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Double Group Transfer Reactions as Indicators of Aromatic Stabilization

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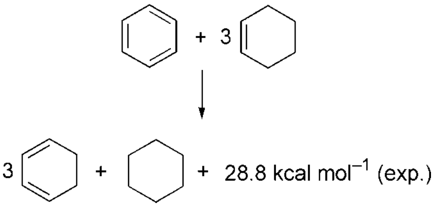
The main features of double hydrogen atom transfer reactions in *syn*-sesquinorbornanes, which involve the concomitant formation of an aromatic ring, have been studied computationally within the framework of Density Functional Theory. The very good linear correlations, which exhibit high correlation coefficients between the recently available Aromatic Stabilization Energies (ASE) from the Energy Decomposition Analysis (EDA) method and the activation and reaction energies, as well as geometric features (C–C bond lengths) of the corresponding transition states of the transformations, suggest that the calculated values are useful in estimating the aromatic character of a molecule. The studied process may be used for benchmarking of energetic aromatic indices.

Introduction

Aromaticity is still an amazingly fruitful concept for experimental and theoretical research, which has recently been summarized in a series of reviews.[1] It belongs to the archetypal class of chemical bonding models which are ubiquitously used by chemists, although they have no precise meaning. Thus, aromaticity has been called a typical example of a *unicorn of the chemical bonding models*.[2] Analogous to the mythological animal, aromaticity is known by every chemist but still it is just a virtual, and therefore, a non-observable quantity which is universally understood by convention.

Nevertheless, numerous criteria, which are not free from ambiguities, have been suggested in order to classify aromatic compounds. Among them, the energetic criterion, if well defined, is considered to be the principal one,[3] since it governs the reactions and much of the chemical behavior of a molecule. However, most of the methods used to experimentally or computationally estimate the aromatic stabilization energies (ASE) are based on isodesmic reactions (for example, see the reaction depicted in Scheme 1) which are contaminated by different flaws such as strain, hyperconjugation, "proto"branching, or *syn-anti* effects.[4] Therefore, the calculated ASE values are not always reliable. Thus, it would be helpful if a direct estimate of the ASEs could be made based on a rigorously defined quantum chemical method. Such a method was reported by some of us[5] in a very recent study where we used the energy decomposition analysis (EDA)[6] method to estimate the strength of π-cyclic conjugation in typical aromatic, homoaromatic and antiaromatic compounds by comparing the calculated ΔE_π values (which are a direct measure of the conjugative strength) of the cyclic compounds with acyclic reference systems. The calculation of benzene with all-*trans*-1,3,5,7-octatetraene as the reference molecule gave an ASE value of 42.5 kcal/mol. The latter molecule, which has eight π electrons, was chosen as reference because it has the same number of conjugating σ bonds as benzene, and because it has been suggested that the ASE values exhibit a better correlation with nucleus-independent chemical shift (NICS) values when the latter reference system is chosen.[7] Using the same approach, we found for cyclobutadiene, a molecule which is considered as the archetypal antiaromatic molecule,[8] an ASE value of –31.9 kcal/mol with respect to all-*trans*-1,3,5-hexatriene, which agrees with the classification of cyclobutadiene as antiaromatic species. Therefore, our newly developed methodology provides a reliable scale of aromaticity which has also been successfully applied to estimate the aromatic strength of metallabenzenes,[9] systems where the geometric harmonic oscillator model of aromaticity (HOMA) method and magnetic NICS or magnetic susceptibilities are not applicable.



Scheme 1.

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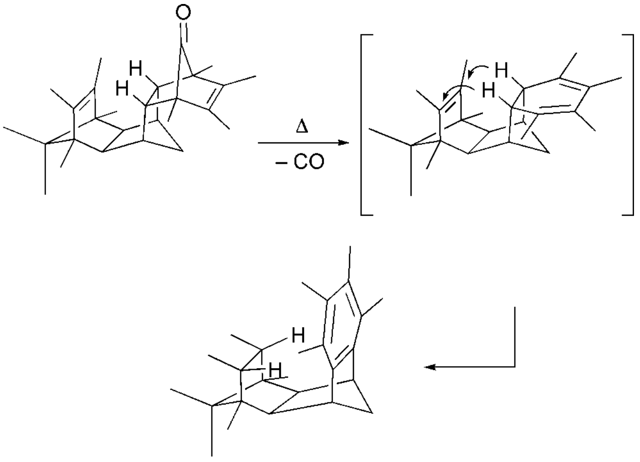
We recently reported that transition structures associated with two-group migrations are *in-plane* analogues of six-membered heteroaromatic rings.[10] This analogy is also applicable to the intramolecular rearrangement in *syn*-sesquinorbornanes, depicted in Scheme 2, which was experimentally described by Mackenzie as a sigmatropic hydrogen transfer in the isodrin series.[11] Thus, this rearrangement, also known as a type-II dyotropic reaction,[12] can be considered as a particular case of double group-transfer reactions involving the concerted and synchronous transfer of two hydrogen atoms from an ethane unit to an ethylene group in a process suprafacial on both reaction sites. Therefore, this transformation may be considered as a thermally allowed pericyclic reaction according to the Woodward and Hoffmann rules.[13] Furthermore, these reactions occur through a highly aromatic *in-plane* transition state[14] in view of the computed high negative NICS values at the [3+1] ring critical point of the electron density as defined by Bader.[15]



Scheme 2.

The two hydrogen-atom migration depicted in Scheme 2 involves the concomitant formation of an aromatic ring and, therefore, both the activation barriers and the reaction energies of the rearrangement should be affected by this aromatization process. The formation of the aromatic ring by the dyotropic movement may be considered as a driving-force of the transformation. Therefore, the ease of the rearrangement should correlate with the aromatic stabilization. The extension of this reaction to analogous processes in which other aromatic rings are formed may provide a reasonable scenario for the definition of aromaticity. Reported in this paper is the successful implementation of this idea.

Computational Details

All the calculations reported in this paper were obtained with the GAUSSIAN 03 suite of programs.[16] Electron correlation was partially taken into account using the hybrid functional usually denoted as B3LYP[17] and the standard 6-31+G* basis set[18] for hydrogen, carbon, oxygen, nitrogen, and sulfur. Zero point vibrational energy (ZPVE) corrections were computed at the B3LYP/6-31+G* level and were not scaled. Reactants and products were characterized by frequency calculations,[19] and have positive definite Hessian matrices. Transition state structures (TS's) show only one negative eigenvalue in their diagonalized force constant matrices, and their associated eigenvectors were confirmed to correspond to the motion along the reaction coordinate under consideration using the Intrinsic Reaction Coordinate (IRC) method.[20] Nucleus independent chemical shifts (NICS)[21] were evaluated by using the gauge invariant atomic orbital (GIAO)[22] approach, at the GIAO-B3LYP/6-31+G(d)//B3LYP/6-31+G(d) level.

The synchronicity[23,24] of the reactions was quantified by using a previously described approach.[25] For a given concerted reaction, "synchronicity" is defined as[26]

$$S_y = 1 - \frac{\sum_{i=1}^{n} \frac{\left|\delta B_i - \delta B_{AV}\right|}{\delta B_{AV}}}{2n-2}$$

where n is the number of bonds directly involved in the reaction (in this case, $n = 6$) and δB_i stands for the relative variation of a given bond index B_i at the transition state (TS), according to the following formula:

$$\delta B_i = \frac{B_i^{\mathrm{TS}} - B_i^{\mathrm{R}}}{B_i^{\mathrm{P}} - B_i^{\mathrm{R}}}$$

where the superscripts R and P refer to the reactants and the product, respectively. The average value of δB_i, denoted as δB_{AV} is therefore

$$\delta B_{\mathrm{AV}} = n^{-1} \sum_{i=1}^{n} \delta B_i$$

The Wiberg bond indices[27] B_i were computed using the natural bond orbital (NBO)[28] method.

As energetic aromaticity criterion, we used our recently introduced EDA-based ASE values.[5] Table 1 shows the ASE values for the compounds which are considered in this report.

Table 1. ASE values (in kcal/mol) from the EDA method.[a]

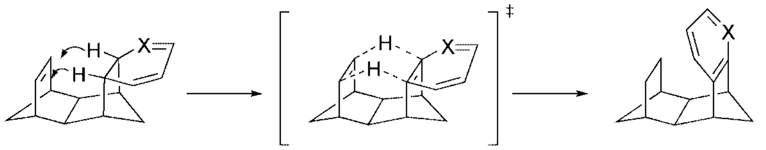
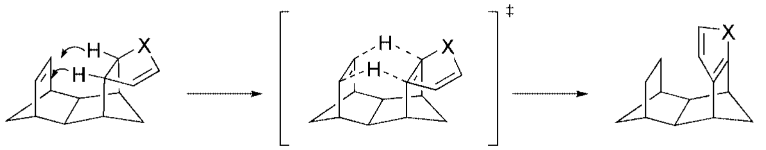
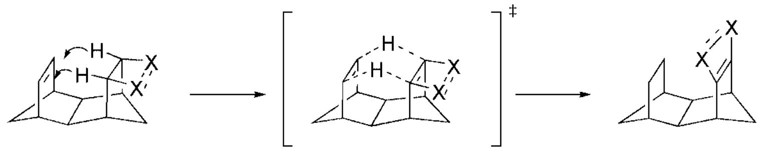
Compound	ASE
Benzene (D_{6h})	42.5
Pyridine (C_{2v})	45.7
Cyclobutadiene (D_{2h})	–31.9
Cyclobutene (C_{2v})	3.5
1*H*-Pyrrole (C_{2v})	21.1
Furan (C_{2v})	16.2
Thiophene (C_{2v})	21.9

[a] ASE values taken from ref.[5], computed at the BP86/TZ2P level.

Results and Discussion

DFT calculations were carried out for the model reactions **1** → **3** (Table 2) at the B3LYP/6-31+G(d) level. As readily seen from the data gathered in Table 2, in all cases the double hydrogen atom transfer occurs concertedly through a highly aromatic *in-plane* transition state (Figure 1). The computed strongly negative NICS values at the

Table 2. Activation energies (E_a, kcal/mol),[a] reaction energies (E_R, kcal/mol),[a] synchronicities (S_y, in a.u.), NICS(0), and NICS(1) values (in ppm), associated with the **1** → **3** double hydrogen atom transfers.

Entry	X	E_a[b]	E_R[c]	S_y	NICS(0)[d]	NICS(1)[e]
 **1a**,**b** **2a**,**b** **3a**,**b**						
1	CH	19.9	–41.1	0.89	–26.03	–12.14
2	N	20.6	–39.5	0.88	–26.59	–12.57
 **1c**–**e** **2c**–**e** **3c**–**e**						
3	O	36.6	–6.8	0.84	–24.57	–12.11
4	S	31.5	–14.0	0.84	–24.85	–11.84
5	NH	31.4	–16.4	0.84	–24.62	–12.19
 **1f**,**g** **2f**,**g** **3f**,**g**						
6	CH	63.3	+46.6	0.93	–16.06	–6.49
7	CH_2	46.9	+15.9	0.92	–24.44	–11.53

[a] All values have been calculated at the B3LYP/6-31+G(d)+ΔZPVE level. [b] Activation energy values computed as $E_a = E(\mathbf{2}) - E(\mathbf{1})$. [c] Reaction energy values computed as $E_R = E(\mathbf{3}) - E(\mathbf{1})$. [d] NICS(0) values computed at the GIAO-B3LYP/6-31+G(d) level at the [3,+1] ring critical point of the electron density. [e] NICS(1) values computed at 1 Å above the ring critical point.

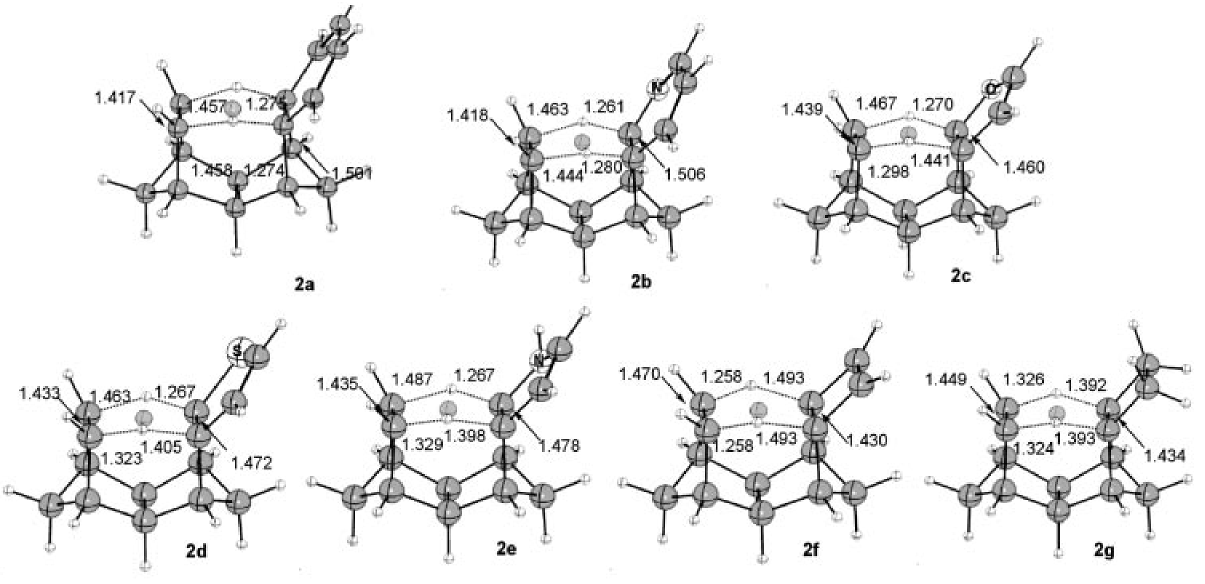


Figure 1. Ball-and-stick representations of transitions states **2a**–**g**. All structures correspond to fully optimized B3LYP/6-31+G(d) geometries. Bond lengths are given in Å. Unless otherwise stated, white and gray colors denote hydrogen and carbon atoms, respectively. The dummy atoms denote the [3,+1] ring critical point of electron density.

[3,+1] ring critical point of the electron density [denoted as NICS(0)] and at 1 Å above that point [denoted as NICS(1)] clearly show the aromatic character of the saddle points. We want to point out that the NICS values are unusually high when compared to benzene (around –11 ppm). This is probably caused by the coupling between the magnetic fields of the parallel components of the contiguous rings. It is noteworthy that the seven studied reactions are found to exhibit rather high synchronicities (S_y = 0.84–0.93, see Table 2).[29]

There is no doubt that the formation of the aromatic ring by the dyotropic movement is the driving force of the transformation. This conclusion is based on the lower values of the activation energies compared to the computed values for the analogous parent reaction where the aromatic ring is replaced by a double bond [E_a = 39.9 kcal/mol at the B3LYP/6-31+G(d) level], and it is also reflected in the high exothermicity of the process, in complete agreement with the experimental findings.[11] The comparison of the energy values in Table 2 for the different aromatic systems clearly shows that the activation and reaction energies correlate with the aromatic stabilization energies (ASE) of the aromatic rings being formed during the dyotropic process. Thus, if the studied dyotropic reactions show the strength of the aromaticity, a high correlation between the calculated ASE values and the activation or reaction energies of these processes should exist. In fact, when we plot the latter parameters vs. the ASE values obtained with the EDA method, very good linear relationships are found (Figure 2: ASE vs. E_a, correlation coefficient of –0.99 and standard deviation of 2.04; ASE vs. E_R, correlation coefficient of –0.99 and standard deviation of 4.47). These excellent correlations confirm that these double group transfer reactions can be used as indicators of aromatic stabilization and therefore, as benchmark for energetic aromaticity criteria. Moreover, the lower standard deviation computed for activation energies compared to reaction energies indicates that the former parameter is even a better indicator of aromaticity.

From the results compiled in Figure 2, we can conclude that the more aromatic the forming ring, the more favorable the dyotropic process is, both from kinetic and thermodynamic points of view, in good agreement with the Hammond postulate.[30] Therefore, the reaction is energetically favorable with strong aromatic groups such as benzene and pyridine (entries 1 and 2 respectively, Table 1) while it is disfavored when the forming ring is a nonaromatic compound such as cyclobutene (entry 7, Table 1) or cyclobutadiene, which is considered as the archetypal antiaromatic compound (entry 6, Table 1). Furthermore, the relative strength of aromaticy in the series benzene, pyridine, pyrrole, thiophene, and furan may be estimated by considering the energetics of the corresponding dyotropic process relative to the reaction involving benzene formation (relative aromaticity strength: 1:0.96:0.40:0.34:0.17 respectively).

Interestingly, the different C–C(former ethylenic moiety) and C–C(ring moiety) bond lengths of the transition states involved in the migration processes (Figure 1) are also affected by the aromatization process. For instance, the C–C bond length of the former ethylenic moiety shortens from **2f** (1.470 Å), a saddle point which corresponds to the formation of a cyclobutene ring, to **2a** (1.417 Å), which is associated with the formation of a benzene ring. Therefore, the double bond character of this bond is the lowest in **2f** (NBO bond order = 1.16) and highest in **2a** (NBO bond order = 1.36). These results are also in accord with the Hammond principle,[30] which states that a more product-like transition state with a larger C–C bond length corresponds to a more endothermic reaction. The data suggest that the latter geometric feature is directly related to the *in-plane* aromaticity of the corresponding transition state, but also indirectly with that of the final aromatic ring. For that reason, it is very likely that this geometric parameter is also a good indicator of the aromatic stabilization, and therefore it is not surprising that very good linear relationships between the different C–C bond lengths and the calculated ASE values were found as well [Figure 3, ASE vs. C–C(former ethylenic moiety) bond length, correlation coefficient of –0.996 and standard deviation of 0.002; ASE vs. C–C(ring moiety)

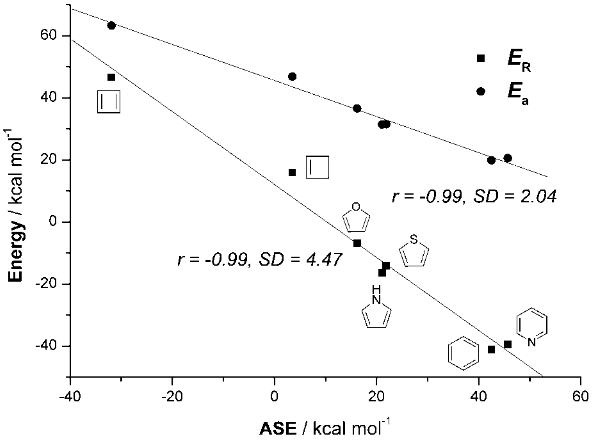


Figure 2. Plot of the ASE values vs. the activation (circles) and reaction (squares) energies for the dyotropic process **1** → **3**.

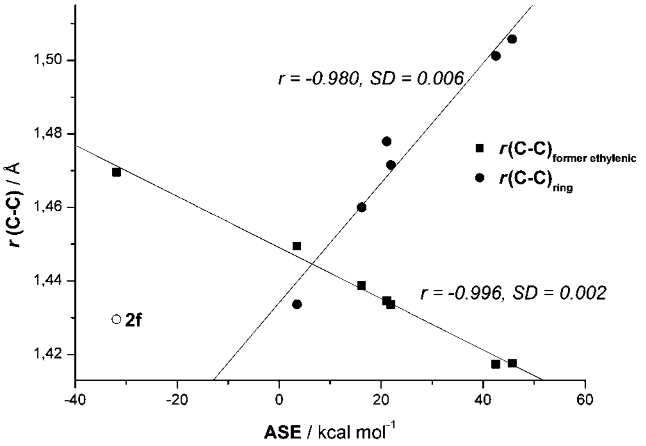
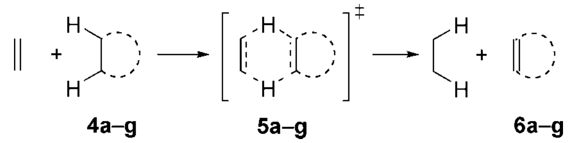


Figure 3. Plot of the ASE values vs. the C–C bond lengths of the transition states **2a**–**g**.

bond length, correlation coefficient of –0.980 and standard deviation of 0.006]. This finding provides further support to the above-mentioned conclusion that the considered double hydrogen-atom-transfer reactions are indeed good systems to indicate the aromatic character of a given compound.

The question of using the corresponding intermolecular process **4** + ethene → **6** + ethane (Table 3) instead of the large systems for the reaction **1** → **3** is finally addressed. As readily seen in Figure 4, and from the very good correlations between activation energies E_a and reaction energies E_R with ASE values (Figure 4: ASE vs. E_a, correlation coefficient of –0.97 and standard deviation of 3.05; ASE vs. E_R, correlation coefficient of –0.98 and standard deviation of 6.19), the intermolecular double hydrogen atom transfer from the hydrogenated compounds **4a–g** to ethane is a good indicator of aromaticity as well. However, the lower values of the correlation coefficients and higher values of standard deviations compared with those which correspond to the intramolecular process (Figure 2) suggest that the intramolecular process is a better choice. This might be due to a better balance of strain and hyperconjugation effects.

Table 3. Activation energies (E_a, kcal/mol)[a] and reaction energies (E_R, kcal/mol),[a] associated with the **4** + ethene → **6** + ethane double hydrogen atom transfers.



Entry	Ring system	E_a[b]	E_R[c]
1	benzene	29.2	–43.0
2	pyridine	29.9	–40.9
3	furan	36.2	–21.8
4	thiophene	35.3	–24.9
5	1*H*-pyrrole	33.3	–31.7
6	cyclobutadiene	62.2	+33.4
7	cyclobutene	46.3	+1.5

[a] All values have been calculated at the B3LYP/6-31+G(d) +ΔZPVE level. [b] Activation energy values computed as $E_a = E(\mathbf{5}) - E(\text{ethene}) - E(\mathbf{4})$. [c] Reaction energy values computed as $E_R = E(\mathbf{6}) + E(\text{ethane}) - E(\text{ethene}) - E(\mathbf{4})$.

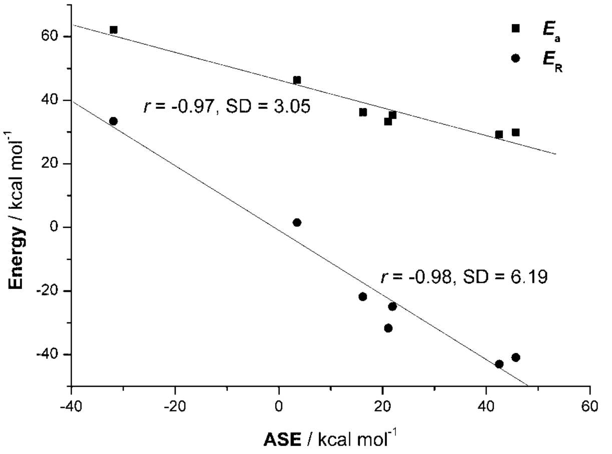


Figure 4. Plot of the ASE values vs. the activation (squares) and reaction (circles) energies for the dyotropic process **4** + ethene → **6** + ethane.

Conclusions

In summary, we have found that the strength of aromaticity can be estimated by double hydrogen atom transfer reactions involving the formation of an aromatic ring. The very good linear correlations, which exhibit excellent correlation coefficients between the energetic aromaticity criterion (ASE values) and the activation and reaction energies, as well as geometric features (C–C bond lengths) of the corresponding transition states of the transformations, suggest that the calculated values are useful in estimating the aromatic character of a molecule. In other words, the reaction type proposed in this report constitutes an isodesmic reaction based upon an intramolecular process, thus providing an adequate benchmark for energetic aromaticity criteria.

Supporting Information (see footnote on the first page of this article): Cartesian coordinates (in Å) and total energies (in a.u., noncorrected zero-point vibrational energies included) of all the stationary points discussed in the text.

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[1] a) Delocalization, pi and sigma, see: *Chem. Rev.* **2005**, 105; b) Aromaticity, see: *Chem. Rev.* **2001**, 101.

[2] G. Frenking, A. Krapp, *J. Comput. Chem.* **2007**, *28*, 15.

[3] a) P. v. R. Schleyer, P. K. Freeman, H. Jiao, B. Goldfuss, *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 337; b) V. I. Minkin, M. N. Glukhovtsev, B. Ya. Simkin, *Aromaticity and Antiaromaticity–Electronic and Structural Aspects*; Wiley, New York, **1994**; c) T. M. Krygowski, M. K. Cyrañski, Z. Czarnocki, G. Häfelinger, A. R. Katritzky, *Tetrahedron* **2000**, *56*, 1783; d) P. v. R. Schleyer, C. Maerker, A. Dransfield, H. Jiao, N. J. R. van Eikema Hommes, *J. Am. Chem. Soc.* **1996**, *118*, 6317.

[4] P. v. R. Schleyer, F. Puhlhofer, *Org. Lett.* **2002**, *4*, 2873.

[5] I. Fernández, G. Frenking, *Faraday Discuss.* **2007**, *135*, 403.

[6] a) F. M. Bickelhaupt, E. J. Baerends, in *Reviews in Computational Chemistry* (Eds.: K. B. Lipkowitz, D. B. Boyd), Wiley, New York, **2000**, vol. 15, p. 1; b) G. te Velde, F. M. Bickelhaupt, E. J. Baerends, S. J. A. van Gisbergen, C. Fonseca Guerra, J. G. Snijders, T. Ziegler, *J. Comput. Chem.* **2001**, *22*, 931; c) M. Lein, G. Frenking, *Theory and Applications of Computational Chemistry: The First 40 Years* (Eds.: C. E. Dykstra, G. Frenking, K. S. Kim, Scuseria G. E.), Elsevier, Amsterdam, **2005**.

[7] Y. Mo, P. v. R. Schleyer, *Chem. Eur. J.* **2006**, *12*, 2009.

[8] T. Bally, *Angew. Chem. Int. Ed.* **2006**, *45*, 6616.

[9] I. Fernández, G. Frenking, *Chem. Eur. J.* **2007**, *13*, 5873.

[10] I. Fernández, F. P. Cossío, M. A. Sierra, *J. Org. Chem.* **2007**, *72*, 1488.

[11] a) K. Mackenzie, *J. Chem. Soc.* **1965**, 4646; b) K. Mackenzie, *J. Chem. Soc. C* **1969**, 1784; c) K. Mackenzie, G. Proctor, D. J.

Woodnut, *Tetrahedron* **1987**, *43*, 5981; d) K. Mackenzie, J. A. K. Howard, S. Mason, E. C. Gravett, K. B. Astin, S. X. Liu, A. S. Batsanov, D. Vlaovic, J. P. Maher, *J. Chem. Soc. Perkin Trans. 2* **1993**, 1211; e) K. Mackenzie, J. A. K. Howard, R. Siedlecka, K. B. Astin, E. C. Gravett, C. Wilson, J. Cole, R. G. Gregory, A. S. Tomlins, *J. Chem. Soc., Perkin Trans. 2* **1996**, 1749.

[12] a) M. T. Reetz, *Angew. Chem. Int. Ed. Engl.* **1972**, *11*, 129; M. T. Reetz, *Angew. Chem. Int. Ed. Engl.* **1972**, *11*, 130; b) M. T. Reetz, *Tetrahedron* **1973**, *29*, 2189; c) M. T. Reetz, *Adv. Organomet. Chem.* **1977**, *16*, 33; d) K. N. Houk, Y. Li, M. A. McAllister, G. O'Doherty, L. A. Paquette, W. Siebrand, Z. K. Smedarchina, *J. Am. Chem. Soc.* **1994**, *116*, 10895.

[13] R. B. Woodward, R. Hoffmann, *The Conservation of Orbital Symmetry*, Verlag Chemie, Weinheim (Germany), **1970**, p. 141.

[14] a) H. Jiao, P. v. R. Schleyer, *J. Phys. Org. Chem.* **1998**, *11*, 655; b) F. P. Cossío, I. Morao, H. Jiao, P. v. R. Schleyer, *J. Am. Chem. Soc.* **1999**, *121*, 6737; c) I. Morao, B. Lecea, F. P. Cossío, *J. Org. Chem.* **1997**, *62*, 7033; d) I. Fernández, M. A. Sierra, F. P. Cossío, *J. Org. Chem.* **2006**, *71*, 6178.

[15] R. F. W. Bader, *Atoms in Molecules–A Quantum Theory*, Clarendon Press, Oxford, **1990**.

[16] M. J. Frisch, G. W. Trucks, H. B. Schlegel, G. E. Scuseria, M. A. Robb, J. R. Cheeseman, J. A. Montgomery Jr, T. Vreven, K. N. Kudin, J. C. Burant, J. M. Millam, S. S. Iyengar, J. Tomasi, V. Barone, B. Mennucci, M. Cossi, G. Scalmani, N. Rega, G. A. Petersson, H. Nakatsuji, M. Hada, M. Ehara, K. Toyota, R. Fukuda, J. Hasegawa, M. Ishida, T. Nakajima, Y. Honda, O. Kitao, H. Nakai, M. Klene, X. Li, J. E. Knox, H. P. Hratchian, J. B. Cross, V. Bakken, C. Adamo, J. Jaramillo, R. Gomperts, R. E. Stratmann, O. Yazyev, A. J. Austin, R. Cammi, C. Pomelli, J. W. Ochterski, P. Y. Ayala, K. Morokuma, G. A. Voth, P. Salvador, J. J. Dannenberg, V. G. Zakrzewski, S. Dapprich, A. D. Daniels, M. C. Strain, O. Farkas, D. K. Malick, A. D. Rabuck, K. Raghavachari, J. B. Foresman, J. V. Ortiz, Q. Cui, A. G. Baboul, S. Clifford, J. Cioslowski, B. B. Stefanov, G. Liu, A. Liashenko, P. Piskorz, I. Komaromi, R. L. Martin, D. J. Fox, T. Keith, M. A. Al-Laham, C. Y. Peng, A. Nanayakkara, M. Challacombe, P. M. W. Gill, B. Johnson, W. Chen, M. W. Wong, C. Gonzalez, J. A. Pople, *Gaussian 03, Revision D.01*, Gaussian, Inc., Wallingford CT, **2004**.

[17] a) A. D. Becke, *J. Chem. Phys.* **1993**, *98*, 5648; b) C. Lee, W. Yang, R. G. Parr, *Phys. Rev. B* **1998**, *37*, 785; c) S. H. Vosko, L. Wilk, M. Nusair, *Can. J. Phys.* **1980**, *58*, 1200.

[18] W. J. Hehre, L. Radom, P. v. R. Schleyer, J. A. Pople, *Ab initio Molecular Orbital Theory*; Wiley: New York, **1986**, p. 76 and references cited therein.

[19] J. W. McIver, A. K. Komornicki, *J. Am. Chem. Soc.* **1972**, *94*, 2625.

[20] C. González, H. B. Schlegel, *J. Phys. Chem.* **1990**, *94*, 5523.

[21] Z. Chen, C. S. Wannere, C. Corminboeuf, R. Puchta, P. v. R. Schleyer, *Chem. Rev.* **2005**, *105*, 3842.

[22] K. Wolinski, J. F. Hilton, P. Pulay, *J. Am. Chem. Soc.* **1990**, *112*, 8251.

[23] a) M. J. S. Dewar, *J. Am. Chem. Soc.* **1984**, *106*, 209; b) W. T. Borden, R. J. Loncharich, K. N. Houk, *Annu. Rev. Phys. Chem.* **1988**, *39*, 213.

[24] Leroy has proposed the term "asynchronism" in similar contexts; see: G. Leroy, M. Sana, *Tetrahedron* **1975**, *31*, 2091.

[25] A. Moyano, M. A. Pericás, E. Valentí, *J. Org. Chem.* **1989**, *54*, 573.

[26] a) B. Lecea, A. Arrieta, G. Roa, J. M. Ugalde, F. P. Cossío, *J. Am. Chem. Soc.* **1994**, *116*, 12314; b) B. Lecea, A. Arrieta, X. López, J. M. Ugalde, F. P. Cossío, *J. Am. Chem. Soc.* **1995**, *117*, 12314.

[27] K. B. Wiberg, *Tetrahedron* **1968**, *24*, 1083.

[28] a) J. P. Foster, F. Weinhold, *J. Am. Chem. Soc.* **1980**, *102*, 7211; b) A. E. Reed, F. Weinhold, *J. Chem. Phys.* **1985**, *83*, 1736; c) A. E. Reed, R. B. Weinstock, F. Weinhold, *J. Chem. Phys.* **1985**, *83*, 735; d) A. E. Reed, L. A. Curtiss, F. Weinhold, *Chem. Rev.* **1988**, *88*, 899.

[29] For a perfectly synchronous reaction, $S_y = 1$; see refs.[1b,3]

[30] G. S. Hammond, *J. Am. Chem. Soc.* **1955**, *77*, 334.

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