

## THE AROMATICITY OF HETEROCYCLES CONTAINING THE IMINE NITROGEN

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**Abstract**—The method of predicting aromaticity based on simple Hückel calculations<sup>1</sup> is applied to heterocyclic systems which contain the imine nitrogen. The necessary heteroatom integrals were determined from thermochemical data. Replacement of C by N in alternant systems produced no dramatic changes, but in nonalternants the effect can be large and unexpected as in the azapentalenes where interesting synthetic possibilities are suggested.

### INTRODUCTION

We have shown previously that the Hückel energies of acyclic conjugated hydrocarbons<sup>1</sup> and of acyclics which contain certain heteroatoms<sup>2-4</sup> are additive. That is, their Hückel energies can be obtained very accurately by merely adding  $\pi$ -bond energy terms. This suggests the definition, as proposed by Dewar,<sup>5</sup> of resonance energy as the difference between the energy of the molecule and the energy of an additive reference structure. For example, the resonance energy of benzene is obtained by subtracting from the Hückel  $\pi$ -binding energy the energy of the model compound cyclohexatriene. This resonance energy represents the additional stabilization of benzene over what it would have had if it behaved like an acyclic polyene.

In contrast to delocalization energies, which are calculated with an ethylene reference structure, resonance energies calculated as described above appear to correlate extremely well with experimental aromaticity for a wide variety of both alternant and nonalternant hydrocarbons<sup>6,7</sup> as well as for heterocycles.<sup>2-4</sup> Furthermore this method accommodates the current idea that some cyclic systems are destabilized relative to the acyclic polyenes, i.e. they are antiaromatic, as in the case of cyclobutadiene.<sup>8</sup> In fact, what is found is a continuum of aromaticities for cyclic systems ranging from very antiaromatic (cyclobutadiene) to non-aromatic (fulvene) to very aromatic (benzene).

We have also shown that the simple Hückel method can be used to obtain quite accurately the heats of atomization of conjugated systems.<sup>2-4,9</sup> This allows a direct quantitative comparison between our theoretical resonance energies and experimental heats of atomization.

The present paper describes the extension of this method to heterocycles containing the imine nitrogen as in pyridine. Such an extension to a new system requires three steps. First, values for any resonance and Coulomb integrals must be gotten. Second, using these integrals, the Hückel  $\pi$ -binding energies of acyclics containing the new atom are computed to see whether they can be

approximated accurately as the sum of empirical bond energy terms. Finally, if the second step succeeds, the resulting bond energy terms are used to compute energies of reference structures and then resonance energies for cyclic compounds.

### RESULTS AND DISCUSSION

*Evaluation of Coulomb and resonance integrals.* Although there are a number of determinations of the imine nitrogen Coulomb and resonance integrals

$$\alpha_N = \alpha_C + h_N \beta_{CC} \quad (1)$$

$$\beta_{CN} = k_{CN} \beta_{CC} \quad (2)$$

in the literature, none were determined systematically from ground state experimental data. Since resonance energy is a ground state property we felt it would be best to fix the nitrogen integrals in this way. We choose to use, in particular, the ground state heat of atomization ( $\Delta H_a$ ). As for hydrocarbons,<sup>9</sup> the heat of atomization of a conjugated compound containing the imine nitrogen can be written

$$\Delta H_a = -(n_{CC} E_{CC} + n_{CH} E_{CH} + n_{CN} E_{CN} + P \cdot \beta) \quad (3)$$

where  $P \cdot \beta$  is the  $\pi$  binding energy of the compound,  $n_{CC}$  is the number of C-C bonds it contains,  $E_{CC}$  is the *sigma* energy of each such bond, and analogously for  $n_{CH}, \dots, E_{CN}$ .

Since there are relatively few thermochemical data available for such compounds, we decided to include also compounds containing the imine-amine bond. Equation (3) then becomes

$$\Delta H_a = -(n_{CC} E_{CC} + n_{CH} E_{CH} + n_{CN} E_{CN} + n_{NH} E_{NH} + n_{CN} E_{CN} + n_{NH} E_{NH} + P \cdot \beta) \quad (4)$$

and three additional integrals are needed in the computation of  $P \cdot \beta$

$$\alpha_N = \alpha_C + h_N \beta_{CC} \quad (5)$$

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$$\beta_{CN} = k_{CN}\beta_{CC} \quad (6)$$

$$\beta_{NN} = k_{NN}\beta_{CC}. \quad (7)$$

Previously determined<sup>2</sup> values of  $E_{CC}$ ,  $E_{CH}$ ,  $E_{CN}$ ,  $E_{NH}$ ,  $h_N$  and  $k_{CN}$  were used and  $h_N$ ,  $k_{CN}$ ,  $k_{NN}$ ,  $E_{CN}$ ,  $E_{NN}$  and  $\beta$  were evaluated as follows. An initial guess was made for  $h_N$ ,  $k_{CN}$  and  $k_{NN}$ , and the  $\pi$  binding energy in units of  $\beta$  (i.e.  $P$  in Eqn (4)) was calculated by the Hückel method for the six compounds in Table 1. These  $\pi$  binding energies were substituted into Eqn (4), and the least squares method used to fit calculated to experimental  $\Delta H_a$ 's. The pattern search technique<sup>10</sup> was then employed to vary  $h_N$ ,  $k_{CN}$  and  $k_{NN}$  and minimize the sum of squares of the differences between experimental and calculated heats of atomization. The resulting heats of atomization are shown in Table 1 and the best parameters in Table 2.

We note that this determination is based on a minimal number of experimental heats of atomization. Ideally one would like thermodynamic data for more and for a much wider range of compounds, but unfortunately they are not available. Nevertheless, the results obtained appear to be reasonable when compared with other estimates.<sup>11,12</sup>

**Empirical bond energy terms.** To obtain resonance energies of heterocyclics which contain the imine nitrogen, the empirical additive  $\pi$ -bond energies must first be obtained from the energies of acyclics. That is, one must determine whether one can approximate the  $\pi$  binding energy accurately as a sum of empirical bond energies

$$P \cdot \beta \approx \sum_i n_i E_i^* \quad (8)$$

where  $n_i$  is the number of bonds of type  $i$  and  $E_i^*$  is an

Table 1. Observed and calculated heats of atomization

Compound	Obsd. (eV)	Calcd. (eV)	Diff. (eV)
Pyridine	51.84	51.82	0.02
Pyrimidine	46.51	46.52	-0.01
Pyrazine	46.51	46.51	0.00
Quinoline	85.34	85.34	0.00
Pyrazole	39.24	39.24	0.00
Benzpyrazole	72.77	72.78	-0.01

Table 2. Parameters obtained using the heats of atomization in Table 1

Parameter	Value
$h_N$	0.38
$k_{CN}$	0.70
$k_{NN}$	1.27
$E_{CN}$	-3.4725 eV
$E_{NN}$	-1.8045 eV
$\beta$	-1.3173 eV

empirical constant. The sum in Eqn (8) runs over all types of bonds in the molecule. We have done this not only for the C-N bonds, but also for the N-N bonds. As in the case of the hydrocarbons it was necessary to consider not just a single bond value and a double bond value, but to consider different types of each bond according to the number of attached p-centers as well as to their orientation. If one does this one finds there are five C=N bonds, two C-N bonds and three N-N bonds (Table 3). We chose a total of 74 acyclic compounds which contained one or more of the bonds listed in Table 3 and calculated their  $\pi$  binding energies. These with the previously determined empirical  $\pi$ -bond energies of C-C bonds<sup>1</sup> and the C-N bonds<sup>2</sup> were used to obtain the  $\pi$ -energies listed in Table 3. This was done in exactly the same manner previously described<sup>1,2</sup> and, as was the case with hydrocarbons, one of the  $\pi$ -bond energies had to be assigned arbitrarily due to linear dependence. This of course in no way affects the resonance energy values which follow. Because of this arbitrariness no particular physical interpretation of the bond energies should be attempted; they are to be used only in the computation of resonance energies. Again, as previously, the acyclics were found to be additive. The standard deviation between the Hückel and additive energies divided by the number of  $\pi$ -electrons was 0.0029 $\beta$ . This is quite an acceptable fit since, as will be seen, resonance energies per  $\pi$  electron for cyclic compounds turn out to be about an order of magnitude larger.

**Resonance energies.** The  $\pi$ -bond energies in Table 3 may now be used to calculate resonance energies of heterocyclics which contain the C-N and/or N-N bond. One merely determines the number of each type of bond in a resonance form of the heterocycle and sums the corresponding bond energies using Eqn (8). This sum is then subtracted from the Hückel  $\pi$ -binding energy of the heterocycle to give the resonance energy. Listed in Table 4 are the resonance energies and resonance energies per  $\pi$  electron (REPE) for a variety of imine containing heterocycles. The additive energies are an average of the energies of all resonance forms when more than one is possible. In no case were these individual additive energies for a given molecule significantly different.

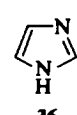
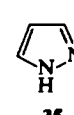
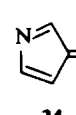
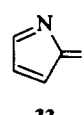
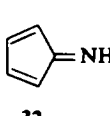
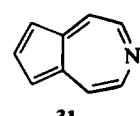
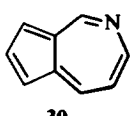
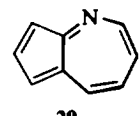
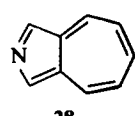
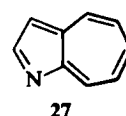
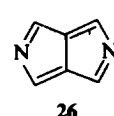
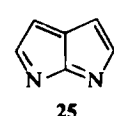
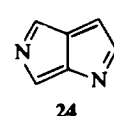
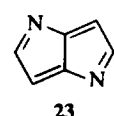
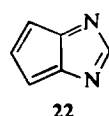
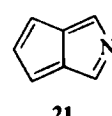
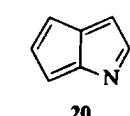
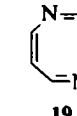
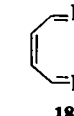
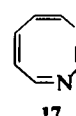
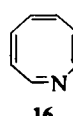
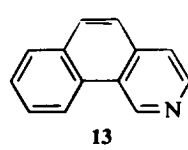
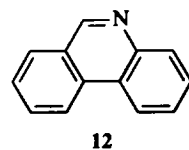
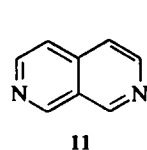
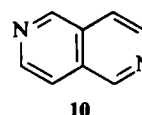
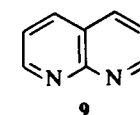
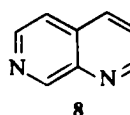
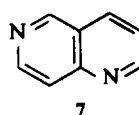
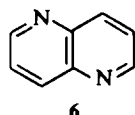
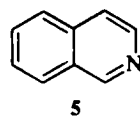
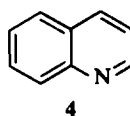
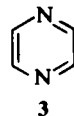
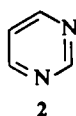
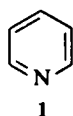
Table 3. Empirical  $\pi$ -bond energies

Bond type	$\pi$ -Bond energy ( $\beta$ )
CH=NH	1.5492
CH=N	1.1010
C=NH	1.6025
CH=N	1.2296
C=N	1.3231
CH-N	0.6000 <sup>a</sup>
C-N	0.5986
N-NH <sub>2</sub>	1.0332
N-NH	1.0444
N-N	1.0251

<sup>a</sup> Arbitrarily assigned.

Table 4. Resonance energies

Compound	$\pi$ -Binding energy ( $\beta$ )	Additive energy ( $\beta$ )	Resonance energy ( $\beta$ )	REPE ( $\beta$ )	Compound	$\pi$ -Binding energy ( $\beta$ )	Additive energy ( $\beta$ )	Resonance energy ( $\beta$ )	REPE ( $\beta$ )
1	7.249	6.901	0.348	0.058	19	8.570	8.731	-0.161	-0.020
2	6.492	6.195	0.297	0.049	20	9.719	9.932	-0.213	-0.027
3	6.488	6.195	0.293	0.049	21	9.831	9.890	-0.059	-0.008
4	12.978	12.462	0.516	0.052	22	8.969	9.268	-0.299	-0.037
5	12.939	12.425	0.514	0.051	23	9.001	9.268	-0.267	-0.033
6	12.264	11.793	0.471	0.047	24	9.096	9.226	-0.130	-0.016
7	12.232	11.756	0.476	0.048	25	8.983	9.268	-0.285	-0.036
8	12.226	11.756	0.470	0.047	26	9.177	9.184	-0.007	-0.001
9	12.261	11.793	0.468	0.047	27	12.773	12.468	0.305	0.031
10	12.186	11.718	0.468	0.047	28	12.654	12.426	0.228	0.023
11	12.194	11.718	0.476	0.048	29	12.595	12.468	0.127	0.013
12	18.742	18.010	0.732	0.052	30	12.635	12.426	0.209	0.021
13	18.707	17.976	0.731	0.052	31	12.581	12.426	0.155	0.015
14	3.726	4.366	-0.640	-0.160	32	6.889	7.081	-0.192	-0.032
15	3.206	3.659	-0.453	-0.113	33	6.850	6.800	0.050	0.008
16	9.157	9.437	-0.280	-0.035	34	6.784	6.772	0.012	0.002
17	8.558	8.731	-0.173	-0.022	35	5.438	5.108	0.330	0.055
18	8.376	8.731	-0.355	-0.044	36	4.747	4.496	0.251	0.042



The REPE's of alternant systems 1-19 closely parallel those of the analogous hydrocarbons. Compare for instance the REPE of pyridine (0.058 $\beta$ ) with that of benzene (0.065 $\beta$ ). The only significant conclusion which really can be made about these results is that the behavior of these systems should be closely similar to those of the corresponding hydrocarbons. This is in fact well known to be the case.

However, the nonalternants (20-34) are more interesting. Note the range in REPE for the aza- and diazapentalenes (20-26). Compound 22 is predicted to be highly antiaromatic (-0.037 $\beta$ ) while 26 is predicted to be nonaromatic (-0.001 $\beta$ ), and compare this with the REPE of pentalene (-0.018 $\beta$ ). This strongly suggests that the choice of placement of a nitrogen in the pentalene system may affect the stability of the system. The recent preparations of alkyl-substituted pentalenes<sup>13,14</sup> appear to make the possibility of testing these predictions synthetically possible.

A similar result is found with the azaazulenes. The substitution of a nitrogen into the azulene system definitely appears to affect the REPE of the resultant compound depending upon its placement. Even more dramatic is the case of the azafulvenes (32-34). Fulvene itself is nonaromatic (-0.002 $\beta$ ). However, substitution for the *exo*-carbon (32) leads to a highly antiaromatic system (-0.032 $\beta$ ). On the other hand, substitution in the ring does not really change the REPE from that of the hydrocarbon significantly.

We are grateful to a referee for point out that many of the trends above can be predicted easily by treating nitrogen substitution as a perturbation on the corresponding hydrocarbon. The resulting changes in Coulomb and resonance integrals are related to charge and bond order,

$$\frac{\partial E_{\pi}}{\partial \alpha_i} = q_i \quad (9)$$

$$\frac{\partial E_{\pi}}{\partial \beta_{ij}} = \rho_{ij} \quad (10)$$

Thus the effect on REPE of changing  $\alpha_i$  is approximately

$$\Delta \text{REPE} = (q_i - q_i(\text{ref})) \Delta \alpha_i \quad (11)$$

The reference structure is a hypothetical polyene. It is therefore alternant and  $q_i(\text{ref}) = 1$ . If the compound in question is also alternant,  $q_i = 1$ , and  $\Delta \text{REPE} = 0$ . The

effect of changing  $\beta$ , is more difficult to estimate. If we may neglect it,<sup>15</sup> then the entire effect is given by Eqn (11) and the resonance energies of all alternants are, to first order, unaffected by N-substitution. This agrees roughly with our results. However, note that the three diazacyclocotatetraenes do differ substantially in REPE. For non-alternants  $q_i$  may be greater or less than one. If  $q_i > 1$ , nitrogen substitution should increase REPE (in units of  $\beta$ ). Conversely, for  $q_i < 1$ , nitrogen substitution should decrease stability. Thus, as found above, N substitution in the  $\alpha$  position of pentalene ( $q = 0.81$ ) is destabilizing, while stabilizing in the  $\beta$  position ( $q = 1.17$ ).

So far as we are able to tell then, it appears that the simple Hückel method, together with Dewar's definition of resonance energy, can make accurate predictions of the aromaticity of conjugated imines, as it can in all other cases we have examined.

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