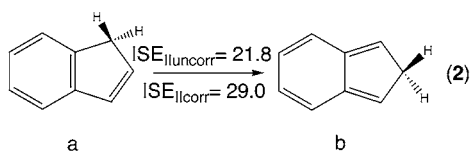
We now introduce a new "indene (**a**)−isoindene (**b**)" aromatic stabilization energy (ASE) evaluation method, illustrated by equation (**2**), which employs fused five-membered ring appendages. This approach (designated ISE$_{II}$) is homodesmotic and has the advantage that all carbons in the [n]annulene moiety are sp^2-hybridized in both isomers.

(7) (a) Anet, F. A. L. *J. Am. Chem. Soc.* **1962**, *84*, 671. (b) Anet, F. A. L.; Bourn, A. J. R.; Lin, Y. S. *J. Am. Chem. Soc.* **1964**, *86*, 3576. (c) Oth, J. F. M. *Pure Appl. Chem.* **1971**, *25*, 573. (d) Luz, Z.; Meiboom, S. J. *J. Chem. Phys.* **1973**, *59*, 1077. (e) Naor, R.; Luz, Z. *J. Chem. Phys.* **1982**, *76*, 5662.

(8) Krygowski, T. M.; Pindelska, E.; Cyrański, M. K.; Häfelinger, G. *Chem. Phys. Lett.* **2002**, *359 (1−2)*, 158.

However, like ISE$_{SP}$, ISE$_{II}$ requires the application of syn−anti corrections.[10,11] These arise because s-cis (syn) butadiene conformations are considerably less stable than the s-trans (anti) forms.[10] Note that isoindene (**b**) has two more anti conformations (which needs corrections)[12] than indene (**a**), but the syn−anti relationships in the [12]-, [16]-, and [20]-annulene counterparts (Scheme 1) are just the reverse. Syn−

ISE$_{SP}$= -35.2
ISE$_{IIuncorr}$= -31.4

ISE$_{SP}$= 0.6
ISE$_{IIuncorr}$= -10.2
ISE$_{IIcorr}$= -2.9

ISE$_{SPcorr}$= -9.0
ISE$_{IIuncorr}$= -5.0
ISE$_{IIcorr}$= -8.2

ISE$_{SPcorr}$= -6.1
ISE$_{IIuncorr}$= -0.3
ISE$_{IIcorr}$= -5.6

ISE$_{SPcorr}$= -4.8
ISE$_{IIuncorr}$= 2.4
ISE$_{IIcorr}$= -4.0

^{a} Planar geometries were employed.

anti corrections in both the ISE$_{II}$ and ISE$_{SP}$[13] methods also may be evaluated, as shown in equation **3** for [12]annulene, by employing the dihydro derivatives of the fused bicyclic annulene and its nonaromatic isomer as conjugated reference species. Such corrections have been applied to the ISE$_{II}$ data[14] in Table 1 and Scheme 1.

The benzene ISE$_{II}$, computed at B3LYP/6-31G*+ZPE by equation **2**, is 29.0 kcal/mol, nearly the same as that obtained

(9) (a) Allinger, N. L.; Sprague, J. T.; Finder, C. J. *Tetrahedron,* **1973**, *29*, 2519. (b) Roth, W. R.; Lennartz, H.-W.; Vogel, E.; Leiendecker, M.; Oda. M. *Chem. Ber.* **1986**, *119*, 837. (c) Nevins, N.; Lii, J. H.; Allinger, N. L. *J. Comput. Chem.* **1996**, *17*, 695.

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

(11) Details of the correction evaluations are explained fully in Supporting Information.

(12) When fused to an arene, the cyclopentene moiety is taken by our convention to have a syn conformation irrespective of the Kekulé form of the aromatic ring.

(13) (a) Syn−anti corrections for SP's ISE method were evaluated as the energy difference between the dihydrogen derivative of methyl-[4n]-annulene and their respective nonaromatic isomer.

(14) All energies refer to forced C_s geometries optimized at B3LYP/6-31G* using Gaussian 98 (reference in Supporting Information). Zero-point energies computed at B3LYP/6-31G* were applied.

Table 1. Difference between Shortest and Longest [4n]Annulene Bond Length (Δr), Hess−Schaad Resonance Energies Per π-Electron (REPE), Syn−Anti Corrected Isomerization Stabilization Energies (kcal/mol) Evaluated by the Schleyer− Pühlhofer Method (ISE$_{SPcorr}$) and the Indene−Isoindene Approach (ISE$_{IIcorr}$), Magnetic Susceptibility Exaltations (Λ, cgs ppm), and Averaged Inner (δ H$_{inner}$) and Outer (δ H$_{outer}$) ^{1}H NMR Chemical Shifts of the Antiaromatic [4n]annulenes in Planar Bond Alternating Geometries

		Δr (Å)	REPE[a]	ISE$_{SPcorr}$[b]	ISE$_{IIcorr}$[b]	Λ[c]	NICS(0)[d]	NICS(0)$_\pi$[d]	δ H$_{inner}$[d]	δ H$_{outer}$[d]
[6]	D_{6h}	0.000	0.065	33.2[e]	29.0[f]	17.6[g]	−8.8[g]	−20.7[g]		7.5[g]
[4]	D_{2h}	0.243	−0.268	−35.2	−31.4	−13.0	20.8	−0.2		5.9
[8]	D_{4h}	0.130	−0.060	0.6	−2.9[f]	−79.4	35.9	28.4		2.0
[12]	D_{2h}	0.174	−0.011	−9.0	−8.2	−98.8	24.5	19.2	32.4	2.8
[16]	D_{2h}	0.129	−0.006	−6.1	−5.6	−187.7	23.4	20.2	33.1	0.9
[20]	D_{2h}	0.110	−0.003	−4.8	−4.0	−296.6	21.5	19.5	33.3	1.4
[24]	C_s	0.087		−3.1	−3.1	−407.3	19.3	18.1	33.0	−1.9

[a] REPE (taken from ref 5c) in units of β. [b] Evaluated at B3LYP/6-31G*+ZPE (B3LYP/6-31G*) + syn−anti corrections (see Supporting Information). [c] $\Lambda = \chi_M - \chi'_M$. Magnetic susceptibilities of parent [4n]annulenes, χ_M, at CSGT-B3LYP/6-31+G*//; magnetic susceptibilities of nonaromatic models, χ'_M, evaluated using increments (see ref 22). [d] NICS(0), NICS(0)$_\pi$, H$_{outer}$, and H$_{inner}$ at IGLO/TZ2P//B3LYP/6-31G*. [e] Taken from ref 10. [f] Syn−anti correction of 7.2 kcal/mol made to ISE$_{IIuncorr}$. [g] Taken from ref 16.

from experimental data.[15] The benzene ISE$_{SP}$ from equation **1** is somewhat larger, but both exceed the Dewar−de Llano resonance energy of 17 kcal/mol considerably. This Dewar− de Llano RE does not include the syn−anti corrections.

Geometries. The [4n]annulene geometries and energies were evaluated by imposing planarity in order to maximize the π interactions. While all the larger [4n]annulenes have nonplanar minima, the planar restriction is not unrealistic.[6] All the [4n]annulenes favor bond-alternating geometries at B3LYP/6-31G*. The difference in lengths between the longest and shortest bonds (Δr, see Table 1) provides a geometric aromaticity index. This may be compared to the computed 0.078 Å single-/double-bond difference in the interior of long-chain conjugated polyenes. With the exception of COT (Δr 0.130 Å), there is a regular decrease from the large Δr of cyclobutadiene (0.243 Å) to 0.087 Å for [24]-annulene.

Energies. The [4n]annulene ISE$_{SP}$ values, computed by the SP method with corrections (Table 1 and Scheme 1), agree very well with the ISE$_{II}$ (corrected) results.

As we concluded earlier,[16] Dewar's π-approximation largely underestimates the REs for [4n + 2]annulenes. Examples are his unrealistically low 2.8 kcal/mol RE for [18]annulene,[5c,17,18] and his prediction that the RE of large aromatic annulenes should decrease to 2.8 kcal/mol. We confirmed[16] Choi and Kertesz's[18b] finding that these energies approach a much higher constant value.

The negative REPEs derived from application of the Dewar reference within the framework of the Hückel method,[5d] as noted above, indicate all [4n]annulenes to be destabilized (Table 1 and Figure 1, which include benzene). The large [4n]annulenes also are destabilized, but only to a small extent. Both ISEs exhibit progressions to more positive values with increasing ring size. In accord with the earlier molecular mechanics[9] and ab initio investigations,[19] but in disagreement with the large REPE destabilization, planar D_{4h} COT, perhaps the best studied [4n]annulene, is only desta-bilized minimally. At least part of the disagreement between the REPE and ISE methods is due to the different choice of reference structures. The REPE method, being based on Hückel π energies, uses linear polyenes and does not take syn and anti energy differences into account. These energy differences are an essential component of the ISE method; therefore, the idealized reference structures proposed by Dewar are not employed.
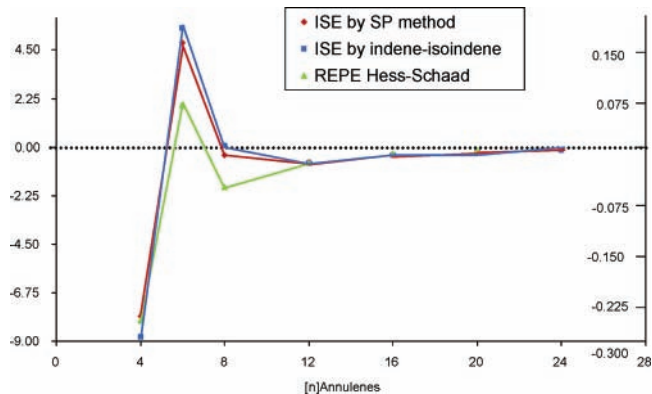

Figure 1. ISE per π-electron (ISEPE) of the [n]annulenes computed by the Schleyer−Pühlhofer (ISE$_{SP}$) and by the indene− isoindene (ISE$_{II}$) methods compared with scaled REPEs.

Contrary to Breslow's antiaromaticity definition that "a cyclic conjugated system has its π electron energy higher

(15) (a) Pedley J. B.; Naylor R. D.; Kirby S. P. *Theromochemical Data of Organic Compounds*; Chapman and Hall: London, 1986. (b) Afeefy, H. Y.; Liebman, J. F.; Stein, S. E. Neutral Theromochemical Data. In *NIST Chemistry WebBook*, NIST Standard Reference Database No. 69; Linstrom, P. J., Mallard, W. G., Eds.; National Institute of Standards and Technol-ogy: Gaithersburg, MD; http://webbook.nist.gov (accessed July 2001).
(16) Wannere, C. S.; Schleyer, P. v. R. *Org. Lett.* **2003**, *5*, 865.
(17) Dewar M. J. S.; Dougherty R. C. *The PMO Theory of Organic Chemistry*; Plenum: New York, 1975.
(18) (a) Baldridge, K. K.; Siegel, J. S. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 745. (b) Choi, C. H.; Kertesz, M. *J. Chem. Phys.* **1998**, *108*, 6681.

(19) (a) Murray, J. S.; Seminario, J. M.; Politzer, P. *Int. J. Quantum Chem.* **1994**, *49*, 575. (b) Politzer, P.; Murray, J. S.; Seminario, J. M. *Int. J. Quantum Chem.* **1994**, *50*, 273.

than that of a suitable reference compound which is not cyclically delocalized," we find that the [4n]annulenes, with the exception of CBD, are not destabilized appreciably.

Magnetic Properties. In contrast to the energies, more sensitive measures of [n]annulene aromaticity or antiaromaticity are provided by the magnetic criteria (Λ,[20] ^{1}H NMR chemical shifts, as well as NICS[21] [nucleus-independent chemical shifts] and its dissection). These properties are influenced directly by the special ring current effects attributable to cyclic π-electron conjugation. Like our aromatic annulene results,[16] we now find the magnetic properties of [4n]annulenes to be more sensitive than the energies.

Although the magnetic susceptibility exaltation, Λ, for only a few [4n]annulenes are known experimentally,[20a] Λ is closely associated with aromaticity. The computed[22] Λ of D_{4h} COT is large and negative (-79.4 cgs ppm, Table 1). The data in Table 1 show an increase in Λ from [8]- to [24]-annulene. However, recall that Λ for cyclic conjugated systems depend on the square of the ring area.[16] Nevertheless, the negative [24]annulene Λ indicates unfavorable cyclic π-electron interactions and antiaromaticity in [4n]annulenes.

The computed proton chemical shifts, also summarized in Table 1, are extremely sensitive to the geometries and to the cyclic π-electron currents. In contrast to the large antiaromatic destabilization of CBD, its protons (δ 5.9) appear[23] in the olefinic region. COT (δ 2.0) and the outer Hs of [12]-, [16]-, [20]-, and [24]annulene are displaced upfield (δ -1.9 to $+2.8$), while the inner protons are strongly deshielded (downfield) ($\delta \sim 33$). The computed downfield chemical shifts of the inner Hs and the upfield chemical shifts of the outer Hs indicate strong paratropic ring currents in [4n]annulenes and the expected antiaromatic behavior.

Understandably, the NICS[24] in the ring centers and above mirror the behavior of the chemical shifts of the inner protons. The [4n]annulenes NICS(0) are large and positive due to the strong induced paratropic ring currents arising from cyclic π-electron interaction. D_{4h} COT shows the largest NICS(0) value in the [4n]annulene set. NICS(0) decreases, but only slightly, with increasing ring size. Similar to the Λ data, the large positive NICS(0) values indicate strong paratropic ring currents in [4n]annulenes. Since NICS(0)

values include both σ and π contributions, dissected NICS values[21b] are more instructive in assigning the paratropic π-bond contributions. The CBD NICS(0)$_\pi$ value (-0.2) is exceptional in showing no net π contributions.[21c] The other [4n]annulenes have large and positive π contributions. Like NICS(0), NICS(0)$_\pi$ also is largest at the center of D_{4h} COT, but the NICS(0)$_\pi$ values of the other [4n]annulenes are nearly the same.

In conclusion, SP's ISE procedure gives reliable and consistent data for [4n]annulenes if appropriate corrections are applied. The reliability of SP's method also is confirmed by the close agreement with the newly introduced ISE$_{II}$ (indene−isoindene) approach, which is fully homodesmotic.

The [4n]annulene antiaromaticity criteria give somewhat inconsistent results. CBD is exceptional in having a uniquely large destabilization energy and negative Λ but exhibiting olefinic proton chemical shifts and a near zero NICS(0)$_\pi$ value. D_{4h} COT has a near zero stabilization energy but also the largest NICS(0) and NICS(0)$_\pi$ values. Otherwise, there are regular progressions in the degree of bond alternation with ring size but no notable differences in the remaining properties listed in Table 1.

Remarkably, the destabilizing effects in larger [4n] systems are insignificant. This finding undermines definitions of antiaromaticity based on energy for systems with more than 4 π-electrons. The degree of bond alternation of the antiaromatics is larger than for conjugated olefins. While ISE does not reveal significant antiaromatic behavior for COT and the larger [4n]annulenes, the computed proton chemical shifts, Λ, and NICS show strong paratropic ring currents in these larger [4n]annulenes.

Consequently, the [4n]annulene aromaticity indices can be regarded as statistically multidimensional.[25] The best antiaromaticity indicators appear to be the proton chemical shifts and the closely related NICS rather than energies. For example, planar D_{4h} COT is nonaromatic energetically but exhibits an upfield proton chemical shift (δ 2.0) and a positive NICS, indicating antiaromaticity. Similar antiaromatic behavior also is shown by the larger [4n]annulenes. The term antiaromaticity, applied to [4n]annulenes with $n > 1$, is better based on magnetic behavior than on energetic destabilization.

Supporting Information Available: Detailed computational output information for all of the structures in Scheme 1 and Table 1. This material is available free of charge via the Internet at http://pubs.acs.org.

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(20) (a) Dauben, H. J.; Wilson, J. D.; Laity, J. L. *Nonbenzenoid Aromaticity* Snyder, J. P., Eds.; Academic Press: New York, 1971; Vol 2, and references therein. (b) Jiao, H.; Schleyer, P. v. R. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1763. (c) Herges, R.; Jiao, H.; Schleyer, P. v. R. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 1376. (d) Schleyer, P. v. R.; Jiao, H. *Pure Appl. Chem.* **1996**, *68*, 209.

(21) (a) Schleyer, P. v. R.; Maerker, C.; Dransfeld, A.; Jiao, H.; Hommes, N. J. R. v. E. *J. Am. Chem. Soc.* **1996**, *118*, 6317. (b) 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. (c) 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.

(22) Evaluations ($\Lambda = \chi_M - \chi'_M$) are based on the difference between the magnetic susceptibilities of an antiaromatic compound (χ_M) and their closely related nonaromatic model (χ'_M). χ'_M was based on an increment scheme, which is based on magnetic susceptibilities of ethylene and butadiene. The CH_2= and =CH− increments are -7.3 and -5.1 cgs ppm, respectively.

(23) Wannere, C. S.; Schleyer, P. v. R. *Org. Lett.* **2003**, *5*, 605.

(24) Negative value of absolute magnetic shieldings calculated at revealing points (generally center of the ring) in [n]annulene system.

(25) Such conclusions also were made from a study of aromatic systems comprised of 105 compounds. For example, see: Cyrański, M. K.; Krygowski, T. M.; Katritzky, A. R.; Schleyer, P. v. R. *J. Org. Chem.* **2002**, *67*, 1333.