HETEROAROMATICITY (REVIEW)*

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The concept of heteroaromaticity has been formulated as a set of theoretical hypotheses related to the effect of the heteroatom on the aromatic properties of heterocycles. The essence of the electronic and stereochemical differences between the three major types of heteroatoms, the types of aromatic and anti-aromatic heterostructures and the most important criteria for heteroaromaticity are discussed in this review on the basis of this concept.

In accord with the Hueckel rule, planar monocyclic conjugated systems containing $4n + 2$ π-electrons (n = 0, 1, 2, 3, ...) are considered aromatic. This concept remains valid for polynuclear condensed systems if the Hueckel number of π-electrons are located in peripheral atomic orbitals. In principle, the formation of an aromatic π-electron ensemble may occur due to the p-orbitals not only of carbon atoms but of other atoms as well. Thus, in addition to such carbocyclic compounds as benzene and naphthalene, an extensive class of heteroaromatic structures exists.

For many decades, the concept of aromaticity has remained one of the pivotal theoretical problems in organic chemistry (see the reviews of Efros [1], Badger [2], and Bergmann [3]). The development of this concept has been a function of the progress of theoretical chemistry and advances in organic synthesis. In particular, in recent years there has been considerable progress in the synthesis of new types of heteroaromatic structures including heteroannulenes, pyrrole and pyridine analogs containing heavy group V and VI elements as the heteroatoms, heterocycles with multiple heteroatoms, and even completely inorganic analogs of benzene. Analysis of the properties of these compounds indicates the very great effect of the heteroatom on their physicochemical properties and reactivity. In this context, there is complete justification within the framework of the general concept of aromaticity to delineate the problem of heteroaromaticity. The key aspect of this problem is the effect of the nature of the heteroatom including its hybridization, electronegativity, and stereochemistry on aromaticity. This is specifically the approach employed in the present review and distinguishes it from the reviews of Katritizky [4] and Vysotskii [5], which were also devoted to the subject of heteroaromaticity. This article consists of two major parts. The first section is a consideration of the different types of heteroatoms and heteroaromatic structures, while the most important criteria for heteroaromaticity are treated in the second part. This review does not pretend to be an exhaustive summary of the data accumulated on this subject. Attention is given primarily to the principal directions in current research and recent progress.

1. TYPES OF HETEROATOMS AND HETEROAROMATIC STRUCTURES

For a better understanding of the nature of the various types of heteroatoms, it is convenient at the very onset to take carbocyclic systems and divide them into three groups relative to charge: electroneutral (benzene), anionoidic (cyclopentadienyl anion), and cationoidic (tropylium cation). Each of these structural types has its own isoelectronic heterocyclic analog. Thus, by replacing a —CH= group in benzene by a heteroatom, we may go to pyridine, phosphobenzene (phosphorine), arsabenzene, stibabenzene, bismabenzene, silabenzene or to pyrilium, thiapyrilium, selenapyrilium, and telluropyrilium cations (1-10). The heteroatom in these compounds in the Kekulé formulas is formally double-bonded and contributes one electron to the π-orbital. Such heteroatoms (which we designate —Y=) are called pyridine heteroatoms.

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*This article is published to further the discussion of fundamental problems in the chemistry of heterocyclic compounds.

1—10   11—17   18—20
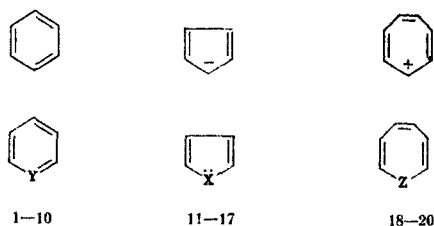
1) Pyridine, Y = N; 2) phosphorine, Y = P; 3) arsabenzene, Y = As; 4) stibabenzene, Y = Sb; 5) bismabenzene, Y = Bi; 6) silabenzene, Y = Si; 7) pyrilium, Y = O^+; 8) thiapyrilium, Y = S^+; 9) selenapyrilium, Y = Se^+; 10) telluropyrilium, Y = Te^+; 11) pyrrole, X = NH; 12) phosphole, X = PH; 13) arsole, X = AsH; 14) furan, X = O; 15) thiophene, X = S; 16) selenophene, X = Se; 17) tellurophene, X = Te; 18) borepin, Z = BH; 19) alumopin, Z = AlH; 20) gallepin, Z = GaH.

The replacement of a —CH= group by a heteroatom in the cyclopentadienyl anion leads to five-membered heteroaromatic structures such as pyrrole, furan, and their analogs (11-17). In order to satisfy the Hueckel rule, the heteroatom must contribute two electrons to the π-system and have only single bonds in the Kekulé structure. This type of heteroatom (which we designate —X—) is called a pyrrole heteroatom.

Going from cationoid carbocyclic structures to neutral heterocycles is possible only by replacing the —CH= group by a heteroatom with a vacant p-orbital (designated Z and called a borepin heteroatom) which is able to accept π-electrons and provide for the delocalization through the ring:
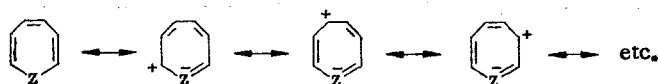

Boron, gallium, and aluminum may act as such a heteroatom (18-20). A few representatives of this class have been synthesized, in particular derivatives of borepin (18) [6], which are very unstable although they display weak aromaticity relative to a number of criteria.

The variety of heteroaromatic systems is explained by the circumstance that their rings may contain not one but several heteroatoms of the same type or of different types. Thus, pyridine along with its azaanalogs, diazines, triazines, and tetrazines form the azine family. Although less common, heteroaromatic structures with several (usually two) pyrrole heteroatoms have been reported. Examples are 1,4-dihydrodiazocine 21 and pyrrolo[1,2-a]imidazole 22. Heterocycles containing a pyridine nitrogen atom and pyrrole atom of any type (NH, O, S, Se) in one ring are called azoles. The vast majority of azoles are five-membered heterocycles such as 23 and 24. However, in the case of peri-condensed systems, six-membered azole structures are possible such as naphtho[1,8-d,e]pyridazine 25, perimidine 26 or naphtho[1,8-d,e]triazine 27.

21   22   23   24   25 Y_1=N,Y_2=CH
26 Y_2=N,Y_1=CH
27 Y_1=Y_2=N
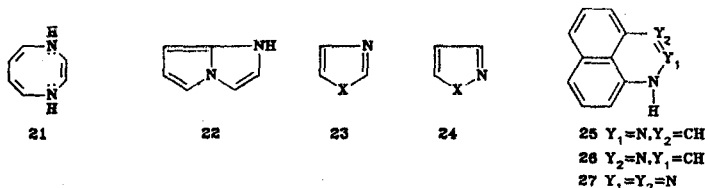
Pyridine and pyrrole heteroatoms may also be present in different systems such as in azaindoles. Such compounds should not be classified as azoles since the heterocycles in these structures significantly retain their individuality [7].

Pyridine and pyrrole heteroatoms in condensed systems may be found simultaneously in two or even three rings. Such a heteroatom is called a common or bridging heteroatom. Examples of such compounds may be found in indolizine 28, cyclo[3.2.2]azine 29, quinolizinium ion 30, or 10,9-boroazanaphthalene 31.

The structures 28-32 appear at top with numbers 28, 29, 30, 31, 32.
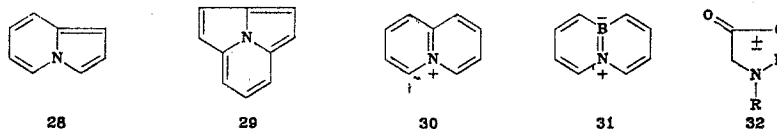
Sidnones which may be considered as derivatives of 1,2,3-oxadiazole are a unique class of aromatic heterocycles [8]. They are usually given bipolar structure 32 without precise indication of the charge localization since none of the covalent structural formulas can properly reflect the electronic structure of such compounds. From the viewpoint of aromaticity, structures 32a and 32b with a sextet of cyclic electrons would appear most logical. However, the CO band at 1710–1740 cm^{-1} and CO bond length (1.20 Å) leave no doubt that the negative charge is largely found on the ring atoms. The electronic structure of the molecule in this case may be given as a hybrid of structures 32c, 32d, and 32e which formally have seven cyclic π-electrons. How can this apparent violation of the principle of aromaticity in sidnones be explained? This question is answered by x-ray diffraction structural data [9], which show that the C–O and C–N bonds are essentially single bonds (1.41 and 1.34 Å), i.e., the cyclic oxygen atom virtually does not participate in conjugation. On this basis, sidnones should be considered as resonance-stabilized cyclic azomethinimines 32d and 32e:

32a   32b   32c   32d   32e
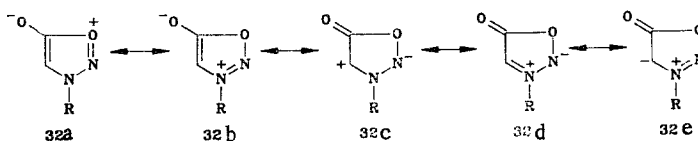
How many heteroatoms can be found within a single aromatic ring? In principle, the ring may be constructed entirely of noncarbon atoms. A well-known example is borazine 33, called "inorganic benzene." However, rings consisting of atoms of one element are unstable. Thus, tetrazole is a stable aromatic compound but all attempts to obtain pentazole 34 (R = H) have been unsuccessful. Only N-arylpentazoles 34 (R = Ar), which are colorless, unstable compounds, havebeen synthesized by the reaction of the azide ion with aryldiazonium salts [10]. Tetrazine 35 is extremely unstable; the red color of this compound holds interest. This compound may be stored only at low temperature and in an inert atmosphere. No derivative of pentazine 36 has been reported [11].

33   34   35 Y = CH   37
                      36 Y = N
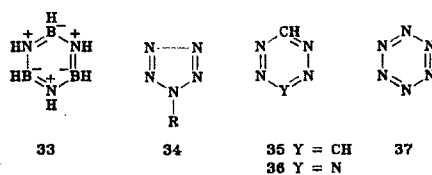
Chemists have long been intrigued by the properties of hexaazobenzene or hexazine 37. Vogler et al. [12] have recently reported that this compound has apparently been obtained in a matrix by the dimerization of two azine radicals. Hexazine was described as a yellow compound (λ_{max} 380 nm) which exists briefly at 77°K and decomposes with loss of color and liberation of nitrogen. This communication caused a lively discussion among theoreticians. Thus, according to the calculations of Huber [13], hexazine cannot be obtained in principle since it should decompose into three nitrogen atoms without any activation barrier. In contrast, in a later work using an improved method of calculation, Saxe and Schaefer [14] showed that 37 lies at the minimum of a potential energy curve which describes all the N_6 species. The hexazine molecule should be aromatic with N–N bond length equal to 1.288 Å. The transition state on the path to three nitrogen molecules lies 43 kJ/mole higher than this minimum and has a planar structure with alternating bonds: r_1(N–N) = 1.178 and r_2(N–N) = 1.551 Å.

Macrocyclic systems hold great interest in the chemistry of heteroaromatic compounds. Such compounds include porphin 38, which contains 18 peripheral π-electrons (this sum is carried out for the envelope encompassing the pyridine nitrogen atoms but excluding the pyrrole nitrogen atoms); the total number of π-electrons in porphin is 26, which is in accord with the Hueckel rule. Great advances have been achieved in recent years in the synthesis of heteroannulenes. The chemistry of heteroannulenes with a pyrrole heteroatom such as 39 has been reviewed by Anastassiou [15, 16, 18] and Schroeder [17]. Recently, syntheses have
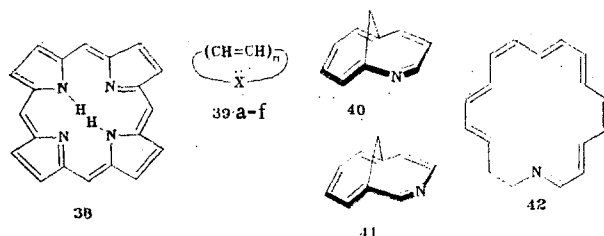
39a) aza[9]annulene, 1H-azonine, X = NH, n = 4; 39b) aza-
[13]annulene, X = NH, n = 6; 39c) aza[17]annulene, X = NH,
n = 8; 39d) oxa[9]annulene, oxonine, X = O, n = 4; 39e)
oxa[13]annulene, X = O, n = 6; 39f) oxa[17]annulene, X =
O, n = 8.

been reported for aza[10]annulene derivatives 40 and 41 [19] which may be considered as 10π-electron analogs of quinoline and isoquinoline (it is interesting that 40 even has an odor similar to quinoline). Isomer 42 of aza[18]annulene was also prepared [20].

An interesting problem lies in the synthesis of heteroaromatic systems with small rings, specifically heteroanalogs of the cyclopropenylium cation (43). The realization of such 2π-electron compounds is theoretically possible only if the heteroatom has a vacant p or d orbital. Many variants of such structures have been proposed with boron, silicon, germanium, and positively-charged sulfur [4, 21]. However, all attempts for a long time to prepare such compounds were unsuccessful, mainly due to facile dimerization to six-membered rings such as 44.
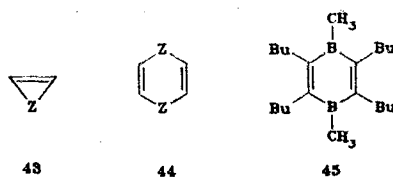

Z = BR, SiR$_2$, GeR$_2$ etc.

Only recently, Schleyer et al. [22] have prepared 1-methyl-2,3-di-tert-butylborirene 46 as a result of the reaction of di-tert-butylacetylene with dibromomethylborane in the presence of an intercalation compound of graphite with potassium. Apparently, CH$_3$B: is generated in this reaction; this species is a carbene analog which inserts into the triple bond of an alkyne (see also the work of Packaly and West [23]):
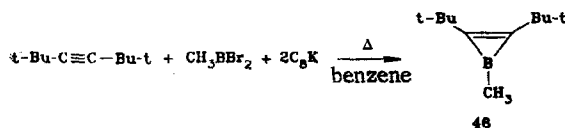
Borirene 46 is a colorless liquid which is very sensitive to moisture and air but is quite thermally stable. This stability is in accord with quantum chemical calculations, indicating marked aromatic stabilization of the borirene ring. The resonance energy of borirene itself was calculated to be 70-75% of the resonance energy of the cyclopropen-lium cation [24]. The possibility of obtaining 46 is clearly related to the difficulty of its dimerization as a consequence of the two bulky tert-butyl groups. This hypothesis is supported by the finding that if di-n-butylacetylene is taken as the starting compound, the only reaction product is six-membered ring 45. Various thiirenium ion derivatives have been synthesized (43, Z = CH$_3$S$^+$) [25], some of which have proved quite stable. An NMR study of 1-methyl-2-phenyl-3-tert-butylthiirenium hexachloroantimonate has shown that the sulfur atom in these ions has rigid pyramidal configuration.

An understanding of heteroaromaticity highly facilitates the study of antiaromatic heterocycles, i.e., compounds with 4n ring π-electrons. Examples of such systems are 47-58. As in the case of aromatic heterocycles, these structures contain pyrrole and pyridine heteroatoms. Most of the antiaromatic heterosystems, in particular small rings, are extremely un-

47 X=NH 50 51 X=NH 52a 54 X=NH 57
48 X=O   52 X=O   55 X=O
49 X=S   53 X=S   56 X=S   58

X=O
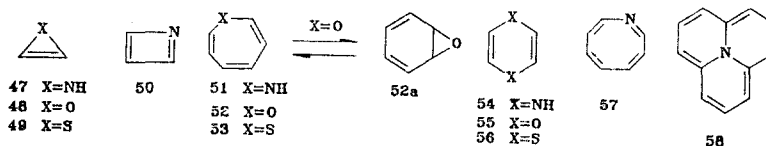
stable. Thus, only recently, Krantz and Laureni [26] have detected thiirene and its deriva-
tives in an argon matrix and Strausz et al. [27] have reported the first oxirene 48, 2,3-bis-
(trifluoromethyl)oxirene. 2-Phenylbenzaazete which is a derivative of azete 50 is stable
only to —80°C [28]. The stability of antiaromatic heterocycles increases with increasing
ring size. This is the result, to a significant extent, of the capacity of large rings to
adopt a more stable nonplanar conformation. In addition, as shown by Dewar [29], the bound-
ary between aromatic and antiaromatic systems is gradually eliminated with increasing number
of π-electrons, and while the resonance energy of aromatic systems drops, the resonance energy
of antiaromatic systems increases in comparison with small rings and approaches zero, which
is characteristic for conjugated nonaromatic compounds. Syntheses have been reported for
1H-azepin 51 and many of its derivatives [30, 31]. Oxepin 52 is characterized by valence
isomerization to benzene oxide 52a and both isomers are present under ordinary conditions
in approximately equal amounts [32, 33]. Thiepin 53 and its simplest derivatives are un-
stable due to the facile extrusion of sulfur. Only several derivatives of 2,7-di-tert-butyl-
thiepin have been prepared [34]. Derivatives of 1,4-dihydropyrazine 54, 1,4-dioxine 55, and
1,4-dithiine 56 which exist in boat form have been reported [35, 36]. Analogously, derivatives
of azocine 57 also exist in boat form [37]. One of the few known planar antiaromatic hetero-
cycles is cyclo[3.3.3]azine 58, which has 12 peripheral π-electrons [38, 39]. This compound
is extremely stable in an inert atmosphere, but decomposes in only a few minutes in the air
[40].

2. HYBRIDIZATION AND STEREOCHEMISTRY OF THE HETEROATOMS

Effective π-electron delocalization in heteroaromatic structures requires that they be
planar. Hence, trigonal sp^2 hybridization should be characteristic for all types of hetero-
atoms. In this regard, however, we must ask what is the essence of the differences in the
valence states of the pyridine and pyrrole heteroatoms. Such differences, if we take account
of the different number of electrons supplied to the π-system, the bond angles in the hetero-
cycles with pyridine and pyrrole atoms, and other factors, should be extremely significant.
Let us examine the valence states of the group V and VI heteroatoms.
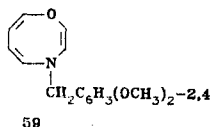
2.1. Nitrogen

The ground state of the nitrogen atom is s^2p^3. If the bonds of nitrogen with other
atoms involve the pure 2p orbitals, the bond angle in ammonia would be close to 90°. Theoret-
ical calculations, however, have shown that there is strong repulsion both between the elec-
trons of the three σ-bonds and between the hydrogen bonds for this geometry. This accounts
for the actual H—N—H bond in the NH_3, which is 107°. For angles close to tetrahedral, the
nitrogen atom may form bonds only due to orbitals to approximately sp^3 or $s^{1/4}p^{3/4}$ per orbit-
al. Since each orbital is one-fourth s orbital and three-quarters p orbital, while five
electrons are distributed in all the orbitals, the valence state of the nitrogen atom in sp^3
hybridization may be designated as $s^{5/4}p^{15/4}$. Such an approach, developed, in particular,
by Dewar [41], clearly indicates that the transition of the nitrogen atom from the s^2p^3
ground state to the $s^{5/4}p^{15/4}$ state is related to the transfer of three-fourths of an s elec-
tron to a p orbital. The energy required for such a transition is presumably supplied due
to energetically favorable expansion of the bond angle from 90° to 107°. Nitrogen is
pyramidal in this state, while the axis of its unshared electron pair and three σ-bonds are
oriented toward the apices of an almost proper tetrahedron.

The planar geometry of the bonds with bond angle 120° corresponds to sp^2 hybridization.
The unshared electron pair occupies a pure 2p orbital, whose axis is oriented perpendicular
to the plane of the three σ-bonds. Ideally, this arrangement of the valence orbitals corres-
ponds to the pyrrole nitrogen atom. Taking account of the total number of electrons, the
valence state of a pyrrole nitrogen atom may be designated sp^4. Thus, the change in nitro-
gen hybridization from sp^3 to sp^2 requires the transfer of an additional one-fourth 2s elec-
tron to a 2p orbital ($s^{5/4}p^{15/4} \rightarrow sp^4$). How are the energy expenditures related to this
transfer? The experimental value of barrier to the inversion of the nitrogen pyramid, for
example in piperidine [42], is 25 kJ/mole. Since the transition state of this process is

planar, this value is the energy required for the transfer of the remaining one-fourth 2s electron to a 2p orbital.

At first glance, the conjugation energy of the pyrrole nitrogen atom with the rest of the π-system in heteroaromatic systems would appear to be quite sufficient to compensate for the energy losses related to the realization of planar geometry. However, we encounter another significant factor. The conjugation of the nitrogen atom with the π-system in the case of pyramidal configuration is very considerable and is about two-thirds of the conjugation energy of the planar nitrogen atom [41, 43]. Hence, in the case of relatively small resonance energies (less than 70-75 kJ/mole), there is only a weak energetic stimulus at the nitrogen atom for transition from pyramidal to planar structure. Only partial compression of the pyramid is most often observed. This specifically is found for aniline [44] and dimethylaniline [45]. Taking account of these arguments, Dewar has proposed that nitrogen retains pyramidal structure in pyrrole [43]. In his opinion, the microwave spectral data on the planar nature of nitrogen in pyrrole may be interpreted as an averaged result of rapid inversion of the pyramid. Unfortunately, there are no x-ray diffraction structural data on pyrrole and N-alkylpyrroles which would support or refute Dewar's hypothesis. However, it would appear that the resonance energy of pyrrole (see Table 14) is quite sufficient to provide for its planar structure. This is also indicated by the finding that 1,4-dihydro-1,4-diazocine 21 [46, 47] and a derivative of 1,4-oxaazocine 59 [48], which are less aromatic than pyrrole and for which x-ray diffraction analyses were performed, have rigorously planar configurations.

$$\underset{\underset{59}{\underset{\mathrm{CH_2C_6H_3(OCH_3)_2-2,4}}{|}}}{\overset{O}{\underset{N}{\bigcirc}}}$$

In examining the hybridization of the pyrrole nitrogen atom, we should also take account of its dependence on the size of the heterocycle. The internal bond angles in the five-membered ring are significantly less than 120°. Thus, orbitals with a large degree of p character should be used by the heteroatom in the direction of the ring bonds. On the other hand, the s character of the orbitals used in forming the external bonds or of the orbitals of the pyrrole atom within a six-membered ring will be enhanced. Thus, when considering the hybridization of the heteroatom, we should recall that it rarely may be taken as pure sp^3 or sp^2. The actual situation is clarified only as a result of a quantum mechanical analysis of the occupancies of the different bonds and unshared electron pairs by s and p electrons (as, for example, in the data for the pyrrole molecule [49]).

The pyridine nitrogen is also sp^2-hybridized but, in contrast to the pyrrole nitrogen atom, only four electrons participate in its hybridization and only one electron is supplied to the π-system (Table 1). It is readily calculated that the valence state of the pyridine nitrogen atom is $s^{4/3}p^{11/3}$, i.e., the hybridization requires promotion of two-thirds of an s electron to a p orbital, and not a whole electron as in the case of the pyrrole nitrogen atom. Thus, the pyridine nitrogen atom is energetically favored relative to the pyrrole nitrogen atom.

2.2. Phosphorus and Other Group V Elements

The differences in stereochemistry and hybridization between trivalent nitrogen and phosphorus are very significant. These differences are all in some way related to the large size of the $3s^23p^3$ orbitals of phosphorus relative to the $2s^22p^3$ orbitals of nitrogen. The phosphine molecule, for example, is a pyramid with H-P-H bond angle equal to 94°, i.e., the phosphorus 3p orbitals predominantly participate in bond formation with a slight admixture of the 3s orbital, while the unshared electron pair occupies an almost pure 3s orbital. The pyramidal configuration of phosphorus is very stable and the inversion barrier in PX₃ compounds is about 150 kJ/mole [50]. The stability of the pyramid may be ascribed to the increased length of the 3pσ-bonds such that the substituents X which form the base of the pyramid repel each other less.
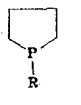
These effects are also encountered in phospholes which are π-electron analogs of pyrrole [50]. In phosphorus-substituted phospholes 61, the phosphorus atom is significantly removed from the plane of the diene system, while the internal C-P-C angle hardly exceeds 90°. In addition, the barrier to pyramidal inversion of phosphorus in phospholes is only

TABLE 1. Idealized Heteroatom Valence States

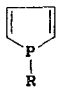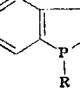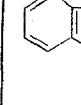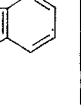| Heteroatom type	Atomic orbitals*				Valence state	Number of promoted s electrons
	s	p_x	p_y	p_z		
Pyridine N̈	↓↑	↓	↓	[↓]	$s^{4/3}p^{11/3}$	2/3
Pyrrole N̈	↓	↓	↓	[↓↑]	sp^4	1
Pyridine Ö	↓↑	↓↑	↓	[↓]	$s^{5/3}p^{13/3}$	1/3
Pyrrole Ö	↓↑	↓	↓	[↓↑]	$s^{4/3}p^{14/3}$	2/3

*The electron participating in the formation of the aromatic π-system are given in brackets. Here and subsequently, these electrons are arbitrarily placed in $2p_z$ orbitals. Since the three p orbitals are degenerate, for purposes of clarity, the electron pair of the pyridine oxygen atom Ö is placed in the $2p_x$ orbital, while the electron pair of the pyrrole oxygen Ö is placed in the $2p_z$ orbital.

TABLE 2. Barriers to Pyramidal Inversion [51]*

Compound	60	61	62	63	64
$\Delta G^{\neq}$, kJ/mole	150	63—67	98	109	142

*The structure of substituents R does not have a marked effect on the inversion barrier.

about 65 kJ/mole, i.e., significantly less than in saturated compounds 60 (Table 2). The lowering of the barrier undoubtedly indicates some interaction of the phosphorus unshared electron pair and the diene π-system (3pπ-2pπ interaction), which reduces the energy of the planar transition state. We should stress that theoretical calculations indicate that the conjugation energy in pyramidal phospholes is 60-70% of that in the planar model [52]. An additional factor which hinders the realization of planar configuration of the ground state of phospholes is the well-known instability of 3pπ-bonds due to the greater diffuseness of the 3p orbitals and greater length of the 3pσ-bonds [53].*

The barrier to pyramidal inversion in benzophosphole derivatives 62 and 63 is markedly higher than in simple phospholes (Table 2). This barrier in arsole was theoretically estimated to be 142 kJ/mole, i.e., this heterocycle should be virtually lacking in aromatic properties [55].

In phospho-, arsa-, and stibabenzenes which are pyridine compounds, the internal C—Y—C bond angle is close to 90° [56], i.e., the heteroatom uses pure p orbitals to construct σ-bonds, while the unshared electron pair occupies the 3s, 4s, and 5s orbital, respectively.

2.3. Oxygen and Sulfur

The specific nature of oxygen as a heteroatom lies in the requirement of one-third s electron less to a 2p orbital (taking account of the hybridization) than in the case of the nitrogen atom in order to convert it to a state corresponding to the pyridine or pyrrole type (Table 1). The valence state of the pyridine oxygen may be described as $s^{5/3}p^{13/3}$,

*The instability of silabenzene 6 which has been detected only in argon matrix at 10°K [54] is attributed to this factor as well as to the significant polarity and polarizability of the C—Si bond.

while that of pyrrole oxygen may be described as $s^{4/3}p^{14/3}$. The C—O—C bond angle in the pyrilium cation is 122° [57], i.e., the oxygen atom is sp^2-hybridized. The question of the hybridization of pyrrole-type oxygen is more complex since the C—O—C bond angle in furan (106°) is far from the trigonal value. There are two possibilities in this case. In the first case, we may assume, for example, that the oxygen atom forms the C—O bond due to orbitals having greater p character (a type intermediate between sp^3 and pure p), while the unshared electron pair which is not involved in the aromatic system is located in an orbital having greater s character (sp^2 with an admixture of s orbital). Then, the second oxygen electron pair which participates in the aromatic sextet should be found in a pure $2p_z$ orbital, i.e., the overall hybridization of oxygen nevertheless corresponds to sp^2. In the second case, the oxygen orbitals in furan retain approximately the same tetrahedral nature as in water. As already noted, some departure from parallel alignment between the orbital of the heteroatom unshared electron pair and the p orbitals of the remaining ring atoms does not lead to complete violation of conjugation between these orbitals. The data presently available are not sufficient to make an unequivocal conclusion in favor of one of these two hypotheses.

The central theoretical problem in the chemistry of sulfur heteroaromatic systems lies in whether the vacant sulfur 3d orbitals participate in bond formation [58]. Relative to thiophene, for example, the inclusion of d orbitals would imply the necessity of considering structures with negatively charged sulfur 65c and 65d in addition to the ordinary resonance structures 65a and 65b:
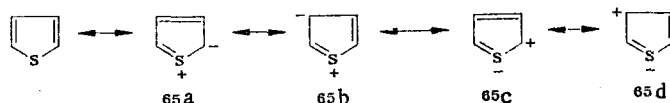
Many theoretical calculations, including those by *ab initio* methods [59] indicate that the energy of the thiophene molecule is hardly affected by the inclusion of the sulfur d orbitals, i.e., we may neglect the sulfur d orbitals, at least for the ground state. However, in the case of the thiapyrilium cations, Yoneda et al. [60] have indicated the significant participation of sulfur 3d orbitals in the ground state. In their opinion, this accounts, in particular, for the greater than ordinary downfield shift of the PMR signal for the β-protons of the thiapyrilium ring. The corresponding effect is given by structures with tetrabonded sulfur 66c:
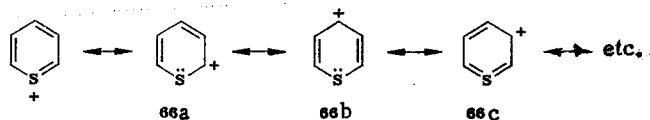
There is no basis to expect a marked contribution of sulfur 3d orbitals in derivatives of thiabenzene 67. In these highly colored and extremely unstable compounds, sulfur is in a pyramidal configuration [61, 62], while their structure is apparently best given as sulfonium ylide 67a.
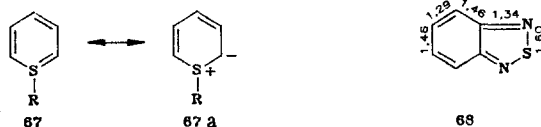
In recent years, there has been wide discussion of the question of the participation of sulfur 3d orbitals in heterocycles containing a sulfur—nitrogen bond. This is a consequence of the metallic and superconducting properties in the $(SN)_x$ polymer which have raised interest in the corresponding heteroaromatic systems. It is difficult to correlate the experimental data on the geometry of 1,2,5-thiadiazole 69 and other such compounds having an S—N bond with a d-orbital effect. Such an effect would have led to an enhanced contribution of the structure with tetravalent sulfur 69c to the resonance hybrid and strong contraction of the S—N bond. In fact, the length of this bond in 69 (1.63 Å [63]) corresponds to a bond order of 1.5, which is typical for 3pπ—2pπ conjugation. Thus, the electronic structure of 1,2,5-thiadiazole may be given satisfactorily by three of the structures presented below:

The structures at top (69, 69a, 69b, 69c) are chemical resonance structures.
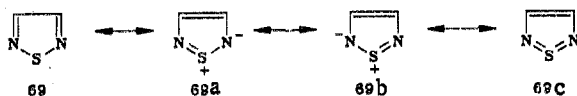
The bond lengths in benzo[1,2,5]thiadiazole 68 found by x-ray diffraction structural analysis also indicate that sulfur is double-bonded and are in accord with quinoid structure of the benzene ring [9].

The hybridization of the valence orbitals of pyrrole-type sulfur in heteroaromatic systems apparently does not have great significance. This is indicated, for example, by the C—S—C bond angle in thiophene, which is equal to 92°. It is striking that the bond angles at sulfur in 69 and 68 are expanded to 99° and 102°, respectively, i.e., the role of the hybridization of the 3s and 3p orbitals in these compounds is enhanced.

3. THE NATURE OF THE DIVISION OF HETEROATOMS INTO THREE TYPES

The division of heteroatoms into three types, namely pyrrole, pyridine, and borepin types, is a convenient and logical basis for the classification of heteroaromatic systems. Indeed, usually only a single glance of a heteroaromatic molecule is required in order to predict, in general terms, its chemical behavior (tendency to undergo electrophilic or nucleo- philic substitution), acid—base properties, and the possibility of tautomeric transitions ac- cording to the type of heteroatoms. Nevertheless, we should not forget that this classifica- tion is largely arbitrary, as indicated by frequently encountered situations in which the as- signment of the heteroatom to a specific type is difficult or even impossible. Thus, both the nitrogen atoms in the imidazole anion are completely identical and formally share three π-electrons. This may be represented either by mesomeric structure 70 or limiting resonance structures 70a and 70b:
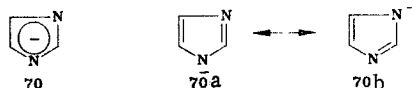
The assignment of the heteroatoms to the pyridine or pyrrole types in the imidazole anion (as in the case of its cation) is clearly pointless. Aspects of this uncertainty are found for imidazole itself, which is usually represented by structure 71, in which the nitro- gen atom of the NH group is of the pyrrole type, which N-3 is of the pyridine type. However, since imidazole is markedly less acidic than pyrrole and significantly more basic than pyrid- ine, the contribution of bipolar resonance hybrid 71a should also be taken into account. The nitrogen atom bound to hydrogen in 71a is formally of the pyridine type, while N-3 is now of the pyrrole type. We consider that the classification based on 71 is correct and makes the major contribution to the resonance hybrid.

Hence, the assignment of the heteroatoms to a specific type is entirely dependent on the correct selection of the structure which best describes the actual molecular structure. Let us examine the pyrilium cation in this regard. Taking account of carbocationic struc- tures 72a-c, in which the oxygen atom is formally of the pyrrole type, is very important in describing the chemical behavior of this species.
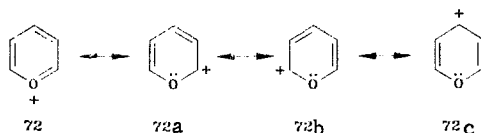
Various quantum mechanical calculations [57, 64, 65] have shown that only 20-30% of the positive charge in the pyrilium cation is localized on the oxygen atom (lower estimates have also been reported), i.e., the contribution of structures 72a-c is indeed significant. On the other hand, the oxygen atom in furan which supplies π-electrons to the ring also acquires positive charge and significant double bond character:

TABLE 3. Experimental Bond Lengths and Angles in Five-Membered Heterocycles with One Heteroatom*

X	Method	Bonds, Å			Angles (deg)		
		1—2	2—3	3—4	2—1—5	3—2—1	4—3—2
NH	MWS	1,37	1,38	1,42	110	108	107
P-CH₂Ph	XSA	1,78	1,34	1,44	91	110	114
O	MWS	1,36	1,36	1,43	106	111	106
S	MWS	1,71	1,37	1,42	92	112	112
Se	MWS	1,86	1,37	1,43	88	112	115
Te †	XSA	2,06	1,36	1,41	82	112	119
CH₂	MWS	1,51	1,34	1,47	103	109	109

*The microwave spectral (MWS) data were taken from the re-view of Mislow [62], while the x-ray structural analysis (XSA) data were taken from Kitaigorodskii [9] and Katritzky [67].
†The measurements were carried out for tellurophene-2-carboxylic acid.
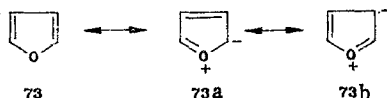
John and Radom [66] used an *ab initio* method to calculate this charge, which was found equal to +0.29, i.e., it is of the same order as in the pyrilium cation. The C–O bond lengths in the 2,4,6-triphenylpyrilium cation [57] and in furan [63] are also identical (1.36 Å). These findings indicate that the actual difference between the heteroatoms in furan and the pyrilium cation are significantly less than would be expected from their usual structural formulas 72 and 73. This difference apparently largely consists in a slight difference in electronegativity which is somewhat greater for the oxygen atom in the pyrilium cation. Nevertheless, for systematic purposes, the division of heteroatoms into three classes may be considered justified.

4. CRITERIA FOR HETEROAROMATICITY

Aromatic compounds have a set of specific properties which are often called aromatic characteristics. In particular, such characteristics include the lack of marked bond-length alternation, enhanced thermodynamic stability, the capacity to maintain a diamagnetic ring current, and a tendency toward substitution reactions. Virtually all these and other proper-ties of aromatic compounds are the result of cyclic conjugation of the π-electrons. The de-tection of these properties by itself does not present difficulties, and thus it is relative-ly easy to characterize a compound as aromatic, nonaromatic, or antiaromatic. However, more than one generation of chemists has worked on the more difficult problem of describing arom-aticity in quantitative terms. The ultimate aim of such work is the determination of a quantitative scale for aromaticity based on an experimental or theoretical parameter (or set of parameters) which is intimately related to the aromatic nature of the compound and, con-currently, is largely independent of other factors not related to aromaticity.

Many different quantitative indices for aromaticity have been proposed [4]. Unfortunate-ly, however, many of these indices are imperfect. Some are suitable only for a narrow range of compounds while others are not in good accord with the actual properties of real molecules. There are two major factors which account for this circumstance. The first factor is related to the not always clear answer to the question of whether aromaticity should be assigned ex-clusively to the molecular ground state. The justification for using chemical properties as a quantitative or even semiquantitative criterion for aromaticity depends on the answer to this question. Experience has shown that a consistent notion of a quantitative aromaticity

TABLE 4. Geometry of Six-Membered Heterocycles with One Heteroatom [56]

Y	Method	Bonds, Å			Angles (deg.)			
		1—2	2—3	3—4	2—1—6	3—2—1	4—3—2	5—4—3
N	MWS	1,34	1,39	1,39	117	124	118	118
P	MWS	1,73	1,41	1,38	101	125	124	122
As	MWS	1,85	1,39	1,40	97	—	—	—
Sb	MWS	2,04	1,40	1,40	93	—	—	—
O*	XSA	1,36	1,37	1,41	122	119	120	118

*For 2,4,6-triphenylpyrilium [57]. Similar results were obtained for 2,4,6-trimethylpyrilium [68].

index obtains only if aromaticity is considered as a property of the ground state. Attempts to use the difference between the energies of the ground and transition states have been largely unfruitful. The second difficulty in the quantitative evaluation of aromaticity lies in the frequently unsuccessful selection of a physicochemical parameter for the molecular ground state. Thus, there have been many efforts to derive indices based on the magnetic properties of aromatic compounds but such properties were subsequently found to be useful only as a qualitative criterion.

In our further discussion, stress will be placed on the quantitative or semiquantitative evaluation of the aromaticity of heterocycles. We shall consider four major groups of criteria for aromaticity involving structural, magnetic, energy, and chemical properties. Although we have already noted that magnetic and chemical aromaticity criteria give only a qualitative characterization of aromaticity, the importance of such properties for aromatic compounds is so great that they must be treated in considerable detail.

4.1. Structural Criteria

Cyclic conjugation leads to a leveling out of the differences in bond length. Thus, the benzene molecule, tropylium cation, and cyclopentadienyl cation are proper planar polyhedrons with 1.40 Å edge length (the length of the standard aromatic C ... C bond).Upon introducing a heteroatom into the ring, the electron density distribution becomes less uniform, conjugation partially breaks down, and the bond lengths begin to depart from 1.40 Å in both directions. The bond angles are also distorted (Tables 3 and 4; Fig. 1).
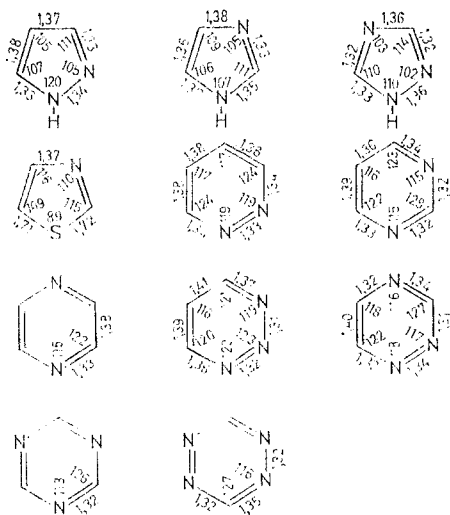

Fig. 1. Geometry of heterocycles with several heteroatoms [9, 63] (the measurements were carried out in the case of 1,2,3- and 1,2,4-triazines for 4,5,6-tri(p-anisyl) and 5-(p-chlorophenyl) derivatives, respectively).

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TABLE 5. Julg Aromaticity Structural Indices

Compound	Taking account of all bonds			Taking account of only C—C bonds		
	A_1	A_2	A	A_1	A_2	A
Benzene	1,00	1,00	1,00	1,00	1,00	1,00
Pyridine	0,92	0,92	0,85	0,97	0,99	0,96
Pyrrole	0,98	0,90	0,88	0,99	0,99	0,98
Furan	0,92	0,94	0,86	0,94	0,99	0,93
symm-Triazine	1,00	0,56	0,56	—	—	—

The departure of the ring bonds from the standard values may be used in principle to evaluate the aromaticity of heterocycles. Thus, in the case of five-membered heterocycles with one heteroatom, aromaticity is frequently evaluated relative to the $C_{(2)}$—$C_{(3)}/C_{(3)}$—$C_{(4)}$ bond length ratio. The diene system is more clearly established and the aromaticity reduced with decreasing value of this ratio (the contribution of the nonpolar Kekulé structures is greater). The corresponding values of this ratio give the following sequence for decreasing aromatic properties: thiophene (0.962), selenophene (0.962), tellurophene (0.961), pyrrole (0.959), furan (0.951), phsophole (0.934), and cyclopentadiene (0.913).

Julg [69] proposed the aromaticity index A_1, which characterizes the extent of uniformity of the peripheral bonds:

$$A_1 = 1 - \frac{225}{n} \sum_{(rs)} (1 - d_{rs}/\bar{d})^2, \tag{1}$$

where d_{rs} is the length of the bond between aroms r and s, $\bar{d}$ is the average bond length, and n is the number of ring π-electrons.

Equation (1) was derived such that $A_1 = 1$ for benzene, while $A_1 = 0$ for its Kekulé structure. The values for A_1 for various heterocycles calculated using Eq. (1) and given in Table 5 are extremely similar and hardly differ from benzene regardless of whether only the C—C bonds are taken into account as in the initial work of Julg or the lengths of all the ring bonds are considered.* Julg later introduced a new index considering all the ring bonds $A = A_1A_2$ [70]. The correction term A_2 is given by Eq. (2) and accounts for the resistance to the cyclic circulation of the π-electrons localized on atoms due to charges:

$$A_2 = \prod_{(ij)} [1 - (\Delta q_{ij}/d_{ij})^2], \tag{2}$$

where Δq_{ij} is the difference in the π-charge on neighboring atoms, and d_{ij} is the interatomic distance.

Although index A is rather commonly cited in the literature, it also cannot be considered satisfactory. Its only advantage is the ability somehow to convey the reduced aromaticity of such symmetrical compounds as 1,3,5-triazine relative to benzene. Although the bonds in 1,3,5-triazine are completely leveled out, the significant distortions in the bond angles and strong alternation of the charges on the atoms should, of course, lead to a considerable breakdown in the cyclic conjugation. However, we must ask why the charge gradients should be taken into account specifically in the form proposed by Julg. No physical justification is given. We should add that the value for A given by Julg [70] for furan (0.06) and pyrrole (0.38) are most likely due to a misunderstanding. Calculations have shown that the charge gradient in pyrrole [49] and furan [66] is not sufficiently high to have a strong effect on the term A_2. Furthermore, this term is actually even slightly higher for furan (Table 5). Another disadvantage of index A is the difficulty in properly evaluating the π-charges, in particular for molecules with heavy heteroatoms.

It is quite clear that the cyclic conjugation in heterocycles should especially break down in the vicinity of the heteroatom and its bonds. Thus, in developing a structural index for aromaticity, neglect of the bonds involving the heteroatoms is impermissible. Since dif-

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*All the values given in Table 5 were calculated by the present author taking account of the geometry of the heterocycles indicated above. In calculating index A, we used the π-charges calculated according to the simple Hueckel method with the parameters of Streitwieser [71]. The use of π-charges calculated using the *ab initio* method does not lead to a significant change in index A.

TABLE 6. Empirical Constants a and b for Calculation of the Bond Order Using Eq. (3) [72]

Bond	a	b	Bond	a	b
C—C	6,80	−1,71	C—Se	15,24	−3,09
C—N	6,48	−2,00	C—Te	21,41	−3,81
C—O	5,75	−1,85	N—N	5,28	−1,41
C—S	11,9	−2,59	N—O	4,98	−1,45
C—P	13,3	−2,89			

ferent types of bonds such as C—C and C—N of the same length have different orders, the use of bond lengths for evaluating heterocyclic aromaticity is incorrect. Consideration of bond orders is more justified. There is a simple relationship between the bond order (N) and its length (R) [72]:

$$N = aR^{-2} + b,\qquad(3)$$

where a and b are empirical constants (Table 6) obtained graphically from the dependence of the bond order on bond length for specially selected standard compounds. Gordy [72] proposed that the length of a C—C single bond (N = 1.0) is 1.58 Å, while the length of a C=C double bond (N = 2.0) is 1.35 Å. When precise values for the bond lengths for calculating coefficients a and b are unknown, the lengths of single and double bonds are initially found using the following equation:

$$R_{AB} = r_A + r_B - \beta(\chi_A - \chi_B),\qquad(4)$$

where R_{AB} is the length of the bond between A and B, r_A and r_B are their covalent radii, χ_A and χ_B are the Pauling electronegativities of these atoms, and β is a coefficient equal to 0.09 in the calculations of single bonds and 0.06 for the calculations for the length of double bonds. Having thereby found the lengths of the A—B and A=B bonds, these values are substituted into Eq. (3) and coefficients a and b are found by solving a system of two equations with two unknowns.

Fringuelli et al. [74] used the sum of the differences in bond orders $\Sigma\Delta N = |N_{1-2} - N_{2-3}| + |N_{3-4} - N_{1-2}| + |N_{3-4} - N_{2-3}|$ as an aromaticity index after calculating the bond orders in five-membered heterocycles with one heteroatom. The $\Sigma\Delta N$ values obtained (given in parentheses) permit us to arrange the following compounds in order of decreasing aromaticity: thiophene (0.90) > selenophene (1.02) > tellurophene (1.30) > furan (1.42). Although this series corresponds to experimental findings, this type of calculation has two disadvantages. First, it does not take into account the circumstance that the lengths of some of the bonds repeat. Second, it does not permit comparison of the aromaticity of different types of heterocycles such as five-membered and six-membered heterocycles. Such disadvantages are not found for the $\Delta\bar{N}$ index which is proposed by the present author. This index is the average of the fluctuations of all the ring bonds including single bonds. The essence of $\Delta\bar{N}$ index may be seen for the pyrrole molecule. Taking account of the geometry of pyrrole given in Table 3, the 1—2, 2—3, and 3—4 bond orders are found to be 1.39, 1.91, and 1.62, respectively. Since the molecule has five ring bonds, the total number of differences is 10. These differences may be given conveniently in the following form:

Bond	1—2	2—3	3—4	4—5	5—1
1—2	—	0.52	0.23	0.52	0
2—3		—	0.29	0	0.52
3—4			—	0.29	0.23
4—5				—	0.52
5—1					—

The sum of all the differences $\Sigma\Delta N = 3.12$ and hence the index $\Delta\bar{N} = 0.31$. The value of $\Delta\bar{N}$ for other heterocycles is given in Table 7. For example, $\Delta\bar{N} = 0$ for benzene, while $\Delta\bar{N} = 0.49$ for nonaromatic cyclopentadiene. Aromaticity may also be given as a percentage if benzene is taken as 100% and cyclopentadiene as zero.

The $\Delta\bar{N}$ index, which is based on rigorous experimental data and has a clear theoretical justification, satisfactorily differentiates the aromaticities of various compounds. For

TABLE 7. Values of the Structural Aromaticity Index, $\Delta\bar{N}$, and Aromaticity Relative to Benzene*

Compound	$\Delta\bar{N}$	Aromaticity, %	Compound	$\Delta\bar{N}_i$	Aromaticity, %
Benzene	0	100	1,2,4-Triazine	0,14	71
Naphthalene	0,18	63	1,2,4,5-Tetrazine	0,06	88
Thiophene	0,27	45	Pyridinium (nitrate)	0,22	54
Pyrrole	0,31	37	Pyrilium (2,4,6-triphenyl)	0,35	28
Selenophene	0,31	37	Pyrilium (2,4,6-trimethyl)	0,28	43
Tellurophene	0,39	20	Phosphorine‡	0,19	61
Furan	0,43	12	Porphin	0,24	51
Phosphole	0,45	8	1,4-Dihydro-1,4-diazocine	0,32	35
Cyclopentadiene	0,49	0	Sidnone	0,41	17
Tetrazole†	0,10	80	2-Pyridone	0,38	22
1,2,4-Triazole	0,14	71	2-Thiopyridone	0,38	22
Pyrazole	0,19	61	1H-Azepin **	0,46	6
Imidazole	0,28	43	Acridine (whole molecule)	0,27	45
Thiazole	0,28	43	Acridine (heterocycles)	0,39	20
Pyridine	0,09	82	Purine (whole molecule)	0,15	69
Pyridazine	0,17	65	Purine (imidazole ring)	0,20	59
Pyrimidine	0,16	67	Purine (pyrimidine ring)	0,10	80
Pyrazine	0,12	75			
1,2,3-Triazine	0,17	65			

*Bond lengths given in Tables 3 and 4 and in Fig. 1 were used. The geometry of thiazole was taken from Mislow [62], while the geometry of 1,4-dihydrodiazocine was taken from Vogel [46] and the geometry of the pyrilium cations were taken from Tamamura [57] and Struchkov [68].
†For the sodium salt [9].
‡For 2,6-dimethyl-4-phenylphosphorine [9].
**For 1-p-bromobenzosulfonylazepin [9].

five-membered heterocycles with a single heteroatom, it decreases in the series: thiophene > pyrrole ≈ selenophene > tellurophene > furan > phosphole. The aromaticities of furan (12%) and phosphole (8%) are especially low and correspond to both theory and experiment. Six-membered heterocycles with a pyridine heteroatom are significantly more aromatic than their five-membered analogs, i.e., relative to aromaticity, pyridine > pyrrole, pyrylium cation > furan, and phosphorine > phosphole. Pyridine itself has very high aromaticity (82%). The aromaticity of diazines is somewhat less, while pyrazine is more aromatic than pyridazine and pyrimidine. 1,2,3- and 1,2,4-triazines have extremely high $\Delta\bar{N}$ values.

There is broad discrepancy in the evaluation of the aromaticity of the pyridinium ion of the basis of x-ray diffraction structural data [9] for its nitrate and chloride. Judging from the geometry of the nitrate, its aromaticity is 54% while a value of 90% is obtained using the data for its chloride. The former result is more logical. There may be a partial charge transfer from the anion to cation in the hydrochloride, which leads to a decrease in the positive charge in the ring and a leveling of the bond lengths.

Azoles occupy an intermediate position between five- and six-membered heterocycles. The aromaticity of these compounds increases with increasing number of aza groups: tetrazole > 1,2,4-triazole > pyrazole > imidazole. It is interesting that the $\Delta\bar{N}$ value for pyrazole is independent of which of the two known crystalline modifications reported [9] is used for the calculation. The greater aromaticity of pyrazole relative to imidazole is also revealed by other methods.

Significant aromaticity (51%) is found for porphin 38. The x-ray diffraction structural data for 1,4-dihydro-1,4-diazocine 21 indicate a planar molecular structure and aromaticity approximately equal to that for pyrrole. The aromaticity of sidnones is only 17% in accord with their structure 32d-32e. The $\Delta\bar{N}$ indices for pyridones and thiopyridones shows that there is a significant breakdown in the cyclic conjugation in these molecules, in accord with data obtained by other methods. There are formally seven π-electrons in the heterocycle of 2-pyridone and 2-thiopyridone 74, i.e., these are anti-Kekulé systems. The residual aromaticity (22%) found for these compounds is attributed to the removal of the "extra" π-electron to the oxygen or sulfur atom, which leads to a marked contribution of the bipolar aromatic structure 74a:

74   74a   75   76
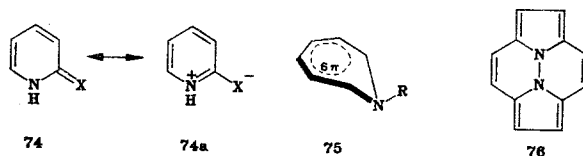
1H-Azepin 51 is a typical anti-Kekule 4n π-system. The x-ray diffraction structural data for this compound show that the nitrogen atom is quite extruded from the plane which contains the six carbon atoms (75). Thus, the observed slight leveling of the bond lengths (8%) may be attributed to homoaromaticity.

An important advantage of the $\Delta\bar{N}$ index is the possibility of its use to evaluate the aromaticity of individual rings in polycondensed systems. Thus, the aromaticity of acridine as a whole is 45%, while it is only 20% in the heterocycle, i.e., significantly less than in pyridine. On the other hand, the leveling of the bond lengths in the heterocycle in carbazole (53%) is higher than in pyrrole. This finding is almost entirely the result of a decrease in the double-bond nature of the side-bonds of the five-membered ring of carbazole due to their conjugation in the benzene rings. The total aromaticity in purine is 69% while the relative aromaticities of the imidazole ring (59%) and the pyrimidine ring (80%) remain as in the monocyclic systems. When x-ray diffraction structural data are available only for substituted heterosystems, we should bear in mind that the substituents have a significant effect on the bond leveling in the ring. Thus, $\Delta\bar{N}$ = 0.35 for the 2,4,6-triphenylpyrilium cation, while the corresponding value for 2,4,6-trimethylpyrilium is 0.28, i.e., the trimethyl-substituted cation is approximately 15% more aromatic.

As in the case of most of the other criteria for aromaticity, the structural index $\Delta\bar{N}$ has a number of limitations. In particular, it is unsuitable for planar antiaromatic systems such as hydrazinoannulene 76. According to an x-ray diffraction structural analysis [75], the total bond leveling in this heterocycle is 62%, while the leveling of the peripheral bonds is 74%. Cyclic conjugation in planar antiaromatic systems is accompanied by an increase in molecular energy although it leads to leveling of the bond lengths. We should note, however, that there is no difficulty in distinguishing antiaromatic systems from aromatic systems using other aromaticity criteria, in particular magnetic criteria.

The $\Delta\bar{N}$ index is also unsuitable for evaluating the aromaticity of such symmetric compounds as 1,3,5-triazine. All the bonds in this heterocycle are identical as in benzene, i.e., $\Delta\bar{N}$ = 0. However, considering the high degree of charge separation between the nitrogen and carbon atoms and the significant distortion of the bond angles (Fig. 1), the π-electron conjugation in this triazine clearly should be less efficient than in benzene. It is not excluded that the high aromaticity index for symm-tetrazine (88%) is to some extent a consequence of molecular symmetrization. Incidentally, tetrazine is the most aromatic azine also relative to criterion of diamagnetic ring current [5].

Hence, the lack of alternation of bond lengths is not a single and sufficient condition for aromaticity of cyclic conjugated systems. Thus, the $\Delta\bar{N}$ index, despite its considerable appeal, should be taken along with the other aromaticity criteria. Recently, Jug proposed that aromaticity should be evaluated not so much relative to the extent of leveling of all the bonds but to the order of the weakest ring bond which he offered as a new aromaticity index [76] since the most significant breakdown in cyclic ring current occurs specifically in the vicinity of the weakest ring bond. Therefore, in general, the aromaticity of a compound should be higher with increasing order of this bond. Using the semiempirical SINDO-1 method, Jug calculated the bond orders of a large number of aromatic and heteroaromatic structures and placed azines and heterocycles with a pyrrole-type heteroatom in the following sequence in order of decreasing aromaticity (the minimal double bond and its order are given in parentheses): pyrazine (1-2, 1.739), symm-tetrazine (2-3, 1.735), pyridine (1-2, 1.731), pyrimidine (3-4, 1.727), symm-triazine (1.724), pyridazine (3-4, 1.716), pyrrole (1-2, 1.463), furan (1-2, 1.430), imidazole (1-5, 1.423), pyrazole (1-2, 1.423), oxazole (1-5, 1.392), isoxazole (1-2, 1.361). These results indicate the greater aromaticity of azine relative to π-excess heterocycles and azoles. In addition, the order of azine aromaticity is quite similar to that given by the $\Delta\bar{N}$ index. On the other hand, the data for π-excess heterocycles and azoles raise some doubt. In contrast to the data of Jug, all evidence indicates the furan is less aromatic than imidazole, pyrazole, oxazole, and isoxazole. There are other discrepancies in Jug's calculations. In particular, his results predict greater aromaticity for the cyclopropenylium cation (1.775) than for benzene (1.751) and the lack of aromaticity in pyrazole.

TABLE 8. Diamagnetic Susceptibil-
ity Constants for Various Atoms
(according to Pascal) [78]

$-10^6\chi_m$	$-10^6\chi_m$	Bond corrections	
		bond	$-10^6\chi_m$
H	2,9	C=C	−5,5
C	6,0	C=N	−8,2
N	5,6	C=O	−6,3
O	4,6	N=N	−4,0
S	15,0	C≡C	−0,8

In evaluating aromaticity, it may be necessary to take account of the bond angles and
the effective atomic charge in addition to bond orders. However, the proper treatment of
these parameters for this purpose remains an unresolved problem. Palmer et al. [77] pro-
posed the adoption of the extent of isolation of the heteroatom electron pair from the quart-
et of the remaining ring π-electrons as an index of aromaticity on the basis of electron
density calculations. In other words, the contribution of structures such as 72a-c for the
pyrilium cation or of dienic structure 73 for furan to the resonance hybrid. The following
isolation indices were obtained: benzene (0.0), pyridine (0.154), thiophene (0.340), thio-
pyrilium (0.420), phosphorine (0.583), pyrrole (0.680), furan (0.84), phosphole (0.82),
pyrilium (0.97), pyridinium (1.04). The results for the pyrilium and pyridinium cations are
in strong contrast to those obtained for the structural index $\Delta\overline{N}$. It is unlikely that arom-
aticity can be reduced exclusively to molecular charge distribution.

4.2. Magnetic Criteria

The magnetic properties of conjugated and, in particular cyclic conjugated systems, are
extremely important for understanding their electronic structure and physicochemical behavior.

4.2.1. Diamagnetic Susceptibility Exaltation. The molar magnetic susceptibility of
diamagnetic compounds, χ_m, is an additive term and it may be calculated by adding the suscep-
tibilities of the atoms forming the molecule (Table 8).

As a rule, the agreement between experimental values of χ_m and values calculated by an
additive scheme, χ'_m, is very good for saturated molecules. Corrections for the diamagnetic
susceptibility of double and triple bonds must be introduced for compounds containing isolated
multiple bonds in order to obtain such agreement. However, the experimental χ_m values exceed
the calculated values for molecules with conjugated bonds. For example, in the case of 1,3-
butadiene, this increase (exaltation) is $-10^6\Lambda = 0.5$, while for cyclooctatetraene it is 2.7.
Especially large diamagnetic susceptibility exaltations are observed for aromatic compounds.
Thus, for benzene and pyridine, the $-10^6\Lambda$ value is about 18 cm³/mole (Table 9). The calcula-
tion for the diamagnetic susceptibility according to an additive scheme is usually carried
out for the most stable limiting structure which is the Kekulé structure (1) in the case of
pyridine:

$$-10^6\chi'_m = 5\chi_C + 5\chi_H + \chi_N + 2\lambda_{C=C} + \lambda_{C=N} = 5\cdot 6.0 + 5\cdot 2.9 +$$
$$5.6 + 2(-5.5) - 8.2 = 30.9 \text{ cm}^3/\text{mole} \cdot$$

The experimental value, $-10^6\chi_m = 49.2$ cm³/mole, and hence the exaltation, $-10^6\Lambda = 18.3$ cm³/
mole.

What causes such large exaltations for aromatic compounds? The diamagnetic susceptibil-
ity is directly proportional to the radius of the orbit traversed by an electron. These
orbits in atoms are relatively small. In saturated molecules, the π-electrons circulate
within the multiple bond, which leads to a slight additional magnetic moment taken into ac-
count by the introduction of multiple bond correction factors. There is weak delocalization
within the limits of the multiple bonds in nonaromatic compounds with conjugated bonds such
as cyclooctatetraene. As a result, χ_m, and thus the diamagnetic susceptibility, increase,
leading to a slight discrepancy between the experimental and calculated values.

TABLE 9. Molar Diamagnetic Susceptibilities and Diamagnetic Susceptibility Exaltations of Heterocycles

Compound	$-10^6\chi_m{}^*$	$-10^6\chi'_m$	$-10^6\Lambda$
Benzene	54,8	36,9	17,9
Pyridine	49,2	30,9	18,3
N-Ethyl-2-pyridone	74,0	61,0	13,0
Pyrazine	37,6	24,9	12,7
Pyrrole	47,6	33,1	14,5
Furan	43,1	29,2	13,9
Thiophene	57,4	39,6	17,8
Selenophene	66,8	48,1	18,7
Pyrazole	42,6	27,1	15,5
Thiazole	50,6	33,6	17,0
Sidnone	38,7	24,6	14,1
Quinoline	86,0	49,7	36,3
Isoquinoline	83,9	49,7	34,2
Indole	85,0	51,2	33,8

*The experimental diamagnetic susceptibilities were taken from the following sources: sidnone [18], selenophene [74], and the remaining compounds [79].

The circumstances are markedly altered in aromatic systems, in which the π-electrons no longer belong to individual atoms. Thus, the action of an external magnetic field perpendicular to the ring plane causes the free circulation of π-electrons through the circular orbital (diamagnetic ring current, Fig. 2). The magnitude of the ring current is much greater than the electron currents induced in the atoms or isolated multiple bonds due to the large size of the ring in comparison with the atomic orbitals. The secondary magnetic field created by the ring current in aromatic molecules and thus the diamagnetic susceptibility exaltations, are correspondingly much greater. This field is oriented such that its lines of force at the center of the ring are opposite to the external magnetic field and weaken it since the lines of force of both fields outside the ring coincide and the resultant field here is amplified.

Palmer et al. [77] proposed using the diamagnetic susceptibility exaltation as an aromaticity criterion. The data for various heterocycles are given in Table 9, in which the χ'_m values were calculated using Pascal atomic constants. These values show that all heteroaromatic structures have large exaltations. When the aromaticity clearly breaks down, the exaltation is reduced. For example, N-ethyl-2-pyridone is 30% less aromatic than pyridine. The introduction of one pyridine-type nitrogen atom into the benzene ring has only a slight effect on Λ (compare the values for benzene and pyridine). However, the introduction of a second nitrogen atom leads to a marked decrease in aromaticity as seen for the case of pyrazine.

Heterocycles containing a pyrrolic heteroatom are less aromatic than heterocycles with a pyridinic heteroatom. The aromaticity drops in the following series for five-membered heterocycles: selenophene ≥ thiophene > pyrrole > furan. There is little information available on the diamagnetic susceptibility exaltations of azoles. In the case of pyrazole, we see that the introduction of an aza group into the pyrrole ring makes the molecule more arom-
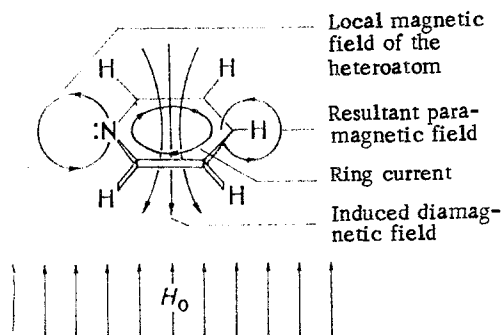

Fig. 2. Ring current and magnetic lines of force in pyridine with an external magnetic field H_0.

TABLE 10. Chemical Shifts for Protons in Various Hetero-
cycles δ, ppm (in CDCl₃) [82]

Compound	2-H	3-H	4-H	5-H	6-H
Benzene	7,20	7,20	7,20	7,20	7,20
Pyridine	8,60	7,00	7,60	7,00	8,60
Pyridazine	—	9,21	7,50	7,50	9,21
Pyrimidine	9,21	—	8,77	7,36	8,77
Pyrazine	8,63	8,63	—	8,63	8,63
symm-Triazine	9,25	—	9,25	—	9,25
Phosphorine [56]	8,61	7,72	7,38	7,72	8,61
Arsabenzene [56]	9,68	7,83	7,52	7,83	9,68
Stibabenzene [56]	10,94	8,24	7,78	8,24	7,78
Bismabenzene [56]	13,25	9,8	7,8	9,8	13,25
Pyrrole	6,68	6,22	6,22	6,68	—
Furan	7,42	6,37	6,37	7,42	—
Thiophene	7,30	7,10	7,10	7,30	—
Imidazole	7,71	—	7,14	7,14	—
Pyrazole	—	7,62	6,33	7,62	—
Thiazole	8,84	—	7,97	7,41	—

atic. On the other hand, the exaltations are virtually the same for thiophene and thiazole.
The exaltations of furan and sidnone are also similar, which is in accord with the aromatic-
ity found for these compounds on the basis of structural indices. On the whole, however,
the diamagnetic susceptibility exaltations insufficiently differentiate the relative arom-
aticity of various compounds. In fact, the actual differences in aromaticity between benz-
ene and furan and between pyridine and pyrrole are significantly greater than indicated by
the exaltation values. This criterion is apparently completely unsuitable for the evaluation
of the relative aromaticity of systems with different ring size and number of π-electrons.
Thus, the data in Table 9 indicate that quinoline is more aromatic than pyridine (even relative
to one π-electron) although the energy and other criteria show that this is not true. Thus,
the diamagnetic susceptibility exaltation may be considered as a test which permits a clear
distinction between aromatic and nonaromatic compounds. In individual cases, mainly for sys-
tems with the same number of π-electrons, this criterion may be used for evaluation of rel-
ative aromaticity.

The use of the so-called Haberdietzl increments instead of the Pascal constants for the
calculation of χ'_m does not lead to a significant improvement in the results [79].

Vysotskii et al. [5] proposed the evaluation of heterocyclic aromaticity using quantum
mechanical calculation of the π-electron contributions to their diamagnetic susceptibility
since the diamagnetic and paramagnetic components may be separated in this approach. The re-
sults obtained do not provide a completely satisfactory arrangement of azine aromaticity
(symm-tetrazine >1,2,4-triazine, pyrazine, pyridazine > pyridine > pyrimidine > pyrilium
cation), but clearly delineate aromatic and antiaromatic systems.

4.2.2. Magnetic Susceptibility Anisotropy. Diamagnetic susceptibility anisotropy has
great importance in aromatic compounds and especially in heteroaromatic compounds. Isolated
spherical atoms and some spherical molecules such as methane are magnetically isotropic,
i.e., their magnetic susceptibility is the same in all directions. However, the vast major-
ity of compounds do not possess spherical symmetry and are anisotropic. In particular, the
anisotropy of benzene or pyridine lies in the failure of a magnetic field parallel to the
ring plane to give rise to a ring current. The heteroatoms within a π-system are also mag-
netically anisotropic since their electron environment is not spherical. The anisotropy re-
lated to the generation of a ring current has been used for the quantitative evaluation of
the aromaticity of several azines relative to benzene [80]. If we assume that the extent of
π-electron delocalization for benzene is 1.0, the corresponding values for azines are 0.7
for pyridine, 0.7 for pyridazine, 0.5 for pyrimidine, and 0.3 for symm-triazine. Thus, the
enhanced asymmetry of the π-electron cloud characteristic for pyrimidine and especially tri-
azine, significantly hinders cyclic conjugation, i.e., leads to a decrease in aromaticity.
The rather close agreement in the aromaticities found for azines (with the exception of tri-
azine) using the structural index ΔN̄ and magnetic susceptibility anisotropy is striking.

4.2.3. Proton Chemical Shifts. The generation of an induced ring current in aromatic
systems (Fig. 2) leads to deshielding of the external ring protons such that they appear at
significantly lower fields in proton magnetic resonance spectra in comparison with olefinic

TABLE 11. Aromaticity and Proton Chemical Shifts of Several
Polycyclic Heterosystems

Com-pound	Number of π-electrons		δ, ppm	Type of system	Refer-ence
	total	peri-pheral			
29	12	10	7,2—7,9	Aromatic	38
58	14	12	2,07 (3H) 3,65 (6H)	Antiaromatic	38
76	16	12	4,8—4,9	Antiaromatic	75
77	14	14	7,7—8,7	Aromatic	83
78	14	14	7,5—8,2	Aromatic	83
79	14	13	6,1—7,2	Weakly aromatic	83
81	18	16	4,45	Antiaromatic	84
82	16	14	8,1—8,9	Aromatic	84
83	14	13	6,1—6,9	Weakly aromatic	84

protons. The magnetic shielding constant of an atom σ_A which determines the chemical shift
may be represented by the following equation [81]:

$$\sigma_A = \sigma_{dd}{}^{AA} + \sigma_{pp}{}^{AA} + \sum_{B \neq A} \sigma^{AB} + \sigma^{A, \text{ ring}}, \tag{5}$$

where $\sigma_{dd}{}^{AA}$ and $\sigma_{pp}{}^{AA}$ are the diamagnetic and paramagnetic contributions from the electrons
of atom A, σ^{AB} is the contribution from the circulation of electrons on other atoms designated
B, and $\sigma^{A, \text{ring}}$ is the contribution of the interatomic ring current. The latter term predomin-
ates for aromatic compounds. Hence, at one time, it was thought that proton chemical shifts
could be used as an aromaticity index. Specifically, a greater diamagnetic ring current and
greater downfield shift of the ring protons should correspond to more aromatic compounds.
However, it gradually became clear that the other terms in Eq. (5) could not be neglected.
This is particularly true for heteroatomic systems due to the nonuniform distribution of
electron density in these compounds and the effect of the anisotropy of the heteroatom.

Proton chemical shifts are now considered as a good test for aromaticity in general,
which only in individual special cases may serve as a qualitative criterion for relative
aromaticity. Let us examine the proton shifts of several heteroaromatic systems (Table 10).
The proton signals in the PMR spectra of five-memtered heterocycles are at higher field than
for six-membered heterosystems. To a certain extent, this is a consequence of the reduced
aromaticity of the five-membered heterocycles. However, the difference between the charges
on the carbon atoms of the five- and six-membered rings plays an important role in this case.
While the carbon atoms of the six-membered rings have a π-electron deficit, the carbon atoms
of the five-membered rings bear excess π-electron charge, which leads to an upfield shift.
A typical example of the lack of accord between relative aromaticity and proton chemical
shifts may be found for pyrrole and furan. Although the aromaticity of pyrrole by all
criteria is greater, the proton signals in its PMR spectrum are at higher field due to the
greater negative charge on the carbon atoms. Such examples are readily found in the zinc
series. A proper notion of relative aromaticity may be obtained only for closely related
heterocycles with the same number and type of heteroatoms. Thus, the greatest aromaticity
for isomeric naphthoimidazoles (Table 11) is found for the angular isomer 77 and the least
aromaticity is found for peri-isomer 79, which is called perimidine. The same order is
given by energy criteria (see Table 18).
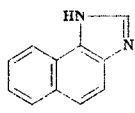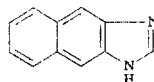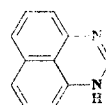
77   78   79

The magnetic anisotropy of heteroatoms, especially pyridinic heteroatoms, has a sig-
nificant effect on the PMR spectrum. The role of this factor increases with increasing
size of the heteroatom. In going from pyridine to phospha-, arsa-, stiba-, and bismabenz-

enes, the signals for the H_α atoms are steadily shifted downfield and the difference in the chemical shifts between the first and last members of this series is 4.5 ppm (Table 10). The heteroatom anisotropy effect also affects H_β and H_γ although its role diminishes with increasing removal of the heteroatom and decreasing heteroatom size.

A separation of the external and internal protons is characteristic for the PMR spectra of macroheterocycles as in the case of higher annulenes. For example, the five internal protons in aza[18]annulene 42 give a multiplet at δ −1.84 ppm, while the signals for the external protons are at 10.05 (two H_α atoms) and 8.86 ppm (10 remaining protons) [20]. These results unequivocally indicate the existence of a strong ring current in 42, i.e., this compound is aromatic. It is interesting that the cation of aza[18]annulene is a mixture of conformers 80 and 80a, in which the NH group proton is oriented inside or away from the ring (the ratio of these isomers is 1:4):

80   80a
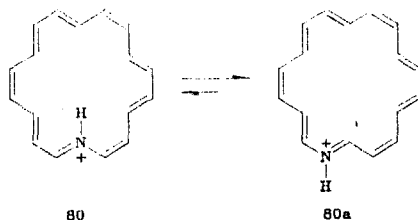
Similar conformational effects are found for other heteroannulenes. PMR spectroscopy is the major method for the study of these effects [16-18].
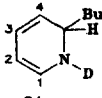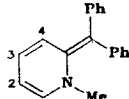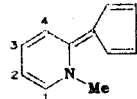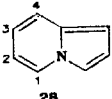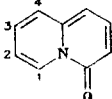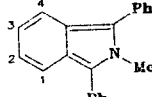
PMR spectroscopy readily permits us to distinguish between aromatic and antiaromatic heterocycles (Table 11). The protons in antiaromatic systems usually have signals at δ 4.5-5.0 ppm as in 1-methylazepin 51 (X = NCH₃) and hydrazinoannulene 76. The protons in cyclo-[3.3.3]azine 58 are found at even higher field (2.1-3.7 ppm). This is apparently the most significant manifestation of this effect for planar antiaromatic systems. The antiaromatic nature of 58 would predict only slight participation of the heteroatom electron pair in the cyclic conjugation and, indeed, an SCF MO calculation indicates that only 0.17 electron is transferred from the heteroatom to the peripheral atomic orbitals [85]. This is also true for cyclo[3.2.2]azine 29, whose PMR spectrum (δ 7.2-7.9 ppm) is typical for an aromatic system, which is possible if only 10 peripheral π-electrons participate in conjugation.

According to current concepts [86], the reason for the paramagnetic shift of the proton signals of antiaromatic systems lies in the characteristically low energy difference between the highest occupied and lowest unoccupied MO. As a result, the triplet state of such compounds is very low and is partially occupied under ordinary conditions. This leads to strong paramagnetic currents, as confirmed by quantum mechanical calculations and, indirectly, by the intense color usually found for antiaromatic compounds. As an example, let us examine the group of peri-condensed naphtho[1,2,6]thiadiazines 81-83. The physical proper-ties of 81 are typical for antiaromatic systems: dark green color, facile electrochemical oxidation, and especially its PMR spectrum, in which the four protons give a singlet at δ 4.45 ppm. Although the total number of π-electrons in 81 is 18, only 16 electrons participate in the peripheral conjugation, i.e., an anti-Hueckel number. This predisposes paramagnetic ring currents in 81 and requires its classification as antiaromatic. The x-ray diffraction structural analysis of this compound [87] indicated strong bond alternation in 81, which cor-responds to the quinoid structure given. It is interesting that 81 is extremely inert chem-ically, which should be incompatible with its antiaromatic nature. However, this circum-stance should not lead to confusion and is to the chemical stability of the N-S bond, which favors stabilization of the molecule.

81   82   83
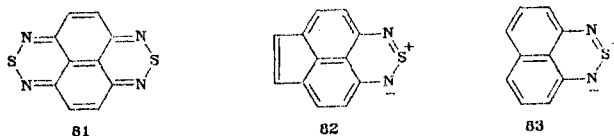
There are 14 peripheral π-electrons in 82 and its PMR spectrum (Table 11) indicates that this compound is aromatic. On the other hand, there are only 13 π-electrons in the peripheral AO in naphtho[1,8-c,d][1,2,6]-thiadizine 83 as in the case of perimidine 79. This is a num-ber intermediate between aromatic and antiaromatic systems. It is remarkable that these

TABLE 12. Ratio of Vicinal Proton Coupling Constants [90]

| Compound	Constants, Hz			$\bar{J}_{rel}$ *
	J_{12}	J_{23}	J_{34}	
84	7,11	5,40	9,80	0,65
85	7,00	5,96	9,72	0,73
86	6,74	6,61	9,27	0,85
28	7,06	6,45	9,07	0,81
87	7,36	6,50	8,91	0,80
88	8,63	6,39	8,63	0,74

* $J_{rel} = [J_{23}/J_{34} + J_{23}/J_{12}]/2$.

heterocycles display features of both aromatic and antiaromatic systems. On the one hand they readily undergo aromatic substitution reactions, while the chemical shifts of their protons lie in the range characteristic for aromatic compounds (although they are close to the upfield limit of this range). On the other hand, they are extremely readily oxidized and reduced [88, 89] and ESR signals are detected for crystalline samples of perimidines and other peri-condensed heterocycles [83]. All these findings indicate significant approximation of the energies of the HOMO and LUMO in 79 and 83 and the availability of the triplet level. Hence, 79 and 83 should be characterized as weakly aromatic.

4.2.4. Spin-Spin Coupling Constants. Attempts have been made to use the ratio of the coupling constants of vicinal protons of adjacent bonds as an aromaticity index. This approach is based on the dependence of the coupling constants on bond length and thus bond order. If the bonds in the ring are completely equal, as in benzene, the ratio of the constants $J_{rel} = 1$. The value of J_{rel} should decrease with increasing bond alternation, thereby indicating a diminution of aromaticity. For example, in pyridine, $J_{23} = 4.86$ and $J_{34} = 7.66$ Hz. Hence, $J_{rel} = J_{23}/J_{34} = 0.63$ and $J_{rel} = J_{34}/J_{45} = 1.0$. The mean value of J_{rel} is 0.81, indicating significant but reduced aromaticity for pyridine. On the other hand, in 1-methylphosphole, $J_{23} = 7.2$ and $J_{34} = 1.9$ Hz. The ratio of the constants is 0.26, which indicates dienic nature for the system and very low aromaticity.

However, the J_{rel} index has not found broad application as an aromaticity criterion since J^{H-H}_{ortho} constants depend not only on the extent of delocalization of the π-electrons, but also on the dihedral angle between the adjacent C—H bonds and on a series of other factors. The dihedral angle is a function of the ring geometry. This explains why the parameter J_{rel} is unsuitable for the comparison of the aromaticities of heterocycles differing in ring size, ring type, and the number of heteroatoms.

Padgett et al. [90] attempted to reduce the effect of geometrical and other factors on the coupling constants to a minimum by studying a series of compounds with similar structure (Table 12). In the original work, values for $J_{rel} = J_{23}/J_{34}$ were calculated for the diene system of the six-membered ring and were found equal to 0.55 for 84, 0.61 for 85, 0.71 for 86, 0.73 for 87, and 0.74 for 88. This calculation is not completely accurate since the constants for the formal double bonds J_{12} and J_{34} differ markedly for five of the six compounds selected. Hence, the averaged value $\bar{J}_{rel}$, which would appear to be more correct, is also given in Table 12.

The J_{rel} values do not reflect the aromaticity of the system as a whole and characterize only the extent of the delocalization of π-electron density in the six-membered ring. The results obtained give a completely consistent picture of the differences in the cyclic conjugation of these compounds. They indicate, for example, the low aromaticity of isoindole derivative 88 and 1,2-dihydropyridine 84 and the relatively effective π-electron delocalization in indolizine 28, 4-quinolizone 87, and especially 86. For the three latter compounds, bipolar structures such as 86a make a significant contribution to the resonance hybrid:
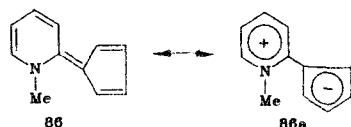

It would appear incorrect to give an absolute sense to these J_{rel} values and compare them, for example, with the J_{rel} value for pyridine (0.81). Pyridine, whose aromaticity is undoubtedly greater than for any of the compounds given in Table 12, has significantly different geometry and π-bond system.

4.3. Energy Criteria

In the past 15 years, considerable progress has been achieved in the development of energy criteria for aromaticity largely due to the work of Dewar. Many authors now regard the energetic approach as the most rigorous and promising method. The different thermodynamic stability of aromatic, nonaromatic, and antiaromatic systems is the basis for the development of energy criteria. Since the term "stability" permits equivocal interpretation, it requires explanation.

4.3.1. Thermal Stability of Heteroaromatic Compounds.
For synthetic chemists, the stability of a compound implies primarily the ability to "hold it in one's hands." Experiments have shown that the vast majority of aromatic compounds satisfy this requirement, i.e., maintain their stability for a prolonged period under ordinary conditions. In contrast, antiaromatic systems, as a rule, are unstable. Upon isolation, they tend to undergo oxidation, decomposition, polymerization, and isomerization. In most cases, the essence of their transformations is related to the tendency of the molecule to avoid the energetically unfavorable 4n π-electron conjugation at all costs. A typical example may be found in the following isomerizations of derivatives of 1,2-diazepine 89 [91], 1,4-dihydropyrazine 90 [92], and the 4H-pyran anion 91 [93]:
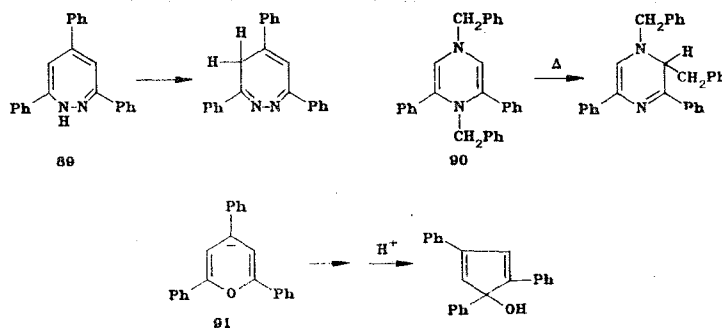
Similar valence isomerizations are also possible for nonaromatic π-systems as well as for systems with reduced aromaticity. Since the process occurs in these cases with a significant rate only upon heating, the thermal stability of these compounds is used as a criterion for their relative aromaticity. Thus, upon heating, 10π-electron heteronines 92 are converted

X	CH_2	O	NH	NMe	NCH_2Ph	NCO_2Et	NCOMe	NSO_2Ph
$\tau_{1/2}$ (50°)	10	3	$6 \cdot 10^3$	240	70	14	13	8

to the bicyclic structure 93 (Table 13). For the nonaromatic initial hydrocarbon, cyclo-nonatetraene, the half-life is 10 min at 50°C. This transition occurs even more readily for oxonine 39d which indicates its olefinic nature. On the other hand, azonine 39a is thermal-ly stable, which indicates its aromatic nature. What is the explanation for the broad range of stabilities for N-substituted azonines? The following rule holds for heteroaromatic com-pounds: for all other conditions similar, aromaticity is greater with decreasing electro-negativity of the heteroatom. This specifically accounts for the extremely high aromaticity of thiophene and the low aromaticity of furan, as well as the lack of aromaticity for oxon-ine. The pyrrolic nitrogen atom is less electronegative than the oxygen heteroatom. Thus, aromaticity decreases such that pyrrole > furan and azonine > oxonine. However, the electro-negativity of nitrogen may be increased by the attachment of electronegative groups such as the benzosulfonyl, acetyl, ethoxycarbonyl, and benzyl groups. Thus, a drop in heterocyclic aromaticity should be found for the N-substituted azonines presented in Table 13. Since the methyl group is not electron-withdrawing, it is not clear at first glance why there should be a large difference in stability between azonine and 1-methylazonine. This discrepancy is attributed to the important role of the nonbonding interactions of the N-substituent with the α-hydrogen atoms of the ring for rings of this size, leading to a distortion of the planar geometry. In addition to electronegativity, this factor likely accounts for the diminution of the aromaticity of other N-substituted azonines. The combined action of these two effects may also explain the much greater thermal stability of the N-anion of azonine relative to azonine itself [15, 16].

There thermal stability of heteronines gives a very clear and consistent indication of their relative aromaticity. Nevertheless, this method for the evaluation of aromaticity is not general. Indeed, quite a few rather stable antiaromatic structures and unstable arom-atic structures have been reported. It is not surprising that this essentially chemical in-terpretation of the term "stability" cannot satisfy the theoretical chemist (see, for example, the discussion of Anastassiou [16] on the correctness of the evaluation of the aromaticity of heteronines on the basis of their thermal stability). A more rigorous term is taken as an index of the stability of conjugated π-systems in theoretical organic chemistry, namely, the resonance energy which is the difference between the electronic energies (total energies or only their π-electron components) of the actual molecule and of a hypothetical limiting structure with localized bonds.

Many methods have been given for the calculation of resonance energy [4]. All these methods may be classified as either purely theoretical or semiempirical. In the former case, the energies of the actual molecule and of the limiting structure are calculated by a quantum mechanical method. In the latter case, the energy of the actual molecule is found experi-mentally (usually through the heats of combustion or hydrogenation), while the energy of the localized structure is calculated using an additive scheme and standard values of the ener-gies of isolated bonds or the heats of hydrogenation of an isolated double bond. The term found in the semiempirical approach is usually called the empirical resonance energy (ERE).

Since the localized structure does not actually exist, the major difficulty in finding the resonance energy lies in the proper selection of this structure and the reliable deter-mination of its energy. The classical Hueckel method for calculating the resonance energy when the localized structure is considered to consist of pure single and double bonds gives an incorrect order of the relative aromaticities of compounds and overestimates the stabil-ity of nonaromatic conjugated structures. A solution was found for this problem by Dewar

TABLE 14. Empirical Resonance Energies (kJ/mole) [95-97]

Compound	ERE	Compound	ERE	Compound	ERE
Benzene	150,2	Pyridazine	51,5	Tetrazole	231,0
Pyrine	116,7	Pyrazine	33,9	Indole	217,6
Quinoline	202,5	Pyrimidine	33,5	Carbazole	397,1
Thiophene	121,8	Pyrazole	112,1	Indazole	246,9
Pyrrole	90,4	Imidazole	53,1	Benzimidazole	203,8
Furan	67,8	1,2,4-Triazole	83,7	Benzotriazole	346,9

[43, 94], who proposed that the model for the localized structure be a conjugated polyene, in which each single bond in fact have a certain π-component. The three most common variants of resonance energy are empirical values obtained from heats of combustion, Dewar resonance energies, and Hess-Schaad resonance energies.

4.3.2. Empirical Resonance Energies. Most of the ERE given in the literature for heterocycles were obtained from heats of combustion. The data of different authors for the same compounds (a summary of these values is given in the review by Katritzky [4]) often differ considerably, which is a consequence of the different methods for evaluating the heats of combustion of the localized structure. A notion of the problems encountered in analyzing ERE values is given by representative data presented in Table 14.* In some cases, the ERE values give the proper aromaticity sequence in accord with other criteria (thiophene > pyrrole > furan; tetrazole > pyrazole > imidazole; and pyridine > diazines), but in other cases they are clearly inconsistent. It is unlikely that furan is more aromatic than imidazole and diazines and thiophene is more aromatic than pyridine. The resonance energy of diazines is unreasonably low and the stability of tetrazole and condensed systems which cannot be more aromatic than benzene is clearly overestimated.

4.3.3. Dewar Resonance Energies. According to Dewar, resonance energies are calculated from the heats of atomization ΔH_a. For a real molecule, the value for ΔH_a is taken from experimental heat of combustion data. If such data are lacking, they are calculated quantum mechanically taking account of both the σ- and π-electrons. The agreement of the calculated and experimental data, as a rule, is very good. Dewar introduced a fundamental improvement in calculations for the heats of atomization of localized structures. Acyclic polyenes or heteropolyenes were taken as models for such structures, which gives very good results. The bonds in such polyenes are localized in the sense that their energy remains unchanged in going from one molecule to another. This circumstance permitted the derivation of the bonds encountered in polyenes (Table 15) and use them in additive calculations for ΔH_a for localized structures. For example, the heat of atomization for the Kekulé structure of pyridine is calculated as follows:

$$\Delta H_{a(\,log)} = 2E_{C=C} + 2E_{C-C} + E_{C-N} + E_{C=N} + 5E_{C-H} = 2 \cdot 5.4648 +$$
$$2 \cdot 4.3860 + 3.7794 + 5.2120 + 5 \cdot 4.4375 = 50.8805 \ eV.$$

The experimental value ΔH_a = 51.80 eV. Hence, the Dewar resonance energy (DRE) is 51.80 − 50.88 = 0.92 eV or 89.1 kJ/mole. To compare the aromaticity of π-electron systems with different numbers of π-electrons, Dewar introduced the REPE (resonance energy per π-electron) index.

Table 16 shows that 4π-electron antiaromatic heterocycles such as 2-azirine, oxirene, and azete have negative resonance energies, which is in accord with their instability. The DRE values give important information on the effect of benzo-annelation on aromaticity. The REPE index indicates that aromaticity falls in the series: pyridine > quinoline > isoquinoline > acridine and pyrazine > quinoxaline, i.e., benzo-annelation destabilizes both azines and arenes. On the other hand, in the case of five-membered heterocycles, benzo-annelation at the C_α–C_β bond leads to stabilization of the molecule: carbazole > indole > pyrrole. Only compounds with quinoid structure such as isoindole or isobenzofuran, in which the benzo-

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*Although, in principle, the resonance energy of an aromatic system is a negative quantity and the resonance energy in an antiaromatic system is a positive quantity, we follow the practice of Dewar and use the opposite signs.

TABLE 15. Polyene Bond Energies (eV) Used in Additive Calculations of Heats of Atomization according to Dewar [98]

Bond	Energy	Bond	Energy	Bond	Energy
C—C	4,3860	C≃N	5,2120	C=O	6,7442
C=C	5,4648	C—N̈	3,5061	Ö—H	4,7600
C—H	4,4375	N—H	4,0025		
C—Ṅ	3,7794	C—O	4,1400		

TABLE 16. Dewar Resonance Energies and REPE Indices (kJ/mole) [98, 99]

Compound	DRE	REPE	Compound	DRE	REPE
2-Azirine	−28,0	−7,0	Benzofuran	101,5	10,2
Oxirene	−23,0	−5,8	Isobenzofuran	26,1	2,6
Azete	−64,9	−16,2	Pyridine	89,1	14,9
Pyrrole	22,2	3,7	Quinoline	142,7	14,3
Indole	125,6	12,6	Isoquinoline	142,7	14,3
Isoindole	74,4	7,4	Acridine	172,8	12,3
Benz[e]indole	179,8	12,8	Pyrazine	71,5	11,9
Benz[f]indole	164,3	11,7	Quinoxaline	117,6	11,8
Benz[g]indole	179,8	12,8	1,5-Naphthiridine	138,9	13,9
Carbazole	200,1	14,3	1,8-Naphthiridine	152,3	15,2
Furan	18,0	3,0	Indolizine	28,9	2,9

annelation is at the C_β—C_β bond are less stable than their noncondensed precursors. In the dibenzo derivatives of five-membered heterocycles, greatest stability is found for structures such as carbazole and least stability is found for linear structures such as benz[g]-indole. Angular benz[e] indole and benz[f]indole occupy intermediate positions. In analyzing the effect of benzo-annelation on aromaticity, we should bear in mind the possible role of other factors, especially steric effects. For example, the heterocycle in 4,5-benzoazonine 94, in contrast to 1H-azonine 39a, displays clear polyene character as indicated by its PMR spectrum [16]. This is a consequence of the strong steric interaction of the two pairs of peri-protons, which plays an especially important role in macrocycles. As a result, the heterocycle significantly alters its geometry and becomes nonplanar.
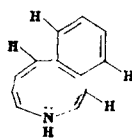
94

4.3.4. Hess—Schaad Resonance Energy. Hess and Schaad [100] showed that the simple Hueckel method (SHM) also leads to resonable results for resonance energies if, following Dewar, the corresponding polyene is taken as the localized model. Since π-electrons are not taken into account in the simple Hueckel method, the energies of a large number of C–C, C–N, and C–O bond types depending on their multiplicity, number, and position of hydrogen atoms, and nature of the heteroatom must be used in calculating the energy of the localized structure. The π-bonded components of the energies of these bonds are given in Table 17.

The π-electron energy of an actual molecule according to Hess and Schaad is determined by the usual method by solving the Hueckel determinant taking account of the Coulomb (α) and resonance (β) integrals derived from the experimental values for the heats of atomization:

$$\alpha_C = \alpha^0 + 0.38\beta^0; \quad \alpha_N = \alpha^0 + 1.5\beta^0; \quad \alpha_O = \alpha^0 + 2.0\beta^0;$$

$$\beta_{C-N} = 0.7\beta^0; \quad \beta_{C-N} = 0.9\beta^0; \quad \beta_{C-O} = 0.34\beta^0; \quad \beta_{N-N} = 1.27\beta^0,$$

TABLE 17. π-Bond Components (in β units) for Calculation
of the Localized Structure Energies according to Hess and
Schaad [100-102]

Bond	E^π	Bond	E^π	Bond	E^π
CH₂=CH	2,0000	C—ṄH₂	0,3096	CH—Ṅ	0,6000
CH=CH	2,0699	CH—Ṅ	0,3101	C—Ṅ	0,5986
CH₂=C	2,0000	C—ṄH	0,3137	Ṅ—ṄH₂	1,0332
CH=C	2,1716	C—Ṅ	0,3187	Ṅ—ṄH	1,0444
CH—CH	0,4660	CH=ṄH	1,5492	Ṅ—Ṅ	1,0251
CH—C	0,4362	CH₂=Ṅ	1,1010	CH—ÖH	−0,0302
C—C	0,4358	C=ṄH	1,6025	CH—Ö	−0,0259
CH—ṄH₂	0,2745	CH=Ṅ	1,2296	C—ÖH	0,0273
CH—ṄH	0,2980	C=Ṅ	1,3231	C—Ö	0,0374

TABLE 18. Hess-Schaad REPE Aromaticity Indices [100-103]

Compound	REPE (β)	Compound	REPE (β)
Benzene	0,065	Cyclo[3.2.2]azine 29	0,040
Pyridine	0,058	Cyclo[3.3.3]azine 58	0,001
Pyrimidine	0,049	Azete	−0,160
Pyrazine	0,049	Azocine	−0,035
Quinoline	0,052	1H-Azepin	−0,036
Isoquinolie	0,051	Pyrazole	0,055
Phenanthridine	0,052	Imidazole	0,042
1,5-Naphthiridine	0,047	Benzimidazole *	0,050
1,8-Naphthiridine	0,047	Indazole*	0,050
Pyrrole	0,039	1H-Naphtho[1,2-d]imidazole 77 *	0,048
Indole	0,047	1H-Naphtho[2,3-d]imidazole 78 *	0,046
Isoindole	0,029	Perimidine 79 *	0,039
Indolizine	0,027	Furan	0,007
Carbazole	0,051	Thiophene	0,032

*The REPE values for these compounds were calculated by
the present author.

where α° and β° are the standard Coulomb and resonance integrals, respectively. As an
example, let us calculate the resonance energy of the pyrazole molecule according to Hess
and Schaad. The following values x are the roots of the determinant corresponding to the
delocalized structure: −2.6867, −1.1827, and −0.5395 (we limit ourselves to the bonding
orbitals). Hence $E^\pi{}_{del}$ = 6α + 8.818β. In calculating the Hess—Schaad resonance energy, the
so-called π-bonding energy is used instead of the total π-electron energy. This term is ob-
tained by subtracting the Coulomb integrals of the heteroatoms from the $E^\pi{}_{del}$ value obtained.
For a pyrrole-type heteroatom which provides two electrons to the π-system, the Coulomb inte-
gral is multiplied by 2:

$$E^\pi_{del} (b) = 8.818\beta - (1.5 \cdot 2 + 0.38)\beta = 5.438\beta.$$

The π-bonding energy of the localized structure is calculated from the data in Table 17:

$$E^\pi_{loc} (b) = E^\pi_{CH=CH} + E^\pi_{CH-CH} + E^\pi_{CH=N} + E^\pi_{CH-NH} + E^\pi_{NH-N} =$$
$$(2.0699 + 0.4660 + 1.2296 + 0.2980 + 1.0444)\beta = 5.108\beta.$$

Hence, the resonance energy

$$E_R = E_{del}{}^\pi(b) - E_{loc}{}^\pi(b) = 5.438\beta - 5.108\beta = 0.330\beta,$$

and the REPE index is equal to 0.330β/6 = 0.055β. The REPE indices for some other hetero-
cycles are given in Table 18. With a few exceptions, the calculated resonance energies ac-

cording to Dewar and to Hess and Schaad give the same order of heterocyclic aromaticity. Hess and Schaad extended their method for sulfur-containing heterocycles [103], but the results obtained were not sufficiently correct. For example, the aromaticity of thiophene was clearly underestimated (Table 18). Their method also apparently underestimates the stability of oxygen-containing systems.

4.4. Chemical Criteria

4.4.1. Substitution and Addition Reactions. The major chemical property of aromatic systems which differentiates them from polyenes is the tendency to undergo substitution reactions rather than addition. In reactions, aromatic compounds are said to be "true to their type" [104]. Although the vast majority of substitution reactions begin with an addition step, the adduct formed is usually readily aromatized. The capacity to retain their type, which follows from the stability of aromatic structures, is the most convincing evidence of aromaticity for the majority of chemists. The discussion of this subject at the First Congress on the Chemistry of Heterocyclic Compounds relative to the aromaticity of uracil [105] is illuminating. In his report, Pfleiderer characterized the $C_{(4)}-C_{(5)}$ bond in uracil as olefinic on the basis of the chemical shifts of the 4- and 5-H protons (δ 7.40 and 5.44 ppm) and uracil itself as a nonaromatic compound. However, most of the participants in the discussion nevertheless concluded that uracil should be considered an aromatic compound since its adducts such as 96 tend to undergo spontaneous aromatization to form 5-substituted uracils 97:
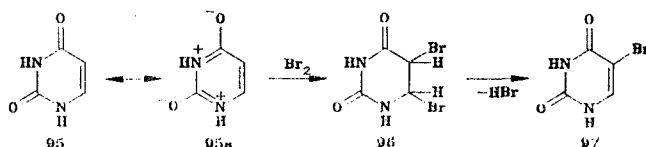

This conclusion is supported by the very high $\Delta\bar{N}$ structural index for uracil aromaticity (0.27), which corresponds to thiophene aromaticity (Table 7). The existence of aromaticity for uracil may be described qualitatively as the result of amide resonance, which enhances the contribution of structure 95a.

An opposite example is found in antiaromatic dibenz[b,f]oxepin 98. The adduct of this compound with bromine does not undergo spontaneous aromatization and HBr may be eliminated only upon the action of potassium tert-butylate [106]:
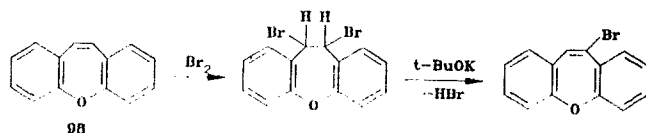
Do these considerations permit us to use the facility of substitution reactions as a criterion for relative aromaticity? We should note that there have been many such attempts, although, as we have already mentioned, there are fundamental difficulties in this approach. Let us examine, for example, the electrophilic substitution reaction. In order to develop a comparable aromaticity index, we should select a standard electrophile and be certain that, for a given group of compounds, the reaction proceeds by precisely the same mechanism. Let us assume that such an electrophile has been selected (say Br_2 or D^+) and the reaction in all cases proceeds by S_E2 addition–elimination:
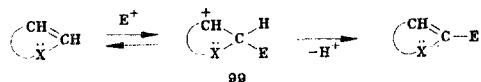
The rate-limiting step in S_E2 reactions is almost always the formation of σ-complex 99, while the aromatization step with loss of a proton proceeds relatively rapidly (Fig. 3).

Hence, the σ-complex will be formed more readily (and the reaction is accompanied by the destruction of the aromatic system) with decreasing aromaticity of the starting compound. An index of the facility of formation of the σ-complex is the difference in the free energies of the starting molecule (ΔG_1°) and of the transition state TS-1 (Fig. 3) which lies on the pathway to the σ-complex (ΔG_2°):
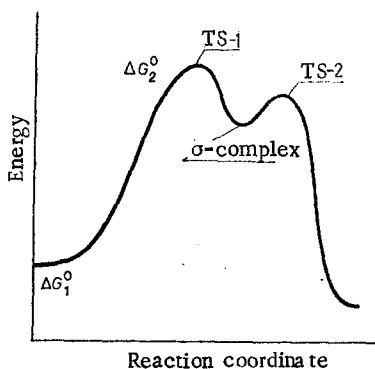
Fig. 3. Typical potential energy curve for S$_E$2 aromatic electrophilic substitution reactions.

$$\Delta\Delta G^0 = \Delta G_2{}^0 - \Delta G_1{}^0 = (\Delta H_2{}^0 - T\Delta S_2{}^0) - (\Delta H_1{}^0 - T\Delta S_1{}^0);$$

$$\Delta\Delta G^0 = (\Delta H_2{}^0 - \Delta H_1{}^0) - T(\Delta S_2{}^0 - \Delta S_1{}^0). \qquad (6)$$

A whole series of assumptions is ordinarily required in order to use the difference $\Delta\Delta G^0$ as an aromaticity criterion. The most important of these assumptions are: 1) the structure of the transition state TS-1 is close to the structure of the σ-complex, 2) the term $(\Delta H_2{}^0 - \Delta H_1{}^0)$ in Eq. (6) depends only on the π-electron component of the total energy in going from compound to compound (the change in the σ-component during the reaction for all reactions is considered approximately constant), and 3) the term $T(\Delta S_2{}^0 - \Delta S_1{}^0)$ remains constant for a group of similar compounds.

In practice, satisfying these and other conditions such as the absence of catalytic effects and similar polarizability and effective atomic charges is a difficult problem. Differences in solvation, which lead to violation of the third of the above conditions, are especially important. Thus, the facility of electrophilic substitution reactions in solution for five-membered heterocycles decreases in the following order: pyrrole >> furan > thiophene > benzene [107], i.e., the positions of pyrrole and furan are not in accord with their relative aromaticity derived from physical and energy criteria. It is now clear that the greater activity of pyrrole is related not so much to its high π-electron excess [108] or the change in the reaction mechanism from the usual S$_E$2 scheme to a radical–cation mechanism as to the more effective solvation of the corresponding transition complex. This is indicated by the finding that no such discrepancy between reactivity and aromaticity is found for electrophilic substitution reactions in the gas phase [109]: furan (5.2), 1-methylpyrrole (2.2), thiophene (1.0), pyrrole (1.0) (the relative rate of reaction with the tert-butyl cation is given in parentheses). We should note that the role of electrostatic factors is very large in the gas phase [110]. For example, this accounts for the high activity of 1-methylpyrrole relative to pyrrole (+I effect of the methyl group). Thus, the quantitative data given in parentheses for gas-phase substitution may be used as a quantitative criterion for aromaticity. In addition, although the order of the relative activity of five-membered heterocycles in the gas phase does not change upon variation in the electrophile, the rate ratios are strongly affected: Harder electrophiles level out the differences in reactivity [109].

The importance of the electrostatic factor (for any medium) is indicated by the circumstance that it is very difficult, if not completely impossible, to select a standard reagent for comparison of the aromaticity of π-excess and π-deficit heterocycles. The former react with electrophiles and do not undergo substitution reactions by the action of nucleophiles. The latter, on the other hand, react with nucleophiles and, under ordinary conditions, do not react with electrophiles. For example, pyridine is nitrated above 300°C, while the nitration of pyrrole occurs even below room temperature. The role of the entropy factor becomes enormous for such differences in temperature without even considering catalytic effects (azines almost always form a coordination complex with electrophiles due to the unshared electron pair of the heteroatom).

In regard to the differences in reactivity between π-excess and π-deficit systems, we must discuss an imprecise and, unfortunately, still extremely common notion. Historically, the theory of aromaticity developed mainly in regard to hydrocarbons, for which electrophilic substitution is typical and not nucleophilic substitution (a proton is lost much more readily than a hydride ion). Thus, electrophilic substitution reactions specifically became

the major chemical test for aromaticity. However, in the case of π-deficit heterocycles, aromaticity is conveniently evaluated relative to nucleophilic substitution reactions which proceed by an addition—elimination mechanism. Disregard of this circumstance may lead to erroneous conclusions. Thus, in his monograph, Ivanskii [111] stated that since pyridine undergoes electrophilic substitution at the β-positions, these positions are more aromatic than the α- and γ-positions. First, aromaticity is the property of an entire π-system and not individual atoms. Second, reactions with nucleophilic reagents such as KOH, NaNH₂, and C₆H₅Li which replaced hydrogen in the α-positions rather than in the β-position, are more characteristic for pyridine.

Compounds with reduced aromaticity often form extremely stable addition products upon the action of various reagents. Thus, the adducts of furan with many electrophiles have been isolated or detected spectrally [112, 113]. Furan readily forms adducts with dienophiles which add at $C_{(2)}$ and $C_{(5)}$. Thiophene [114] and pyrrole [115, 116] undergo this reaction only with much greater difficulty. Nucleophilic addition to dienophiles which permits retention of aromatic ring structure is more characteristic for pyrrole. Analogously, pyridine does not react with simple dienophiles under ordinary conditions but weakly aromatic 2-pyridone forms Diels—Alder adducts [117]. Attempts were made to use the tendency to undergo addition reactions as a quantitative aromaticity index. In particular, the energies for monocentric or dicentric localization was proposed as aromaticity indices (see, for example, the work of Kruszewski and Krygowski [118]). However, localization energies give relatively good results only in the case of aromatic hydrocarbons [118]. Attempts to extend this approach to heterocycles were unsuccessful. For example, the monocentric electrophilic localization energies for benzene and the pyridinium ion are virtually the same [119], while the dicentric localization energies for benzene and pyridine are also almost identical [118]. The dicentric localization energies calculated for heterocyclic compounds by Krygowski [120] led to an order of aromaticity which differs from all other aromaticity scales.

4.4.2. Aromatization of Hydride Adducts.

Although the products of the addition of electrophiles and nucleophiles to heteroaromatic compounds are usually readily aromatized, such adducts with considerable stability are also encountered. In particular, this is true for the hydride complexes of heteroaromatic cations such as 4H-pyran of 1,2-dihydroquinoline. Many acceptors have been proposed for the hydride ion removal, i.e., for the aromatization of such compounds [121, 122]. Is the hydride lability of hydride adducts suitable for use in the evaluation of the relative aromaticity of heteroaromatic cations? With other conditions equal, ready loss of a hydride ion should correspond to greater aromaticity. Unfortunately, there is very little quantitative and especially kinetic data on hydride transfer encompassing a sufficient range of compounds. Most of the information available is derived from experiments on the crossed hydride transfer between pairs of heteroaromatic cations and their conjugate hydride complexes. For example, pyrilium cations dehydrate thiapyrans in accord with the following scheme [123, 124]:

Since the equilibrium for this reaction is shifted strongly toward the right, we may assume that the thiapyrilium cation is more aromatic than the pyrilium cation. There is also independent although limited evidence [77] which does not contradict this conclusion. The data for hydrogenated azoles [121, 125, 126], azines [127, 128], pyrans and pyran analogs [123, 124] indicate the following series for hydride lability:

for X = NR, O, S, Se

745
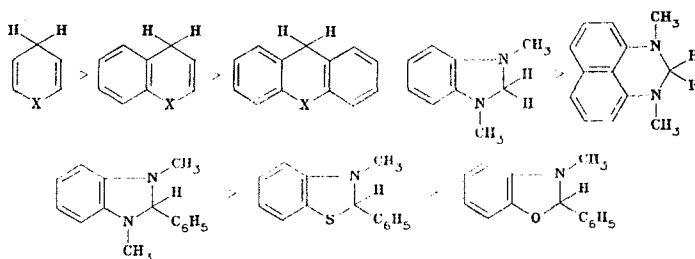
The first of these series indicates decreasing aromaticity in going from monocyclic cations to their benzo- and dibenzo-derivatives, which is in accord with the resonance energies of pyridine, quinoline, and acridine (Table 15). Depending on the nature of the heteroatom, the lability decreases in the following order: $S > O > Se$ (there are no comparable data for dihydropyridines).

In the second series, the greater aromaticity of the benzimidazolium cation relative to the perimidinium cation is also in accord with the data derived by other methods. The sharp decrease in hydride lability found for 1-methyl-3-phenyl-2,3-dihydroperimidine is striking [126]. This effect is explained by the enhanced electronegativity of the nitrogen atom by the action of the N-phenyl group which, as already noted, leads to a diminution of aromatic properties (in this case, for the 1-methyl-3-phenylperimidinium cation).

The aromaticity of benzazolium cations, as seen in the last series of compounds, decreases in the following sequence relative to the heteroatom: $N > S > O$, i.e., the order of the nitrogen and sulfur heterocycles here differs from that in the thiophene-pyrrole pair. The relative aromaticity of the pyridinium and thiapyrilium rings is of interest in this regard. The data of Palmer et al. [77] may be interpreted to imply greater aromaticity for the thiapyrilium cation although independent confirmation of this conclusion is required.

Despite the apparent qualitative relationship between the hydride lability of hydride complexes and the aromaticity of the conjugate cations, care should be employed in using this method for the evaluation of aromaticity as for any such method. It would appear more logical to use aromaticity indices derived from structural, magnetic, and energy data for understanding the reactivity of these compounds than those derived by chemical methods.

CONCLUSIONS

Aromaticity is a property of the ground state of cyclic π-electron structures which entails enhanced thermodynamic stability, planar geometry with little bond alternation, and the capacity to support an induced ring current. Current aromaticity criteria are based primarily on these properties. The energy criteria for aromaticity (resonance energy) have received the greatest quantitative elaboration. Magnetic criteria are quite important, especially as a diagnostic experimental test. Structural indices are also valuable. However, these latter two approaches have inherent limitations. We should stress that even now there are not that many discrepancies between the conclusions derived from energy criteria and those derived from structural and magnetic criteria. This indicates a series of firmly established features for the variation of aromaticity in the heterocyclic series. Thus, structures with a pyridine-type heteroatom as a rule are more aromatic than the corresponding structures with pyrrole-type heteroatom. The effect of benzo-annelation on the aromaticity of π-excess and π-deficit heterocycles and the dependence of aromaticity on the nature of the heteroatom in heterocycles of the pyrrole-thiophene group were explained.

In some cases, the relative aromaticity of a specific group of compounds may be evaluated rather accurately according to their chemical properties. However, in principle, it is more correct to use aromaticity indices derived from theoretical or physical methods for the interpretation of the reaction of heterocyclic molecules.

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