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Aromaticity: a Theoretical Concept of Immense Practical Importance

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1. Introduction

The terms ‘aromaticity’ and ‘aromatic’ are firmly entrenched in the scientific literature and indeed are among those most often used in organic chemistry, as shown by the comparison in Table 1 with other terms from chemistry, biochemistry, biology and medicine. The *Science Citation Database*[1] gives almost 46 000 instances of the use of ‘aromatic properties’ as a key word from 1981 to 1997, which are related to various specific chemical and physicochemical properties of compounds. There are further some 1000 citations of ‘aromaticity’, mostly to aromaticity as a general phenomenon.

Organic chemistry texts also index the term ‘aromaticity’ very frequently: 17–37 times in well known introductory books,[2a–f] more than 60 times in March’s *Advanced Organic Chemistry*,[2g] and 81 times in that of Carey and Sandberg.[2h] There are many additional, related entries including: aromatic character, aromatization, electrophilic-, nucleophilic- and radical-aromatic substitution, aromatic chemical shift, aromatic and antiaromatic transition states, special reactivity of arenes (i.e. benzenoid systems), and aromatic stabilization.

The frequent incidence of terms associated with aromaticity/aromatic character underlines the importance of a proper definition, which should be generally acceptable to those who most need such terms—i.e. students, teachers

Table 1. Frequency of using chemical/biochemical/medical terms in titles or as key-words retrieved from ISI (1981–1998)

H-Bond	387 817	Solvent	55 226
Water	314 874	Aromatic/aromaticity	46 859
DNA	260 914	AIDS	45 961
Cancer	204 036	Chiral/chirality	34 394
Virus	169 292	Substituent	12 449
Life	109 301	Nucleophilic	11 143
Death	72 337	Electrophilic	5 719

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and practitioners of organic, physical-organic and biochemistry. Unfortunately, no such generally agreed precise definition of aromaticity exists. Despite the special Jerusalem conference in 1970 devoted to the clarification of aromaticity,[3] various interpretations persist.[4]

Within chemistry, qualitative concepts such as aromaticity are extremely useful: they were described by Coulson[5] as 'primitive patterns of understanding,' and other typical examples include 'electronegativity', 'van der Waals radius', and 'resonance (or stabilization) energy'. The question of why such vague terms should be used was well answered by E. D. Bergmann in the concluding remarks at the Jerusalem conference: 'We have not solved the problem of what aromaticity is…, but we all agree that aromaticity can be defined only artificially, by convention, if we do not want to go to the extreme of abandoning the notion altogether. However, classification and theory are not ends in themselves. If they generate new experimental work, new compounds, new processes, new methods—they are good; if they are sterile—they are bad'. A recent monograph[4h] demonstrated that the term is indeed useful and fruitful, with developments in many fields of research stimulated by use of the aromaticity concept.

Aromaticity to a greater or lesser extent is expected in the following classes of organic compounds: (a) monocyclic $[4n+2]$ annulenes (n is the number of π-electrons) including benzenoid hydrocarbons and their substituted derivatives and fully conjugated carbocyclic (mono and poly) anions and cations containing $4n+2$ peripheral π-electrons; (b) condensed conjugated carbocycles including benzenoid systems such as naphthalene and other such as azulene;[6a] (c) fully conjugated heterocycles (heteroaromatics) of which a vast variety exist as was pointed out early on by Balaban;[6b] and (d) ferrocenes and related sandwich systems. Around 50% of all known organic compounds may be classified as containing aromatic ring systems. The many aromatic compounds of great biological importance include the porphyrins and the nucleic acids. In addition to these typically organic cyclic π-electron systems, the term aromatic is also used for many systems on the border of organic and inorganic chemistry (e.g. borazine), or which are typically inorganic (e.g. boroxine, aluminobenzene, etc).[6c–e] Any criterion of aromaticity should be sufficiently general to take into account all these classes, but not (in the opinion of the present authors) where the term is extended to systems which (i) do not contain π-electrons at all (e.g. the H_6 structure with D_{6h} symmetry)[7] or (ii) are not cyclic (e.g. a transition state for the trimerization of acetylene).[7] The term quasiaromatic has been used for systems with intramolecular H-bonds.[8]

2. Historical Development of the Aromaticity Concept

The historical development of the term aromatic/aromaticity is outlined in Fig. 1. Benzene—the paradigm of aromatic character—was isolated by Faraday in 1825.[9] Kekulé first suggested the cyclic structure of benzene in 1865 and applied the term aromatic to compounds containing a benzene ring.[10] A year later, Erlenmeyer designated as aromatic those compounds with chemical reactivities similar to benzenes.[11a] At that time, all unsaturated systems with cyclic conjugation were considered to be aromatic, until Willstaetter[11b] showed that cyclooctatetraenes have no chemical similarity to benzenes.

The 19th-century concept of the oscillation of double and single bonds in benzene[12] was replaced by the concept of resonance between canonical structures.[13] Robinson's 1925 concept of the 'aromatic sextet'[14] was followed in 1931 by MO calculations and the Hückel rule,[15] stating that planar monocyclic systems with $[4n+2]$ π-electrons are more stable than those with $4n$ π-electrons. Further theoretical interpretations have appeared as new experimental techniques and have become available and with the dramatic development in quantum chemical theories.

By the 1960s, most chemists agreed that aromatic compounds are:

(i) (Planar) cyclic delocalized π-electron systems and are typified by the following ground state properties:[16]
(ii) more stable than their olefinic analogs by an energy called the 'resonance energy' (for definition, cf. Ref. 13b,c),
(iii) with bond lengths intermediate between those of typical single and double bonds, and
(iv) with a π-electron ring current induced by an external magnetic field, leading to increased diamagnetic

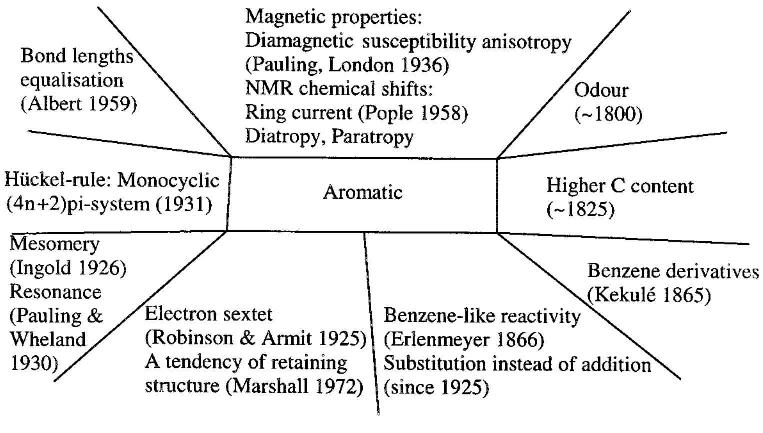

Figure 1.

Table 2. Criteria for aromaticity and antiaromaticity

Property	Aromatic	Olefinic	Antiaromatic
(i) Electronic nature			
	($4n+2$) π-electron cyclic conjugation	No cyclic conjugation	$4n$ π-electron cyclic conjugation
(ii) Energy			
Cyclic conjugation	Stabilization	Standard	Destabilization
Delocalization	Enhanced	Standard	Decreased
HOMO–LUMO gap	Larger	Standard	Smaller
(iii) Geometry			
Bond lengths	Equalization	Alternation	Alternation
(iv) Magnetic properties			
Anisotropy of diamagnetic susceptibility	Enlarged		Small
Susceptibility exaltation	Large		Low
Shifts in ^{1}H NMR spectroscopy	Diatropic (low-field shift)		Paratropic (high-field) shift
Ab initio calculations of NICS (nucleus independent chemical shift)	Large negative		Large positive
(v) Reactivity			
Chemical structure	e.g. Benzene	e.g. Cyclohexadiene	e.g. Cyclooctatraene
Retention of structure	Electrophilic substitution	Electrophilic addition	Addition
(vi) Spectroscopy			
UV spectra	High energy	Standard	Low energy
IR and Raman spectra	Large symmetry		Low symmetry

> susceptibility and typical diatropic [low field] chemical shifts of exocyclic protons in ^{1}H NMR spectra.[17]

An additional characteristic very frequently used by organic chemists, is that:

> (v) aromatic compounds generally undergo substitution reactions (the so-called aromatic substitution) more easily than addition.

Spectroscopically: aromatic compounds

> (vi) show higher energy ultraviolet/visible spectral bands and a more symmetrical structure for their IR spectra.

Table 2 contrasts aromatic and olefinic systems in terms of these criteria. Table 2 also includes criteria for antiaromaticity. Antiaromatic compounds definitely exist although they are much less numerous and less stable than the aromatic and olefinic classes and their ground state is frequently distorted from the symmetry of the true antiaromatic structure. Compounds for which the aromaticity indices are below olefinic should be considered as antiaromatic. The criteria of Table 2 are intuitively acceptable[4h] although they do not define aromaticity uniquely.[†]

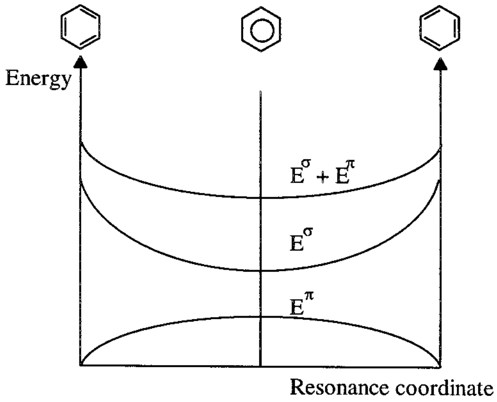

Figure 2. The σ and π separated energies for benzene and its Kekulé structures (following Jug and Koester[19]).

3. The Importance of the Concept of Aromaticity

Although most theoretical treatments of aromaticity are in terms of it as a ground state property, the most frequent and most important usage of the terms 'aromaticity/aromatic character' in organic chemistry is clearly related to reactivity, i.e. feature (v). Thus in March's *Advanced Organic Chemistry*[2g] the term aromaticity is usually associated with the special reactivity of arenes (i.e. benzenoid compounds). A similar situation is found in other textbooks[2] and the same conclusion also results from the *Science Citation Database* analysis[1] mentioned at the beginning of the present report.

The reasons for this are clear. Already in carbocyclic chemistry, it is inconceivable to teach or practice the subject

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[†] Aromaticity has traditionally been treated as a consequence of the π-electron structure. It has long been assumed that the stability is increased by the cyclic delocalization of the π-electrons. Recently, Hiberty and Shaik[18] proposed that the π-system in benzene has a minimum energy for the alternating Kekulé structures, whereas the σ-bond energy minimum is the D_{6h}-structure of equalized bond lengths, as shown schematically in Fig. 2 (calculation of Jug and Koester[19]). This implies that the experimental bond length equalization in benzene is a σ/π cooperative effect dominated by the σ-electron structure. However, the π-electrons provide the frontier orbitals (HOMO and LUMO) of high polarizability which consequently control the aromatic properties of molecules. Accordingly the concept of hardness (half the HOMO/LUMO gap) is well associated with the aromatic character of cyclic π-electron systems.[20] The hypothesis of Ref. 18 is supported by the X-ray structure of chrysene.[21] The central rings of chrysene have low aromatic character. In the charge transfer (CT) complexes of chrysene with tetracyanoquinodimethane or fluoranil, these same rings become more aromatic due to the removal of a portion of the π-electrons from chrysene to the electron acceptor molecules.[21] Fig. 3 presents the numerical data. Thus the reduction of π-electron density appears to increase the aromaticity (as indicated by an increase of HOMA[23] from 0.66 for chrysene to 0.73 for the CT system). Similarly the global HOMA[23] for phenazine of 0.72 increases to 0.79 for the CT complex[22] (for the definition of HOMA see the section Geometric Criteria).

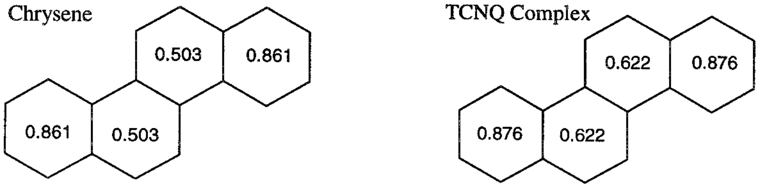


Figure 3. HOMA (harmonic oscillator model of aromaticity) values for the benzene rings of chrysene and the chrysene–TCNQ complex: for the whole chrysene moiety HOMA values are 0.66 and 0.73, respectively.

without making a fundamental distinction between the chemical properties of aromatic and non-aromatic compounds. Any serious student of organic chemistry at any level uses generalizations based on the different behavior of the two classes to guide him/her in their comprehension, retention and application of organic chemistry, and it would be inconceivable to abandon the use of the aromaticity concept.

Turning to heterocyclic chemistry, the importance of the concept of aromaticity is even greater. All treatments of heterocyclic chemistry, from the simplest (e.g. *Heterocycles in Life and Society*[24]) to the most advanced (e.g. *Comprehensive Heterocyclic Chemistry*[25]) place crucial emphasis on the aromaticity concept. In heterocyclic chemistry, aromaticity assumes fundamental importance not only as a qualitative concept but also for its quantitative aspects. Everyone knows, from general experience, that pyridine is for example more aromatic than furan.

The fundamental importance of heterocyclic chemistry in almost all aspects of life and society[24] means that the formulation of quantitative measures of aromaticity is such an important subject that it must receive the attention of true practitioners of the experimental applications of the subject who are engaged in expanding our knowledge of synthesis and reactivity to the benefit of society.

4. Quantitative Criteria of Aromaticity

Many reports utilize features (ii)–(iv), to define various quantitative measures of aromaticity known as 'indices of aromaticity'. These indices have been applied to diverse π-electron systems and the interrelations between them studied.[4h,26] The formulation of any quantitative definition(s) of aromaticity needs to cover the two different standpoints: firstly that of the molecule in its electronic ground state, described by (ii)–(iv), and secondly of (v) reactivity, which depends on the difference in energy between the ground state and a transition state towards an intermediate. We consider as fully aromatic those cyclic π-electron systems which follow all the features (i)–(v) of aromatic character, while those which follow some but not all of (i)–(v) are partly aromatic.

Aromaticity is essentially an 'excess property' i.e. a deviation from an additive scheme. Accordingly most quantitative measures of aromaticity are necessarily based on an assumption of some reference state.

4.1. Energetic criteria

Resonance energy was the first quantitative measure of aromaticity (thermodynamic).[27] Such stabilization can be measured experimentally or estimated theoretically by any of the many different models[4h] which differ in precision, basic assumptions, and the quality of the data. The significant problem that then arises is shown by the stabilization energies for benzene shown in Table 3, which vary by 53.4 kcal/mol! The experimental RE for benzene was estimated by Pauling et al.[27a] and independently by Kistiakowsky et al.[27b] as about 36 kcal/mol. However, a recent experimental value, obtained from group additivities

Table 3. Stabilization energy values for benzene from ab initio MO and DFT calculations based on different reference states, basis sets and procedures

Level of theory	Scheme of reaction[a]	Stabilization energy (kcal/mol)	Reference
MP2/RHF/SBK(d)	1	74.7	28
RHF/SBK(d)	1	61.4	28
MP2/6-31G//6-31G*	1	67.2	29
HF/6-31G*	1	58.2	29
MP4SDTQ/6-31G**/MP2(full)/6-31G**	2	23.9	30
MP4/6-31G+5D	2	24.3	31
MP3/6-31G+5D	2	23.4	31
RMP2/6-311G**	2	28.0	32
RMP2/6-311G*	2	28.7	32
RMP2/6-31G*	2	28.9	32
B3LYP/6-311+G**	2	23.3	This paper
B3LYP/6-311+G**	2[b]	34.1	6d
6-31G** (SCF)	2	24.8	32
6-31G* (SCF)	2	24.7	32
MP4SDTQ/6-31G**/MP2(full)/6-31G**	3	20.3	30
6-31G** (SCF)	3	23.4	33

[a] Schemes of reactions: (1) $C_6H_6+6CH_4=3CH_3CH_3+3CH_2CH_2$; (2) $C_6H_6+3CH_2CH_2=3$ *trans* $CH_2CHCHCH_2$; (3) $C_6H_6+3CH_2CHCHCH_2=3CH_2CHCHCHCHCH_2$.

[b] In scheme 2 for *cis* $CH_2CHCHCH_2$.

of Cohen and Benson[27c] and applied to the heats of formation of benzene (as aromatic) and cyclohexatriene (olefinic), is 21 kcal/mol.[27d]

The difficulties inherent in estimating any stabilization energy are due to the following reasons:

1. selection of a proper and sufficiently well defined reference state;
2. limited precision and accuracy of the energy determination (either experimentally or theoretically);
3. the perturbation of derived energies by extraneous effects such as strain, or change in hybridization.

Apart from hydrocarbons, thermochemical measurements lack in generality because the combustion products of many heterocycles are ill defined. Heats of formation are based on a model,[34] and somewhat arbitrary reference molecules.

Theoretical methods also lack generality due to the arbitrary reference state and/or to a strong dependence of the final results on the level of theory applied. For deriving stabilization energy, ab initio calculations employ the so-called homodesmotic or isodesmic reactions.[35] Even if we apply the highest available level of theory, we may end up with variable results, since they depend strongly on the formulation of the given reaction. The problem becomes very complex when the π-electron systems are polycyclic, and/or contain different heteroatoms.[36]

Another source of energetic information for molecules are theoretical calculations based on graph–topological models.[37] These methods, while sometimes very useful and quite successful, frequently neglect the subtle problems mentioned above.

Therefore we believe that comparative studies based on the same method and applying a well-known aromatic compound as a reference are the best ways to get reliable conclusions. Benzene is certainly the most important reference molecule. In this way, within a series of similar compounds, qualitative agreement between various models should be found.

4.2. Geometric criteria

Experimentally, all the CC bonds in benzene are of equal length, 1.3983 Å (neutron diffraction at 15 K corrected for libration).[38] Bond alternation is assumed to be associated with a decrease of the aromatic character.[39] Bond length alternation is best described by a statistical function of the variance of the bond lengths. One such function was postulated by Julg et al.[39] as an aromaticity index. An obvious limitation was that this index could not be applied to heterocycles (lengths of different types of bonds cannot be averaged). To overcome this difficulty, Bird[40] replaced bond lengths by Gordy's bond order[41] and applied the same technical procedure. The above procedures suffer from the same disadvantage—i.e. any π-electron system with equal bond lengths is aromatic which obviously fails in examples such as radialene with all the CC ring bond lengths around 1.52 Å.[42] Similarly, the pentagonal ring in C_{60} has C_5 symmetry but is certainly not aromatic;[43a–c] see also discussion by Pozharskii.[43d,e] The concept of an optimal reference interatomic distance for an aromatic molecule with full π-electron delocalization was successfully realized in the form of the HOMA model (Harmonic Oscillator Model of Aromaticity)[23,44,45]

$$\begin{aligned}\mathrm{HOMA} &= 1 - \left[\frac{\alpha}{N}\sum(R_{\mathrm{opt}} - R_{\mathrm{i}})^2\right]\\ &= 1 - \alpha(R_{\mathrm{opt}} - R_{\mathrm{av}})^2 - (\alpha/N)\sum(R_{\mathrm{av}} - R_{\mathrm{i}})^2\\ &= 1 - \mathrm{EN} - \mathrm{GEO}\ldots \end{aligned} \qquad (1)$$

This model takes into account two effects which decrease aromaticity:[45] (i) increase of bond length alternation (GEO term) and (ii) increase in the mean bond length in the system (EN term) as clearly formulated in Eq. (1), where n is the number of bonds taken into the summation; and α an empirical constant chosen to scale HOMA=0 for the hypothetical Kekulé structures of an aromatic system. Clearly, HOMA=1 for the system with all bonds equal to the optimal value R_{opt}. The average bond length is R_{av} whereas R_{i} is a running bond length. The terms GEO and EN are both energetic in nature: increase of bond length alternation,[45] and also extension of the bond length, both cost energy. Thus both terms are associated with a decrease of aromaticity. Traditionally, the first term was defined geometric (GEO) and the second energetic (EN), but the second term may also be understood as an acronym for elongation of the bond. The HOMA model has been successful in describing the aromatic character of many diverse π-electron systems.[4i,6e,22,43c,46]

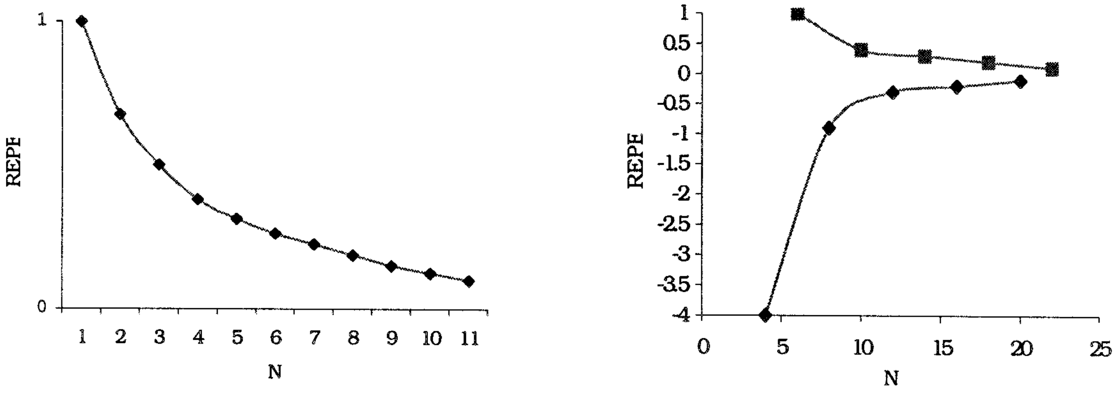
An important advantage of using bond lengths as a criterion of aromaticity is the routine X-ray measurement of molecular geometries and the wealth of experimental data available, especially from the Cambridge Structural Database[47] (over 200 000 entries as of 1999). Obviously, reliable theoretically obtained molecular geometries may also be applied.

4.3. Magnetic criteria

Historically, two magnetic properties have been used for the characterization of aromatic character: diamagnetic susceptibility and proton NMR chemical shifts.

Measurements or theoretical calculations provide two kinds of information on diamagnetic susceptibility: its anisotropy[48] and its exaltation.[49] The anisotropy is the difference between the perpendicular and average in-plane diamagnetic susceptibility. The exaltation is the difference between the measured susceptibility and that calculated by an additive scheme applying bond and atom increments. Aromatic compounds exhibit large values for these anisotropies and exaltations, which however depend on the size of the system. There is a close analogy here with the concept of resonance energy, which originally was also a measure of the non-additivity of bond energies.

^{1}H NMR spectroscopy is very useful for studying aromatic character. Exocyclic protons exhibit characteristic low-field (diatropic) chemical shifts due to the induction of a diamagnetic ring current in a cyclic π-system. In higher [4n+2]



a b

Figure 4. Hess and Schaad resonance energies per π-electron[53f] in the HMO approximation: (a) vs. number of rings in linearly anellated polyacenes and (b) vs. ring size *N* for aromatic (■) and antiaromatic [*N*]annulenes (◆).

annulenes, endocyclic protons show correspondingly high-field (paratropic) shifts if measured at low temperature,[17,50] whereas for [4*n*] annulenes these effects are reversed.

Recently, Schleyer et al.[51] have introduced the so-called NICS parameter (Nucleus Independent Chemical Shift), which they propose as a useful theoretical characterization of magnetic properties related to the aromaticity of ring systems. The more negative the NICS value, the more aromatic the system. Similar to other magnetic indices, NICS suffers from size-dependency.[51] Thus NICS overestimates the aromaticity of the cyclopentadienyl anion (-14.3),[51] which is a smaller ring with the same number of π-electrons as benzene (-9.7), and probably underestimates that for the cycloheptatrienyl cation (-7.6)[51] again with the same number of π-electrons, but larger in size. Further more, NICS does not sharply differentiate between benzene (-9.7) and its Kekulé structure (-7.5);[42b] the Kekulé structure of benzene is evidently assumed to be non-aromatic (even taken as a reference of non-aromatic character in resonance energy calculations).[27] In the opinion of the present authors, the NICS index may be useful for estimating local aromaticity, but should not be used for molecules as a whole. Additionally NICS is not normalized and this may lead to difficulty in comparisons with other indices.

Recent studies on interrelations between energies of rings in benzenoid hydrocarbons, NICS values, and HOMA and its components, led to the conclusion that NICS correlates best with energy and HOMA, and much less with other aromaticity indicies.[42b,46g]

5. Aromatic Character from the Point of View of Chemical Reactivity

In their reactions, aromatic compounds tend to retain the π-electron system. Unfortunately this feature of reacting by substitution rather than addition is usually difficult to express quantitatively. Although a few theoretical indices of aromaticity have attempted this,[52] use of chemical reactivity is mainly qualitative. The quantitative models estimate the energy loss due to the bi-centric π-electron localization $L_{r,s}$ and use the lowest absolute value of $KK=\min/L_{r,s}$ as the energy of a potential localization of bi-centric addition to define an index of aromaticity. For the Kekulé structure of benzene it was 1.53, which for benzene itself it was 3.53 and for pyrene 3.20.[52a,b] In this model, Hückel-aromatic and Hückel-antiaromatic annulenes formed two different families with regular changes of *KK*-values, similar to that shown in Fig. 4b.[53f]

A similar pattern of the variation of aromatic character for annulenes was also found for other quantitative measures of aromaticity.[53] Unfortunately, aromaticity indices based on various models of reactivity have limited applications, and can be used only for simple cases. Moreover, they depend considerably on the level of theory used.

As already emphasized, electrophilic substitution reactions are more typical of aromatic compounds than addition reactions. There are, however, several exceptions to this rule,[4e,h,36a] thus the increasing tendency to addition within the series naphthalene, anthracene, tetracene, etc. is familiar. Beginning with anthracene, the 1,4-addition process becomes more important and in pentacene it is dominant. Tautomerization of phenols varies significantly on annulation: α-naphthol is stable as such, 9-hydroxy-anthracene exists in an equilibrium with 9-anthrone in the ratio 11:89, 11-hydroxytetracene is thermodynamically unstable, and hydroxypentacene is known only in the keto-form.[54a] A similar dichotomy exists even in simple heterocyclic 6π-electron systems: the difference in the reactivity of furan and thiophene in Diels–Alder cycloadditions, and a variety of additions to pyridine derivatives such as 2-pyridones has also been mentioned.[54b]

The Woodward–Hoffmann[55] rules were derived by application of the Hückel rule to electrocyclic transition states: concerted 4π+2π Diels–Alder reactions are thermally favored because of the 'aromatic' character of the transition states, whereas 2π+2π 'antiaromatic' transition states are disfavored, the so-called Dewar–Evans–Zimmermann concept.[56] For more complicated compounds or transition states, the Hückel rule may not be readily applicable.

Table 4. Most often used numerical characteristics of the aromatic character

Aromaticity characteristics	Definition, comments
Resonance energy per electron (REPE)[58]	Difference in energy between the HMO π-electron energy of the molecule and its additive sum of contributions dependent on the kind of CC bonds. A most extensive list of energetic characteristics of π-electron systems.
Diamagnetic susceptibility exaltation[49] and anisotropy of diamagnetic susceptibility[48]	Difference in diamagnetic susceptibility of the molecule and its additive sum of contributions from bonds/atoms.
^{1}H NMR shifts	Diatropy, paratropy
Nucleus independent chemical shift (NICS)[51]	Absolute magnetic shielding computed at ring centers (non-weighted mean of the heavy atom coordinates). May be applied only to a particular ring, can not measure the overall aromaticity of the whole molecule.
Bird's I_5 and I_6[40]	$I=100(1-(V/V_k))$, where $V=100/\bar{N}\sqrt{(\sum(N-\bar{N})^2)/n}$, N is the bond order, $\bar{N}$ the mean bond order, n the number of bonds and V_k a constant depending on the type of ring Failed in cases of π-electron systems with equal bond lengths which are not aromatic (radialenes, etc.)[42]
HOMA[23,44,45]	Eq. (1), allows separation of two contributions which describe different reasons for decreasing aromaticity: bond elongation (term EN) and bond alternation (term GEO)

The higher stability of aromatic compounds compared to their olefinic analogs may sometimes be disputed. We need to differentiate clearly between thermodynamic and kinetic stability. Thermodynamic stability is usually the reason why aromatic systems prefer reactions in which the π-electron system is retained. Typical reactions of this type are electrophilic substitutions, the rates of which may be affected greatly by small changes in π-electron systems due to substituent or topological effects (e.g. different rates at various positions in benzenoid hydrocarbons[57]).

Unlike thermodynamic stability, which is a unique property of the ground state, kinetic stability depends on energies of the ground state, a transition state and intermediate states, with the possibility of various subsequent reactions leading to stable products. For example there exist thermodynamically stable species, such as aniline (resonance energy similar to that of benzene[4h,13c]), which are highly reactive (kinetically unstable), due both to the possibility of an easy electron transfer reaction with oxygen (cf. the easy transformation of aniline into 'aniline black' polymer), and to high susceptibility to electrophilic substitution. Reactivity is closely related to the HOMO and LUMO energies. Bird[40j] showed that the 'hardness' of a molecule (half the HOMO/LUMO gap)[20] correlates with the resonance energy per electron.

6. Comparison of Quantitative Indices of Aromaticity

Benzene, the oldest and best-known aromatic compound, is universally taken as a paradigm for which all the criteria of aromaticity are well fulfilled. The largest and most important classes of aromatic compounds are derivatives of benzene, azoles, azines or other simple heterocycles. Typical non-aromatic (olefinic) systems are acyclic polyenes, and incompletely conjugated cyclic polyenes and related systems, whereas cyclic conjugated $4n$ π-electron systems are antiaromatic.

Thus in a trivial sense, aromaticity may be compared to a centigrade temperature scale that can be high (pyridine), moderate (furan), near zero (olefins, cyclohexadiene or [22]annulene) or negative (cyclobutadiene[4h] and other antiaromatic compounds). A Kekulé structure of benzene is non-aromatic with a resonance energy by definition equal to zero,[27a,b] the same is true for HOMA index.[22,23,42b] In this sense benzene is the hottest molecule!

In principle, almost any of the properties presented in Table 2 may be used as numerical measures of aromaticity. Table 4 presents a list of the most frequently used indices and references a few leading papers with their applications.

Each of these indices of aromaticity needs a few comments. Energetic indices (various types of stabilization energy) and diamagnetic susceptibility can be used only for whole molecules. Their values depend strongly on the level of theory used and/or on the experimental or theoretical model employed (for energetic characteristics cf. Table 3). Originally REPE was introduced by Dewar[58i] where PPP was used for calculating energy. Geometric indices may be used either for the whole molecule or for some particular fragment, i.e. to describe local aromatic character within a molecule. Indices that are a simple function of bond lengths (or bond orders) fail for cases where equal bonds are very long (radialenes, pentagonal rings in fullerenes, etc). Use of optimal bond lengths as a reference improves the situation, but in some hetero-π-electron systems (borazine like),[6e] HOMA values still overestimate aromatic character. An advantage of the HOMA model is the possibility of the identification of the source of the decrease of aromaticity: either due to bond elongation or to bond alternation.[42b,45,46g,i] The recently introduced aromaticity index—NICS[51] has found wide application,[6d,46h,51,59] but, except for monocyclic systems, it relates only to local properties. Disadvantages include overestimation of the aromaticity of the Kekulé structure of benzene and of the central rings in polyacenes (−13.3 for anthracene). Moreover, while NICS is claimed to be a magnetic index, in the case of 15 five-membered heterocycles NICS correlates best with the geometry based indices and in particular with HOMA.[60]

In the last decade it has become clear that such different quantitative indices need not necessarily agree, i.e. they do not need to vary colinearly. By use of principal component or factor analyses,[61] Katritzky et al.,[62] Jug et al.,[63] and others,[64] have clearly demonstrated that aromaticity is a multidimensional phenomenon and that one compound

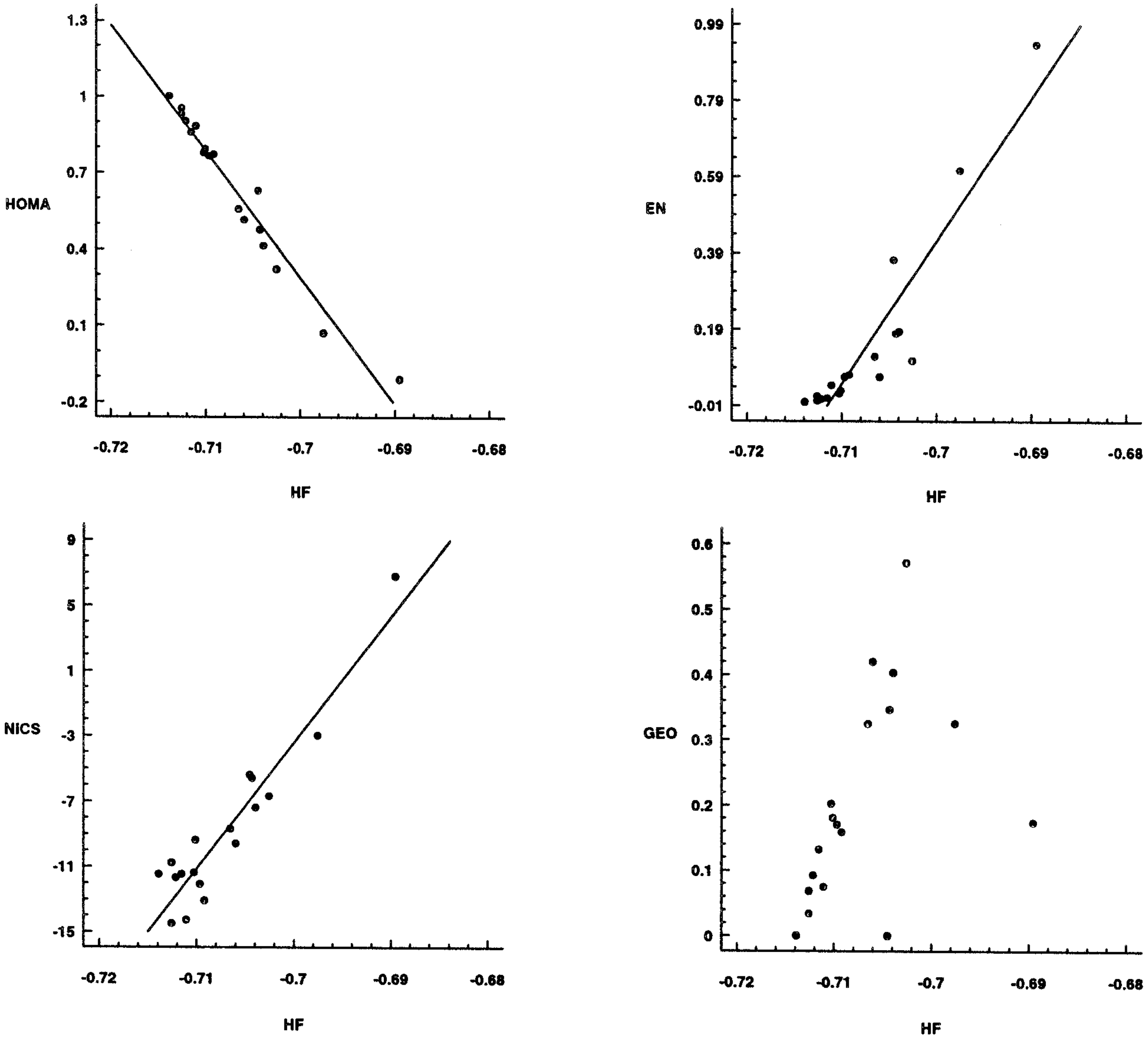


Figure 5. Scatter plots of HOMA, EN, NICS and GEO vs. HF. The correlation coefficients are: −0.980, 0.929, 0.942 and 0.465, respectively.

may be more aromatic than another in one dimension and less aromatic in a second! Undoubtedly, mutual relationships between aromaticity indices depend strongly on the selection of molecules in the sample.[36b,60,65]

In some cases, the inter-correlation of two different indices may be significant. In the case of porphyrins,[46h] the magnetic index NICS and the geometry-based index HOMA change monotonically. Similarly, 18 independent rings in nine benzenoid hydrocarbons showed good colinearity between HOMA and NICS.[66] Schleyer et al.[65] found a colinearity between NICS and ASE (aromatic stabilization energy) as well as ASE and Λ (magnetic susceptibility) for a limited set of heterocyclic systems. For a more extensive set of compounds Katritzky et al.[36b] demonstrated a lack of such colinearity. Very recently it has been shown that, for a series of benzene rings in paracyclophanes,[46e] and in benzenoid hydrocarbons[46g] (calculated for the rings with the bond lengths constrained, as those in the rings in the mother compounds), a very good correlation exists between the geometry based index HOMA and the Hartree–Fock energy (at 6-31G** level of theory). Fig. 5 illustrates how various indices of aromaticity HOMA, EN, GEO, and NICS, correlate with Hartree–Fock (HF) energy of benzene rings of constrained bond lengths taken from benzenoid hydrocarbons.[66] Obviously, even for this homogeneous sample of benzene rings, some of the correlations are very weak whereas others are quite good. The multidimensionality of aromaticity is evident.

Many aromaticity indices based on π-electron theories[53] follow a general scheme as presented in Fig. 4. On the left there is a dependence of REPE on the number of rings in polyacenes. A systematic decrease of resonance energy per electron (REPE) is observed. On the right there is a pictorial and extended representation of the Hückel rule: the antiaromatic annulenes ($4n$) are below zero, whereas the aromatic annulenes are above zero, and both lines approach each other with an increase in the number of π-electrons in the annulene molecules.

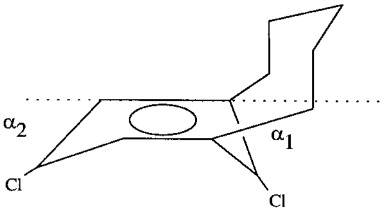


Figure 6. Scheme of [5]metacyclophane indicating folding of the ring $\alpha_1=26.8°$, $\alpha_2=12°$.

7. Variation of the Degree of Aromaticity with Molecular Environment

To add to all the other complications and difficulties in defining and measuring aromaticity quantitatively, it has recently been demonstrated[67] that the classical aromaticity of most heterocycles and of some carbocycles increases with the polarity of the medium. While centrosymetric benzene has no dipole moment, the dipole moments of, e.g. azulene, imidazole, and 4-pyridone, increase significantly from the gas phase to dioxane solution, as do their aromaticities both as measured by various experimental criteria and as assessed by calculation.

The aromaticities as measured by HOMA of the benzene rings of the sodium *p*-nitrosophenolate trihydrate (0.460) and magnesium *p*-nitrosophenolate hexahydrate (0.630) depend significantly on the hydration shell of the *p*-nitrosophenolate anion.[23] In case of the sodium trihydrate, hydration occurs mainly at the oxygen of the NO group, and intramolecular charge transfer from the phenolate oxygen to the nitroso group increases the quinoid canonical structure leading to dearomatization. The magnesium hexahydrate is almost equally hydrated at both functional groups, charge transfer from the oxo-group to the nitroso is smaller, and the compound is less quinoid and more aromatic.

8. Aromaticity Variation with Planarity

Planarity has been assumed to be an important condition for aromaticity as mentioned in the section Historical Development of the Aromatic Concept. Aromaticity indices allow a quantitative estimate of how far breaking the planarity of the π-electron system decreases its aromatic character. Bickelhoupt[68] showed that [5]metacyclophane exists in a boat conformation with strong bending as shown in Fig. 6, however the benzene ring H-NMR signals are still essentially aromatic (δ is in the range 6.75–7.85) and the HOMA is as high as 0.985! Another illustration is that the molecular geometry and HOMA of strained [*n*](2,7)pyrenephanes[69a] shows only a slight decrease of the aromatic character as compared to undistorted pyrene.[69b]

The aromatic character of the naphthalene moiety in octasubstituted naphthalenes depends significantly on the size of the substituent:[23] HOMA for naphthalene is 0.810. For octasubstituted naphthalenes with X=methyl, S-phenyl, fluorine and chlorine, HOMA is in the range 0.71–0.74, and the naphthalene moiety is slightly folded, with a maximal deviation of carbon atoms from the least-squares plane of 0.29 Å. For octabromonaphthalene, HOMA drops to 0.43, and maximal deviations increase to 0.43 Å. Apparently small deviations from planarity have little effect, but larger deviations decrease aromaticity significantly.

9. Conclusions

All the available indices of aromaticity are approximations, which employ either theoretical or experimental methods for generating data; or which use model processes describing some idealized situation(s). *Therefore quantitative results should be treated precisely only if the results obtained can be compared with data obtained by the same method from some reliable reference system.*

The wide use of the term aromaticity in organic chemistry (and its occasional extension to inorganic compounds), precludes interpreting it narrowly with a focus on a single ‘dimension’ as other dimensions are equally accessible. Undoubtedly the different ‘dimensions’ of aromaticity can show different quantitative or qualitative values or variations for a given compound or series of compounds.

The multidimensionality of aromaticity derives partly from the statistical treatments of the data matrices which are built up of variously defined aromaticity indices for many model systems.[62–64] However, multidimensionality also results from the analytical separation of two mechanisms of dearomatization of π-electron systems made within the HOMA model: (i) due to bond length alternation and (ii) to bond length extension (or bond elongation).[42b,45,46g]

The concept of aromaticity or aromatic character is thus both multidimensional, and scale-dependent. For some systems, all or most of the ‘dimensions’ are mutually in line, and the aromaticity of these compounds is fully exhibited. Systems for which there is total disagreement among the indicators of aromaticity are certainly interesting subjects for further study! (Provided that the indices and all the data are sufficiently reliable!)

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Biographical Sketch

Tadeusz Marek Krygowski was born in Poznan, Poland (1937) and received his M.Sc. at the A. Mickiewicz University (Poznan, 1961), his Ph.D. degree in 1969 and a D.Sc. degree (habilitation) in 1973, both from the Department of Chemistry of Warsaw University. Since 1964 he has been working at this university, from 1983 as a Professor of Chemistry. He has lectured at many universities in many countries, serving as an invited Professor in Canada (Guelph), France (Nantes), Austria (Linz/D) and Israel (BeerSheva). President of the Polish Chemical Society (1994–1997). His main research interests are: sedimentology (in geology, in the early 1960s), ion-pairing and generally medium effects in organic electrochemistry (in the 1960s and early 1970s), solvent and substituent effects (1970s and 1980s), problems of aromaticity, structural effects of inter- and intramolecular interactions (till now). His hobby is national folk music and hiking in not-too-high mountains.

Michal K. Cyrañski was born in Warsaw, Poland (1970). In 1994 received the M.Sc. degree and in 1999 the Ph.D. degree, both at the Chemistry Department of the Warsaw University. In 1997 was a holder of the Foundation for Polish Science Grant and in 1998 received a distinction of the Kemula Reward (by the Polish Chemical Society). From 1998 is the secretary of the Executive Committee of the Polish Chemical Society (elected). His main scientific interest is connected with structural chemistry of small organic compounds, crystallochemistry, molecular modeling (ab initio), structural aspects of aromatic character of π-electron systems and definition of aromaticity. His hobby is classical music especially by J.S. Bach and singing in a professional choir.

Zbigniew Czarnocki was born in Warsaw in 1954. He received his M.Sc. degree in 1977, his Ph.D. degree in 1977, and his D.Sc. degree (habilitation) in 1993—all from the Department of Chemistry, University of Warsaw. In 1984 he moved to McMaster University (Hamilton, Canada) working with Professor D. B. MacLean for over two years. Since 1994 he served at the Faculty of Chemistry as a professor of the Warsaw University. Currently he is involved in several research projects focused mainly on the enantioselective synthesis of natural products using chiral inductors of natural origin (sugars, acids, terpenes). He is also interested in synthetic chemistry of heterocyclic derivatives of pharmacological value, bioreductions of prochiral molecules and stereoelectronic factors in lactams and imides (Thorpe–Ingold effect). He enjoys giving popular lectures on modern chemistry and physics. He is married and has two children (14 and 4 years old).

Prof. Dr. Günter Häfelinger, Dipl.-Chemist. Born 1937 at Freiburg, Germany. Study of chemistry at the TH Karlsruhe from 1957 to 1962. Promotion (1962–1965) with Prof. Dr E. Bayer at the University of Tübingen on: ‘Spectroscopy of Schiff’s Bases and their Chelates’. Post doctorate (1965–1967) with Prof. A. Streitwieser at the University of Berkely, California. Habilitation (1970) at the University of Tübingen for organic and theoretical chemistry. Since 1983 C3-professor for theoretical organic chemistry at the University of Tübingen. Fields of research: criteria of aromaticity; experimental and theoretical quantification of ring current effects; reliability of calculations of molecular geometrices and NMR chemical shifts by ab initio MO methods; chromolymphography (dying of lymphatic nodes with azulenens for oncological operations); quantitative analytic determinations of methylated derivatives of tryptamines in urine. Publications: 70 scientific papers; supervision of 17 doctoral thesis and 33 diploma thesis in chemistry; presentation of 50 scientific lectures and 12 poster contributions.

Alan R. Katritzky (born in London, England) taught, researched and consulted in heterocyclic chemistry at the Universities of Oxford, Cambridge and East Anglia (all in the UK) before transferring to Florida in 1980 where he is Kenan Professor and Director of the Institute of Heterocyclic Compounds (see homepage at ark.chem.ufl.edu). He has many international connections and recently has sponsored a new initiative, particularly intended to benefit organic chemists in second and third world countries, comprising a compound depository and a free electronic and print journal (for details see www.arkat.org). He marked the completion of the present report with his favourite relaxation (picture taken on October 9, 1999).