474. *The Heats and Entropies of Ionisation of Some Aromatic and N-Heteroaromatic Amines.*

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The ionisation constants of a series of unsubstituted polycyclic aromatic amines have been measured at 0° and 20° in 50% ethanol–water solution, and those of a series of *N*-heteroaromatic amines at 5° and 35° in water, entropies and enthalpies of ionisation being calculated. The variation in the ionisation constants of the aromatic amines is due equally to the entropy and the enthalpy factor, whilst the variation in the *N*-heteroaromatic series is due primarily to enthalpy changes. The dissociation entropies of the conjugate acids of the *peri*-aromatic amines are larger than those of the unhindered isomers, which in turn have larger values than those of the *N*-heteroaromatic amines. These results are discussed in relation to the solvation of the amine cations and the π-electron energy changes accompanying their dissociation.

THE relative free energies of ionisation of aromatic [1] and *N*-heteroaromatic [2] amines have been related to the π-electron energy change accompanying the protonation of a nitrogen atom. Such changes are internal energy terms, which, strictly, would govern the relative ionisation constants of a series of amines only in the vapour phase at 0° K, and only if steric factors and σ-bond energy changes resulting from the protonation of a nitrogen atom did not vary in the series. However, it has been shown,[3-5] from the frequencies and intensities of the N–H stretching vibration absorption bands, that conjugation between the amino-group and the nucleus is sterically hindered in the *peri*- and *meso*-aromatic and *N*-heteroaromatic amines, and that the hybridisation ratio of the nitrogen orbitals of the N–H bonds varies in both series of amines, particularly in the latter. In order to assess the relative importance of π and σ bond energy changes, and steric and solvation effects, accompanying the protonation of a nitrogen atom in determining the relative ionisation constants of a series of amines in solution at ordinary temperatures, the enthalpies and entropies of ionisation of a number of amines have now been obtained. The ionisation constants of a series of unsubstituted polycyclic aromatic amines have been measured at 0° and 20° in 50% ethanol–water solution (Table 1), and those of a series of *N*-heteroaromatic amines at 5° and 35° in water (Table 2). Calculated enthalpies and entropies of ionisation are shown.

The dissociation of the conjugate acids of the aromatic amines is governed equally by the entropy ($T\Delta S$) and the enthalpy factor (ΔH) at room temperature in aqueous ethanol, both ΔH and $T\Delta S$ varying by some 2 kcal./mole in the series covered (Table 1). The entropy and enthalpy changes mutually compensate to some degree in the series, the more endothermic dissociations being accompanied by the larger entropy changes, so that the free energies of ionisation cover a smaller range (1·7 kcal./mole) than either ΔH or $T\Delta S$. The dissociation entropies of the conjugate acids of the aromatic amines fall into two main groups, $T\Delta S$ being $\pm 0·4$ kcal./mole for the unhindered amines and 0·9—1·7 kcal./mole for the hindered amines, except for 3-aminopyrene where the entropy of ionisation is zero (Table 1).

The positions and intensities of the N–H stretching vibration absorption bands of 3-aminopyrene suggest [4] that this amine is less hindered than the other *peri*-amines, and the rates of solvolysis of 3-pyrenylmethyl chloride indicate [6] that the carbonium-ion

[1] Hush, *J.*, 1953, 684.
[2] Longuet-Higgins, *J. Chem. Phys.*, 1950, **18**, 275.
[3] Mason, *J.*, 1958, 3619.
[4] Elliott and Mason, *J.*, 1959, 1275.
[5] Mason, *J.*, 1959, 1281.
[6] Fierens, Hannaert, Mysselberge, and Martin, *Helv. Chim. Acta*, 1955, **38**, 2009; Dewar and Sampson, *J.*, 1956, 2789; 1957, 2946, 2952.

transition state, structurally similar to the corresponding amine, is less hindered than that of the other *peri*-arylmethyl chlorides. The reduction of steric hindrance between the *peri*-CH and amino-groups in 3-aminopyrene is probably because the C–C bonds separating the *peri*-positions in pyrene [7] are longer than the corresponding bonds in other aromatic hydrocarbons, notably naphthalene [8] and anthracene.[8]

The smaller dissociation entropy of the conjugate acids of the unhindered aromatic amines may be due to the loss of the rotational entropy of the $-\overset{+}{N}H_3$ group when a proton is lost and the amino-group conjugates with the aromatic nucleus, so that it cannot rotate freely about the C–N bond. In the hindered amines the rotation of the amino-group is

TABLE 1. *The* pK_a *values of some polycyclic aromatic amines in* 50% (v/v) *ethanol–water at* 0·2° *and* 20·0° $\pm$ 0·1°, *the enthalpies* (ΔH) *and entropies* (ΔS) *of dissociation of the conjugate acids of the amines, the* H–N–H *bond angle* (θ), *the charge density at the exocyclic position of the corresponding carbanion,* q_x, *and the extra delocalisation energy of that carbanion,* $E_D\beta^{-1}$.

No.	Compound	pK_a (20°) [a]	pK_a (0·2°) [a]	ΔH [d] (kcal./mole)	ΔS [e] (e.u.)	θ [f]	q_x [g]	$E_D\beta^{-1}$ [h]
	Unhindered							
1	Aniline	4·19	4·51	5·9	1·0	111·1°	1·572	0·722
2	*m*-Aminodiphenyl	3·82	4·10	5·2	0·2	111·9	1·572	0·718
3	*p*-Aminodiphenyl	3·81	4·11	5·6	1·5	112·1	1·516	0·756
4	2-Aminofluorene	4·21	4·52	5·7	0·3	111·9	1·516	0·756
5	2-Naphthylamine	3·77	4·03	4·8	−0·9	111·6	1·529	0·744
6	2-Phenanthrylamine	3·60	3·84	4·4	−1·3	111·4	1·543	0·736
7	3-Phenanthrylamine	3·59	3·83	4·4	−1·3	112·4	1·510	0·754
8	2-Anthrylamine	3·40 [b]				112·7	1·471	0·770
	Hindered							
9	*o*-Aminodiphenyl	3·03	3·34	5·7	5·2	113·0	1·516	0·767
	peri							
10	1-Naphthylamine	3·40	3·72	5·9	4·6	110·3	1·450	0·812
11	1-Phenanthrylamine	3·23	3·53	5·6	4·2	110·0	1·463	0·802
12	9-Phenanthrylamine	3·19	3·49	5·6	4·3	109·8	1·446	0·812
13	1-Anthrylamine	3·22	3·50	5·2	2·9	110·6	1·381	0·848
14	3-Aminopyrene	2·91	3·12	3·9	−0·1	110·8	1·364	0·866
	meso							
15	9-Anthrylamine	2·7 [b, c]				109·4	1·286	0·951

[a] $\pm$0·01 unit of pK for the values obtained by titration. Insufficiently soluble: determined spectrophotometrically. [c] Some decomposition with acid. [d] $\pm$0·3 kcal./mole. [e] $\pm$1·0 e.u. [f] Quoted from ref. (4). [g] Calculated by the method of ref. (2). [h] Calculated by Hückel's method.

inhibited by a *peri*- or an *ortho*-CH group in both the neutral molecule and the cation, and changes of internal rotation do not contribute to the entropy of ionisation. In both the unhindered and the *peri*-series of aromatic amines the dissociation entropy of the conjugate acid falls as the number of condensed rings in the nucleus increases (Table 1), probably owing to a decrease in the solvation of the amine cation with the increase in molecular size.

The free energy of ionisation of the polycyclic aromatic amines appears to be related to the π-electron energy change resulting from the protonation of the nitrogen atom (Fig. 1) in spite of the wide variation of the entropy factor in the series studied. Measures of the π-electron energy change due to cation formation in an aromatic amine are provided by the charge density at the exocyclic position of the corresponding carbanion (q_x) or by the resonance energy due to the delocalisation of electrons from the exocyclic position of the corresponding carbanion over the aromatic nucleus ($E_D\beta^{-1}$). These quantities are related empirically over the range of compounds studied (Table 1) by the expression

$$E_D\beta^{-1} = -0·8q_x + \text{constant} \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

[7] Robertson and White, *J.*, 1947, 358.
[8] Ahmed and Cruikshank, *Acta Cryst.*, 1952, **5**, 852.

for the greater the delocalisation of the exocyclic π-electrons, the larger is $E_D\beta^{-1}$ and the smaller is q_x. A form of eqn. (1) given previously [1] is less precise, owing to the use of an inexact value [9] for the delocalisation energy of the 9-anthrylmethyl ion.

When the conjugate acid of an aromatic amine dissociates, the lone-pair electrons of the liberated amino-group are delocalised over the aromatic nucleus, lowering the energy of the molecule by E_D, and the π-electrons as a whole move in the field of the nitrogen atom, affording a further stabilisation of $q_x\Delta\alpha_N$, where $\Delta\alpha_N$ is the increment in the Coulomb integral of a nitrogen atom relative to a carbon atom. The total π-electron energy change due to the dissociation of an aromatic amine cation (ΔE_π) may be expressed in terms of a single variable [1] by means of eqn. (2), where c is the fractional " p " character of the lone-

$$\Delta E_\pi = cq_x(\Delta\alpha_N - 0.8\beta) + \text{constant} \quad . \quad . \quad . \quad . \quad . \quad (2)$$

pair orbital of the nitrogen atom, and β is the resonance integral which may be assumed to be [1,2,10] about -20 kcal./mole for both C–C and C–N bonds.

If the π-electron energy change, ΔE_π, is the major variable governing the relative free energies of ionisation of the polycyclic aromatic amines, a linear relation between pK_a of the amines measured under standard conditions and the charge density of the corresponding carbanion, q_x, should be observed. Such a relation holds approximately (Fig. 1), but the slope of the line is not the theoretical value. The H–N–H bond angles of the aromatic amines have values [4] close to, but slightly larger than, the tetrahedral value (Table 1), so that the coefficient, c, probably has an average value of about 0.7. The gradient $(d\Delta G/dq_x)$ of the relation of Fig. 1 has a value of 7.5 kcal./mole, from which $\Delta\alpha_N$ has the apparent value of 0.25β. A variety of evidence suggests [11] that $\Delta\alpha_N$ is about 0.6β, indicating that the ionisation constants of the polycyclic aromatic amines decrease with q_x more rapidly than required by eqn. (2) on the assumption that ΔE_π is the major variable governing the relative free energies of ionisation of the amines. A value of 0.65β for $\Delta\alpha_N$ has been derived [1] from the relation between q_x and the ionisation constants of the mono- and di-cyclic and one tricyclic aromatic amines in aqueous solution at temperatures in the range 17—25°, but an imprecise form of equation (2) was employed and it was assumed that the coefficient, c, was unity.

It is perhaps accidental that the relation between the ionisation constants of the aromatic amines and the charge densities, q_x (Fig. 1), is common to both the *peri*- and the unhindered series of amines. Thus the conjugate acids of aniline and 1-naphthylamine have the same heat of dissociation (Table 1), for steric hindrance to conjugation between the amino-group and the nucleus reduces the intrinsically greater π-electron energy of the latter amine. However, the 1-naphthylammonium cation has a larger entropy of dissociation than the anilinium cation (Table 1), so that the former is the stronger acid. The fairly exact compensation between the enthalpy and entropy factors in the dissociation of the conjugate acids of the *peri*-series of amines, shown by Fig. 1, may be fortuitous, as the compensation is not at all exact in the case of the more grossly hindered 2-aminodiphenyl (Table 1, Fig. 1).

Amongst the aromatic amines studied there are a number of pairs of compounds with the same or nearly the same charge density, q_x. In each case it is the larger amine of the pair which is the weaker base (compounds 1 and 2; 3 and 7; 5 and 6; 10 and 12; Table 1), suggesting that the pK_a value of an aromatic amine falls as the number of conjugated or condensed rings in the nucleus increases, irrespective of the value of the charge density, q_x. In general, the smaller values of q_x are confined to the larger polycyclic systems, so that the corresponding amines have a weakened basic strength both because of their size and because of their q_x value, thus qualitatively accounting for the observed slope of the relation between pK_a and q_x (Fig. 1) which is larger than required by equation (2) on the

[9] Syrkin and Diatkina, *Acta Physicochim. U.R.S.S.*, 1946, **21, 23,** 641.
[10] Coulson, " Valence," Oxford Univ. Press, 1952.
[11] Mason, *J.*, 1958, 674.

assumption that ΔE_π is the main variable determining the relative basicities of the aromatic amines. The fall in the basic strength of the aromatic amines with increasing size is probably due to the smaller solvation of the cations of the larger amines, since, of each pair of amines with the same or nearly the same charge density, it is the conjugate acid of the larger amine which has the smaller entropy of dissociation and the less endothermic heat of dissociation (Table 1).

In the unhindered and in the *peri*-series of aromatic amines the H–N–H bond angle increases as q_x falls (Table 1), suggesting that both the " p " character of the lone-pair orbital and the " s " character of the N–H bonds increase as q_x decreases. The larger the " p " character of the lone-pair orbital of the nitrogen atom the more extensive becomes the delocalisation of the lone-pair electrons over the aromatic nucleus, and the larger is the lowering of the π-electron energy on the dissociation of the conjugate acid of the amine (equation 2). The greater the " s " character of the nitrogen orbitals of the N–H bonds

Fig. 1. *The relation between the pK_a values of the polycyclic aromatic amines and the charge density at the position of the exocyclic atom in the corresponding carbanion, q_x. (○ unhindered, ◐ peri-, and ◑ meso-amines. The numbers refer to the compounds in Table 1.)*
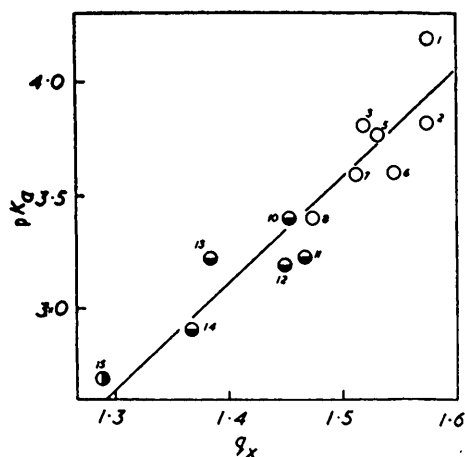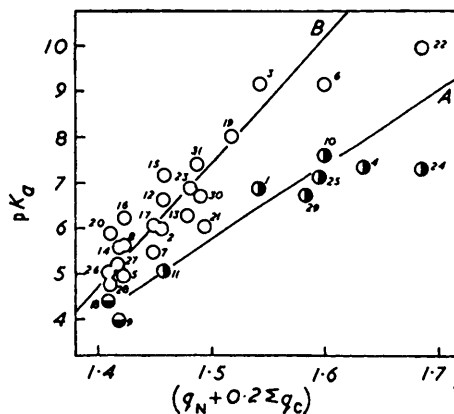
Fig. 2. *The relations between the pK_a values of the N-heteroaromatic amines and the charge density term $(q_N + 0.2\Sigma q_C)$ for (A) the amines with an ortho-nuclear nitrogen atom ◑, and (B) the remaining compounds ○, except for the amines with a peri-nuclear nitrogen atom ◐. (The numbers refer to the compounds listed in Tables 2 and 3.)*

the larger is the N–H stretching force constant,[3] suggesting stronger N–H bonds, so that the greater is the dissociation of the cation to the amine and a hydrogen ion due to σ bond energy changes alone. Thus the changes in the hybridisation ratios of the lone-pair and the N–H bond orbitals of the nitrogen atom in the series of aromatic amines bring about a more rapid fall in pK_a with q_x (Fig. 1) than that expected from eqn. (2) with a constant value of the coefficient, c, and the assumption that ΔE_π primarily determines the relative values of the ionisation constants.

In contrast to those of the aromatic amines, the relative basicities of the N-heteroaromatic amines are governed mainly by the heat of ionisation. In aqueous solution at room temperature the ionisation constants of the N-heteroaromatic amines studied vary by a factor of 10^5 owing to differing enthalpy changes, but only by a factor of 50 because of variations in the entropy of ionisation (Table 2). Thus it is more probable in the N-heteroaromatic than in the aromatic series of amines that the internal energy term, the π-electron energy change due to the dissociation of the conjugate acid of the amine, primarily determines the relative pK_a values.

In the monoaza-heteroaromatic amines the nuclear nitrogen atom is protonated on cation formation. Allowance being made for the inductomeric effect, which is important when the nuclear nitrogen atom is substituted at an unstarred position in the carbanion

corresponding to the amine,[11] the difference in π-electron energy between a monoaza-heteroaromatic amine and its cation, ΔE_π, is given by

$$\Delta E_\pi = q_N(c_1\Delta\alpha_{NH} - c_2\Delta\alpha_N) + \sum q_C(c_1\Delta\alpha_C - c_2\Delta\alpha_{C'}) \quad . \quad . \quad . \quad . \quad (3)$$

where q_N and q_C are the charge densities at the position of the nuclear nitrogen atom and carbon atom adjacent to that nitrogen atom respectively in the corresponding carbanion, $\Delta\alpha_{NH}$ is difference between the Coulomb integrals of a positively charged nitrogen atom and a carbon atom, $\Delta\alpha_C$ and $\Delta\alpha_{C'}$ are the increments in the Coulomb integral of a carbon atom when it is placed adjacent to a positively charged and a neutral nitrogen atom respectively, and c_1 and c_2 are the fractional " p " character of the lone-pair orbital of the exocyclic nitrogen atom in the cation and the neutral molecule of the amine respectively. The Coulomb integral increment of a carbon atom due to the inductive effect of an adjacent nitrogen atom should be proportional to the increment of the latter atom, and, as in the series of N-heteroaromatic hydroxy-compounds,[11] the experimental data are best accommodated by the assumption that

$$\Delta\alpha_C = 0.2\Delta\alpha_{NH} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

a similar equation holding for the increments of a neutral nitrogen atom and an adjacent carbon atom. Combination of eqns. (3) and (4) then gives

$$\Delta E_\pi = (q_N + 0.2\sum q_C)(c_1\Delta\alpha_{NH} - c_2\Delta\alpha_N) \quad . \quad . \quad . \quad . \quad (5)$$

If the π-electron energy change due to the dissociation of the conjugate acid of an N-heteroaromatic amine is the major variable governing the relative free energies of ionisation in the series of amines, a linear relation between the charge densities $(q_N + 0.2\sum q_C)$ and the pK_a values of the amines should be observed, provided that the coefficients, c_1 and c_2, do not vary too widely. The H–N–H bond angles of the monoazo-heteroaromatic amines vary from $110.5°$ to $118.5°$ (Tables 2 and 3), but if we exclude the compounds with a nuclear nitrogen atom *ortho* or *peri* to the amino-group, which deviate markedly [2] from the simpler relation between q_N and pK_a, the range is smaller (110.5—$113.5°$), corresponding to a fractional " p " character of the lone-pair orbital of the amino-group nitrogen atom in the neutral molecule, *i.e.*, c_2, of 0.78—0.85. In the cation the fractional " p " character of that orbital, *i.e.*, c_1, is probably larger, as the nuclear nitrogen atom is more electron-attracting when protonated, and the H–N–H bond angle of an aromatic amine is increased by electron-attracting substituents.[3] The coefficient c_1 probably varies less widely than c_2 in the series of amines, and it may well be unity in most cases.

Two relations between the pK_a values of the monoaza-heteroaromatic amines and the charge density term $(q_N + 0.2\sum q_C)$ are observed, one covering the amines with an *ortho*-nuclear nitrogen atom (Fig. 2, *A*) and the other the remaining compounds (Fig. 2, *B*) apart from the amines with a *peri*-nuclear nitrogen atom. Neither relation is linear over a range of charge densities greater than 0.2 of an electron, the amines with large q_N values being weaker bases than expected from eqn. (5). When the charge density at the position of the nuclear nitrogen atom is large, that atom is negatively charged in the neutral molecule and carries less than a unit positive charge in the cation of the amine, so that the Coulomb increments, $\Delta\alpha_N$ and, more particularly, $\Delta\alpha_{NH}$, are smaller than those of an amine in which q_N is small or zero. The result is a reduction in the magnitude of the Coulomb term $(c_1\Delta\alpha_{NH} - c_2\Delta\alpha_N)$ of eqn. (5), so that beyond the value of about 1.15 electrons an increase in the charge density, q_N, brings about a progressively smaller increase in the pK_a value of the amine (Fig. 2).

The compound with a nuclear nitrogen atom *ortho* or *peri* to the amino-group are weaker bases than the other amines with similar charge density values. The reduction in basicity is due to the inductive influence of the exocyclic nitrogen atom and to intramolecular

hydrogen-bonding, both effects diminishing the proton-accepting capacity of the nuclear nitrogen atom. However, the fall in pK_a of the *ortho*-amines, relative to those of analogous amines with similar charge densities, increases with q_N, as is shown by the gradients of the relations expressed in Fig. 2 (*A* and *B*). Intramolecular hydrogen-bonding, which is present [3] in the *ortho*- as well as the *peri*-amines, opens the H–N–H bond angle (Tables 2

TABLE 2. *The* pK_a *values of some* N-*heteroaromatic amines in water at* 5·4° *and* 35·0° $\pm$ 0·1° *and* 20°, *the enthalpies* (ΔH) *and entropies* (ΔS) *of the dissociation of the conjugate acids of the amines, the* H–N–H *bond angles* (θ), *and the charge densities at the positions of the nuclear nitrogen atom,* q_N, *and the carbon atoms adjacent to it,* q_C, *in the corresponding carbanion.*

No.	Compound	5·4°	20°	35·0°	ΔH (kcal./mole)	ΔS (e.u.)	θ [c]	q_N [d]	q_C [d]
1	2-Aminopyridine	7·18 $\pm$ 0·01	6·86 [a]	6·55 $\pm$ 0·01	8·4 $\pm$ 0·3	$-2\cdot9 \pm 1$	115·3°	1·143	1·0
2	3- ,,	6·41 $\pm$ 0·01	5·98 [a]	5·95 $\pm$ 0·01	5·1 $\pm$ 0·3	$-7\cdot4 \pm 1$	111·6	1·0	1·143
3	4- ,,	9·74 $\pm$ 0·01	9·17 [a]	8·93 $\pm$ 0·01	10·8 $\pm$ 0·3	$-5\cdot8 \pm 1$	113·5	1·143	1·0
4	2-Aminoquinoline	7·81 $\pm$ 0·02	7·34 [a]	7·07 $\pm$ 0·02	9·8 $\pm$ 0·5	$-0\cdot5 \pm 2$	116·3	1·235	1·0
5	3- ,,	5·16 $\pm$ 0·03	4·95 [a]	4·76 $\pm$ 0·02	5·3 $\pm$ 0·7	$-4\cdot6 \pm 2$	111·6	1·0	1·059
6	4- ,,	9·61 $\pm$ 0·02	9·17 [a]	8·71 $\pm$ 0·02	11·9 $\pm$ 0·5	$-1\cdot2 \pm 2$	112·7	1·200	1·0
7	5- ,,	5·72 $\pm$ 0·03	5·46 [a]	5·30 $\pm$ 0·02	5·6 $\pm$ 0·7	$-6\cdot2 \pm 2$	110·5	1·050	1·0
8	6- ,,	5·94 $\pm$ 0·02	5·63 [a]	5·48 $\pm$ 0·01	6·1 $\pm$ 0·4	$-5\cdot3 \pm 1$	112·1	1·0	1·059
9	8- ,,	4·24 $\pm$ 0·01	3·99 [a]	3·86 $\pm$ 0·01	5·0 $\pm$ 0·3	$-1\cdot3 \pm 1$	116·3	1·0	1·050
10	1-Aminoisoquin- oline	8·19 $\pm$ 0·01	7·62 [a]	7·40 $\pm$ 0·01	10·5 $\pm$ 0·3	$+0\cdot1 \pm 1$	114·5	1·200	1·0
11	3- ,,	5·26 $\pm$ 0·01	5·05 [b]	4·88 $\pm$ 0·01	5·0 $\pm$ 0·3	$-6\cdot0 \pm 1$	116·6	1·059	1·0

[a] Quoted from Albert, Goldacre, and Phillips, *J.*, 1948, 2240. [b] Quoted from Osborn, Schofield, and Short, *J.*, 1956, 4191. [c] Calculated from the frequencies of the symmetric and antisymmetric N–H stretching vibrations; ref. (3) and unpublished results. [d] Calculated by the method of ref. (2).

TABLE 3. *The* pK_a *values of some* N-*heteroaromatic amines in water at* 20°, *the* H–N–H *bond angles* (θ), *and the charge densities at the positions of the nuclear nitrogen atom,* q_N, *and the carbon atoms adjacent to it,* q_C, *in the corresponding carbanion.*

| No.	Compound	pK_a	θ [c]	q_N [d]	q_C [d]
12	7-Aminoquinoline	6·65 [a]	112·7°	1·059	1·0
13	4-Aminoisoquinoline	6·28 [b]	110·8	1·0	1·200
14	5- ,,	5·59 [b]	110·0	1·0	1·050
15	6- ,,	7·17 [b]	113·7	1·059	1·0
16	7- ,,	6·20 [b]	112·4	1·0	1·059
17	8- ,,	6·06 [b]	111·0	1·050	1·0
18	1-Aminoacridine	4·40 [a]	118·5	1·0	1·024
19	2- ,,	8·04 [a]	113·5	1·118	1·0
20	3- ,,	5·88 [a]	112·4	1·0	1·029
21	4- ,,	6·04 [a]	110·8	1·095	1·0
22	5- ,,	9·99 [a]	112·9	1·286	1·0
23	6-Aminophenanthridine	6·88 [a]	113·2	1·082	1·0
24	9- ,,	7·31 [a]	116·5	1·286	1·0
25	2-Amino-4-methyl-5 : 6-benzoquinoline	7·14 [a]	116·0	1·196	1·0
26	1′-Amino-5 : 6-benzoquinoline	5·03 [a]		1·0	1·020
27	4′- ,, ,,	5·20 [a]	110·5	1·019	1·0
28	3-Amino-6 : 7-benzoquinoline	4·78 [a]	111·8	1·0	1·029
29	2-Amino-4-methyl-7 : 8-benzoquinoline	6·74 [a]		1·184	1·0
30	8-Amino-1 : 2-benzacridine	6·72 [a]	113·5	1·091	1·0
31	8-Amino-3 : 4-benzacridine	7·42 [a]	113·5	1·088	1 0

[a] Quoted from Albert, Goldacre, and Phillips, *J.*, 1948, 2240. [b] Quoted from Osborn, Schofield, and Short, *J.*, 1956, 4191. [c] Calculated from the frequencies of the symmetric and antisymmetric N–H stretching vibrations, ref. (5) and unpublished results. [d] Calculated by the method of ref. (2).

and 3), so that the " p " character of the lone-pair orbital of the amino-group nitrogen atom in an *ortho*-amine is probably larger than that of isomeric amines with similar q_N values. From the H–N–H bond angle of 116° (Tables 2 and 3) the coefficient, c_2, has the value of approximately 0·92, so that the Coulomb term ($c_1\Delta\alpha_{NH} - c_2\Delta\alpha_N$), which determines the

gradients of the relations in Fig. 2, should be smaller in the series of *ortho*-amines than in that of their isomers, as is found.

The values of the Coulomb term $(c_1\Delta\alpha_{NH} - c_2\Delta\alpha_N)$ derived from the relations of Fig. 2 are 1.8β for the main series of amines and 1.1β for the *ortho*-compounds. A value (1.9β) close to the former has been obtained [11] from the free energy of the ionisation process of *N*-heteroaromatic hydroxy-compounds (II) analogous to the dissociation of the conjugate acids of the corresponding amines (I). In the study of *N*-heteroaromatic hydroxy-compounds [11] it was assumed that the coefficients c_1 and c_2 were both unity, but it is apparent from the H–N–H bond angles of the corresponding amines that c_2 at least is somewhat less than unity and is variable in the series of amines. The Coulomb term $(c_1\Delta\alpha_{NH} - c_2\Delta\alpha_N)$ is therefore composite, providing only approximately a measure of the electronegativity difference between a neutral and a positively charged nitrogen atom, since it expresses through the non-stationary coefficients, c_1 and c_2, variable σ-bond energy changes and variable π-electron delocalisation energy changes due to alterations in the fractional " p " character of the amino-group lone-pair orbital on cation formation in the series of amines.

A value of 1.2β has been obtained [2] for the difference between the Coulomb integrals of a neutral and a positively charged nitrogen atom from a correlation between pK_a and q_N in a series of *N*-heteroaromatic amines, the inductomeric effect being neglected. However, the inductive enhancement of the electronegativity of a carbon atom by an adjacent nitrogen atom is an important determinant of the basicity of the amines with the nuclear nitrogen atom substituted at an unstarred position. The pK_a values of such amines cover a range of 2.3 units, compared with 6.0 units for the series as a whole (Tables 2 and 3). The variation of the pK_a value and of the charge density on the carbon atoms adjacent to the nuclear nitrogen atom, q_C, are both relatively large in the series of *meta*-amines (compounds 2, 5, 13, and 28, Tables 2 and 3), these quantities being linearly related. The gradient of the relation gives 0.34β for the Coulomb term $(c_1\Delta\alpha_C - c_2\Delta\alpha_C)$, compared with 0.36β derived from the slope of Fig. 2 (*B*) and eqn. (4), and 0.38β obtained [11] in a study of the corresponding hydroxy-compounds.

(I)   (II)
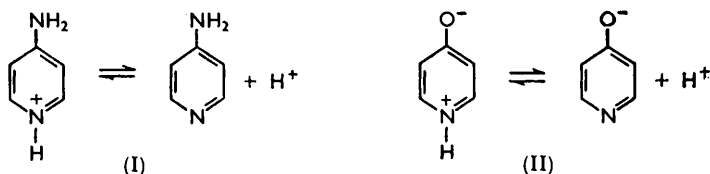
The steric effect of a CH group *peri* to the amino-group upon the basicity of the *N*-heteroaromatic amines appears to be small, though the infrared evidence suggests that there is some hindrance to conjugation between the amino-group and the nucleus in such compounds.[4,5] In contrast to the series of aromatic amines, the entropies of ionisation of the heteroaromatic compounds with a CH group *peri* to the amino-group do not differ systematically from those of the unhindered isomers (Table 2). However, the amino-group is conjugated with the nucleus in both the neutral molecule and the cation of *N*-heteroaromatic amines, so that differences in the entropy of internal rotation between the hindered and unhindered amines, suggested for the aromatic series (see above), are not to be expected in the *N*-heteroaromatic series. The majority of the *N*-heteroaromatic compounds with a CH group *peri* to the amino-group are somewhat weaker bases than their unhindered isomers with the same or a similar charge density term $(q_N + 0.2\sum q_C)$ (Fig. 2, Tables 2 and 3), but the base-weakening is much less than that due to the inductive and hydrogen-bonding effects present in the compounds with an amino-group *ortho* or *peri* to the nuclear nitrogen atom.

The conjugate acids of the *N*-heteroaromatic amines have, in general, smaller entropies

of dissociation (ΔS) than those of the aromatic amines, ΔS having the average values of $-3\cdot9$ and $+1\cdot5$ e.u., respectively (Tables 1 and 2). The solvation entropy of an ion due to the charging process is given by [12]

$$\Delta S = \sum_r \sum_s q_r q_s (\text{d ln } D/\text{d}T)/2DR_{rs} \qquad \ldots \ldots (6)$$

where q_r and q_s are the fractional charges on the atoms r and s, which are separated by the distance R_{rs}, and D is the dielectric constant of the solvent. In the cation of an N-hetero-aromatic amine the positive charge is dispersed, being shared principally by the nuclear and exocyclic nitrogen atoms, so that the cation as a whole has a smaller entropy of solvation, by eqn. (6), than that of an aromatic amine where the positive charge is largely localised on the nitrogen atom. Within the series of N-heteroaromatic amines, the cations which have the smaller separations between the principal charge centres, namely, those with the amino-group *ortho* to the nuclear nitrogen atom, have, in general, the larger entropies of dissociation (Table 2), as required by eqn. (6).

EXPERIMENTAL

Materials.—The polycyclic aromatic amines were as in Elliott and Mason,[4] and 2-, 3-, and 4-aminopyridine as in Mason.[3] 1- and 3-Aminoisoquinoline were kindly provided by Professor H. N. Rydon and Mr. K. Undheim, and by Dr. K. Schofield [13] respectively. The aminoquinolines were either commercial specimens or, in the case of the 5- and the 6-isomer, were prepared by reduction of the corresponding nitroquinolines. After recrystallisation, the aminoquinolines were sublimed, their m. p.s being those reported by Albert, Goldacre, and Phillips.[14]

Ionisation Constants.—These were determined by the potentiometric titration of air-free solutions under nitrogen in a thermostat, glass and calomel electrodes in conjunction with a Cambridge pH meter being used. In aqueous solutions at $5\cdot4°$ and $35\cdot0° \pm 0\cdot1°$ the amino-pyridines were titrated at $0\cdot02$M, the aminoquinolines and 1-aminoisoquinoline at $0\cdot01$M, and 3-aminoisoquinoline at $0\cdot005$M. Owing to the low solubility of the polycyclic compounds in water, the aromatic amines were titrated, at $0\cdot2°$ and $20\cdot0° \pm 0\cdot1°$, in 50% (v/v) aqueous ethanol; aniline, 2-, 3-, and 4-aminodiphenyl, and 1- and 2-naphthylamine at $0\cdot01$M, 1- and 9-aminophenanthrene at $0\cdot0025$M, and the remaining aromatic amines (Table 1) at $0\cdot005$M. The pK_a values of the N-heteroaromatic amines were determined from the equation

$$pK_a = pH - \log [B]/[BH^+] \qquad \ldots \ldots \ldots (7)$$

where [B] and [BH$^+$] are the concentrations of the amine and its cation respectively. With the aromatic amines, equation (7) gave pK_a values with deviations up to $0\cdot1$ of a pK unit. Accordingly, the empirical relationships between the stoicheiometric hydrogen-ion concentration in 50% (v/v) aqueous ethanol at $0\cdot2°$ and $20\cdot0°$ and the pH meter reading were determined, and they were used to calculate the classical ionisation constants of the conjugate acids of the aromatic amines. The negative logarithms of these constants, which have a deviation of $\pm0\cdot01$ of a pK unit, are listed in Table 1. Owing to the low solubility of 2- and 9-amino-anthracene, their pK_a values were determined spectrophotometrically at $0\cdot0001$M, the deviations being $\pm0\cdot02$ and $\pm0\cdot2$ of a pK unit respectively.

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[12] Hush and Blackledge, *J. Chem. Phys.*, 1955, **23**, 514; Hoijtink, de Boer, van der Meij, and Weijland, *Rec. Trav. chim.*, 1956, **75**, 487.
[13] Osborn, Schofield, and Short, *J.*, 1956, 4191.
[14] Albert, Goldacre, and Phillips, *J.*, 1948, 2240.