

THERMODYNAMICS OF PROTON DISSOCIATION. III.*

ELECTROSTATIC FACTORS OF DISSOCIATION OF ANILINE DERIVATIVES

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Electrostatic contributions to the values of ΔG° and ΔS° for dissociation of *ortho*, *meta* and *para* derivatives of aniline were calculated approximately on the basis of a simplified model involving dipole moments. The electrostatic contributions enable to explain to a large extent the decrease of ΔS° with increasing ΔG° for the mentioned compounds as discussed in the preceding communication, as well as positive deviations of ΔS° for certain *ortho* derivatives.

Dissociation of protonated forms of aniline and its derivatives in aqueous solutions has been studied in detail regarding the influence of both internal (intramolecular) phenomena and the interaction of the protonated molecule with the external aqueous medium. The thermodynamic functions of dissociation were then expressed and interpreted as the sum of internal and external contributions¹ due to both mentioned factors. Such concept proved very useful in the case of aniline derivatives²⁻⁵; however, certain problems remained unsatisfactorily elucidated. *meta* and *para* derivatives of aniline show a common linear dependence of ΔS° on ΔG° or ΔH° of dissociation at 25°C^{2,3} with a clearly negative slope, unusual with other series of reactions similar to one another. Hence follows the variability of ΔS° , which is in disagreement with the so-called "compensation rule". *ortho* derivatives of aniline show both positive and negative deviations from the mentioned dependence according to the kind of substituent, described in detail in the preceding communication⁶. The occurrence of positive deviations could not be fully explained by the above-mentioned concept either.

The present work is an attempt to contribute to the elucidation of the mentioned problems by taking into account the electrostatic factors of dissociation of aniline derivatives.

ELECTROSTATIC MODEL

The dissociation of *ortho*, *meta* and *para* derivatives of aniline in water at 25°C is treated in terms of a simple electrostatic model, roughly analogous to the theory of Kirkwood and Westheimer⁷⁻⁹. Substituted anilinium ions or molecules are considered as miniature cavities containing a localized elementary electric charge

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or dipole and surrounded by aqueous medium. The inner space in the cavities and the outer aqueous medium are considered as a homogeneous isotropic dielectric; the size and shape of the cavities are thermally invariant. The value of ΔG^0 of dissociation is expressed as a sum of electrostatic (ΔG_{e1}) and nonelectrostatic (ΔG_{ne1}) contributions:

$$\Delta G^0 = \Delta G_{e1} + \Delta G_{ne1}. \quad (1)$$

However, since the dissociation of monoprotonated forms of aniline derivatives proceeds according to the isoelectric scheme $BH^+ \rightarrow B + H^+$, the value of ΔG_{e1} is given only by the difference of electrostatic energies of the hydrogen ion, W_H , and aminium ion, W_{BH} , together with the energy W_d necessary for removing the formed hydrogen ion from the electric field of the molecular dipole of the amine:

$$\Delta G_{e1} = W_H - W_{BH} + W_d. \quad (2)$$

The substituted aniline molecule is depicted as a permanent dipole of length l with a resulting molecular dipole moment μ placed in the cavity with a low internal dielectric permittivity ϵ_1 . As a result of mesomeric effects in the aromatic system, the primary amino group is its positive pole; the negative pole is in our case represented by another substituent^{10,11}. We assume that the hydrogen ion is after its formation in the smallest distance r_d from the positive pole in the direction of the longitudinal axis of the dipole, and afterward it migrates through a sufficiently large distance. The contribution of the ion-dipole interaction can be expressed as

$$W_d = -N\epsilon\mu/4\pi\epsilon_d r_d(r_d + l), \quad (3)$$

where ϵ_d means effective dielectric permittivity of the ion-dipole interaction analogously as in the Kirkwood-Westheimer theory^{7,8}. The most simple criterion of applicability of Eq. (3) is the dependence of experimental ΔG^0 values of the aniline derivatives under study on the molecular dipole moment μ . It is depicted in Fig. 1 based on values from both the literature and own measurements. Each of the three groups of derivatives (*o*-, *m*-, *p*-) exerts a linear dependence of ΔG^0 on μ with a negative slope in agreement with Eq. (3). Only the group of *ortho* derivatives shows a larger scatter. Both the electrostatic term W_{BH} and nonelectrostatic contribution ΔG_{ne1} in Eqs (1) and (2) can be hence within each individual group presumed constant. The dependence of ΔG^0 on μ can then be written in the empirical form

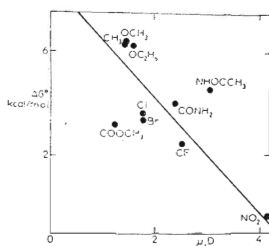
$$\Delta G^0 = A + B\mu. \quad (4)$$

The constants A and B are, of course, different for the individual groups. Different angular coefficients B follow according to Eq. (3) from unequal lengths of the dipole and permittivities ϵ_d as a result of different structures of *o*-, *m*- and *p*-derivatives.

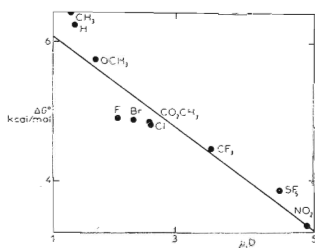
To enable an approximate calculation of ϵ_d , the smallest ion-dipole distance was conventionally chosen¹² as $r_d = 1 \text{ \AA}$. The length l was calculated as average distance between the center of the amino group and another substituent, the constants A and B were obtained from experimental values of ΔG° and μ by the least squares method. The results are summarized in Table I; the value of the effective permittivity is for the sake of simplicity given as relative permittivity ϵ_{rd} . In the group of *o*-derivatives, methyl *o*-aminobenzoate and *o*-aminoacetanilide were not included in the calculations. Both these compounds show marked deviations (Fig. 1a) apparently as a result of a more different dipole length and a possible intramolecular hydrogen bond. Equations analogous to (1) and (2) apply for the entropy of dissociation:

$$\Delta S^\circ = \Delta S_{e1} + \Delta S_{nel}, \quad \Delta S_{e1} = S_H - S_{BH} + \Delta S_d, \quad (5), (6)$$

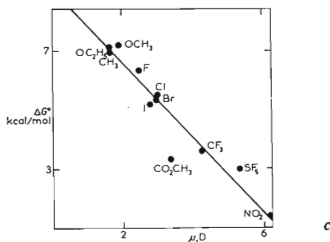
where S_H and S_{BH} denote electrostatic entropies of the hydrogen and aminium ions, ΔS_d entropy increment of the ion-dipole interaction. Eqs (5) and (6) are bound with (1) and (2) by the general relation $S = -\partial G/\partial T$, which on application to W_d ,



a



b



c

FIG. 1

Dependence of $\Delta G^\circ(25^\circ\text{C})$ of Dissociation of Aniline Derivatives on Dipole Moment *a* *ortho* Derivatives, *b* *meta* derivatives, *c* *para* derivatives.

Eq. (3), gives

$$\Delta S_d = W_d \partial \ln \epsilon_{rd} / \partial T \equiv W_d \vartheta. \quad (7)$$

The relative permittivity ϵ_{rd} is a function of the spatial arrangement and of both relative permittivities ϵ_{ri} inside the cavity containing the molecular dipole and ϵ_{rw} of the surrounding aqueous medium:

$$1/\epsilon_{rd} = f_1/\epsilon_{ri} + f_2/\epsilon_{rw}, \quad (8)$$

where f_1 and f_2 are functions of the spatial arrangement assumed independent of temperature. After Kirkwood and Westheimer⁷, ϵ_{ri} is set equal to 2. Since with all groups of derivatives $\epsilon_{ri} < \epsilon_{rd} < \epsilon_{rw}$, it is possible to write approximately

$$f_2 \approx 1 - f_1. \quad (9)$$

With this assumption and by differentiating Eq. (8) we obtain

$$\vartheta = [(\epsilon_{rd} - \epsilon_{ri})/(\epsilon_{rw} - \epsilon_{ri})] \partial \ln \epsilon_{rw} / \partial T. \quad (10)$$

The values of $\vartheta = \partial \ln \epsilon_{rd} / \partial T$ calculated from Eq. (10) for the individual groups of derivatives are given in Table I. From Eqs. (2), (5)–(7) we obtain

$$\Delta S_{e1} - S_H = -S_{BH} + \vartheta W_{BH} - \vartheta W_H + \vartheta \Delta G_{e1}. \quad (11)$$

The values of W_H and S_H are, of course, in all cases the same, whereas W_{BH} and S_{BH} are assumed different for *o*-, *m*- and *p*-derivatives, although constant within each of these groups. Hence, for each mentioned group the linear relationship (11) between ΔS_{e1} and ΔG_{e1} with a slope ϑ holds. By neglecting the term ϑW_H it is then possible to obtain a complete picture of the mutual relation of the dependences of ΔS_{e1} on ΔG_{e1} for the individual groups without dealing with the calculation of W_H and S_H .

TABLE I

Parameters of Ion-Dipole Interaction

A, kcal/mol, *B*, kcal/mol D; cf. Eq. (4); *l* length of dipole, Å; ϵ_{rd} effective relative dielectric permittivity.

Derivatives	<i>A</i>	<i>B</i>	<i>l</i>	ϵ_{rd}	$(\partial \ln \epsilon_{rd} / \partial T) \cdot 10^3,$ K ⁻¹
<i>ortho</i>	8.74	-2.23	2.9	7.94	-0.36
<i>meta</i>	6.95	-0.740	5.1	15.3	-0.80
<i>para</i>	9.01	-1.24	6.0	7.96	-0.36

The terms W_{BH} and S_{BH} were calculated again on the basis of a simplified model similar to the Kirkwood–Westheimer theory^{7,8}. However, since the energy of the electrostatic field of a single charge was to be calculated, the concept of a point charge could not be used. Therefore, every aminium ion is represented again as cavity of a suitable shape surrounded by an aqueous medium. Inside this cavity, however, there is a sphere of radius R bearing a positive elementary charge. The permittivity of the inner space of the cavity is the same as in the case of uncharged molecules. The shapes of the cavities were chosen as a compromise so as to be relatively simple yet to respect at least mutual differences in the shape of protonated forms of the molecules of *o*-, *m*- and *p*-derivatives.

As a model of a *para* derivative, a cavity in the form of a prolate ellipsoid with a longer half-axis, a , and shorter, b , was chosen (Fig. 2). The center of the sphere bearing the elementary charge is on the rotation axis in a distance (depth) d from the peak of the ellipsoid. An approximate model of an *ortho* derivative ion is a spherical cavity of radius b , where the center of the charge is also in a depth d (Fig. 3). The model of a *meta* derivative ion is more complicated (Fig. 4). It is represented by a combination of one half of a prolate ellipsoid with one half of a sphere whose radius is equal to the shorter half-axis of the ellipsoid. The charge center is on the rotation axis in the ellipsoidal part in a distance d from its peak.

The mentioned models enable to perform simplified calculations but they do not respect the flat form of the ions, especially with *ortho* and *meta* derivatives, in the direction perpendicular to the drawing plane. In this way the differences among individual derivatives are exaggerated. Certain approximations were involved also in calculating W_{BH} and S_{BH} , so that the results can give only a rough idea about the

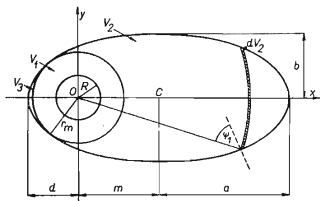


FIG. 2

Cavity in the Form of Prolate Rotation Ellipsoid

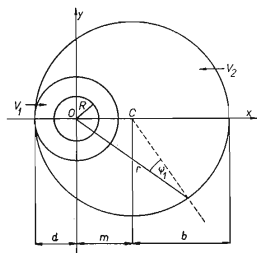


FIG. 3

Cavity in the Form of a Sphere

mutual relations of *o*-, *m*- and *p*- derivatives. Many calculations were performed to find out the influence of the parameters *a*, *b* and *d*; the results serving in the discussion are summarized in Tables II–IV.

CALCULATIONS

Calculation of the coefficients of Eq. (4) and determination of dipole moments. Dipole moments of aniline and some of its derivatives were determined by the method described earlier¹³. In view of the limited solubility of certain compounds in benzene, dioxane was also used as solvent.

TABLE II

ortho Derivatives, Spherical Cavities

b Radius of cavity, Å; *d* depth of charge center, Å; W_{BH} sum of electrostatic field energies inside (W_i) and outside (W_e) the cavities, kcal mol⁻¹; S_{BH} electrostatic entropy, kcal mol⁻¹ K⁻¹.

Notation	<i>b</i>	<i>d</i>	W_i	W_e	W_{BH}	S_{BH}
<i>Ia</i>	3.5	1.6	73.67	368.3	442.0	1.681
<i>Ib</i>	3.5	1.5	72.68	447.7	520.4	2.044
<i>Ic</i>	3.5	1.4	71.54	545.8	617.4	2.493
<i>IIa</i>	3.4	1.6	73.21	350.8	424.0	1.600
<i>IIb</i>	3.4	1.5	72.23	425.5	497.7	1.942
<i>IIc</i>	3.4	1.4	71.09	523.6	594.7	2.391

TABLE III

meta Derivatives, Half-Ellipsoidal and Half-Spherical Cavities

a Longer half-axis of half-ellipsoid, Å; *b* shorter half-axis of half-ellipsoid and radius of sphere, Å; other symbols see Table II.

Notation	<i>a</i>	<i>b</i>	<i>d</i>	W_i	W_e	W_{BH}	S_{BH}
<i>Ia</i>	5.3	3.0	1.6	67.57	407.9	475.5	1.859
<i>Ib</i>	5.3	3.0	1.5	66.34	467.6	534.0	2.132
<i>Ic</i>	5.3	3.0	1.4	69.94	542.1	612.0	2.473
<i>IIa</i>	5.0	3.1	1.6	68.93	390.2	459.1	1.779
<i>IIb</i>	5.0	3.1	1.5	67.74	452.1	519.9	2.062
<i>IIc</i>	5.0	3.1	1.4	66.40	529.0	595.4	2.414
<i>IIIb</i>	5.0	3.2	1.5	68.55	455.5	524.1	2.078

The results are in Table V. Dipole moments of other compounds mentioned in Fig. 1 and used in calculating the coefficients A and B (Table I) were taken from the literature^{11,14}; the values referred to benzene solutions were preferred. The values of ΔG° and pK_a (25°C) were taken from references^{2-4,6,13}.

TABLE IV

para Derivatives, Prolate-Ellipsoidal Cavities

a , b Longer and shorter half-axes of ellipsoid, Å; other symbols see Table II.

Notation	a	b	d	W_i	W_e	W_{BH}	S_{BH}
<i>Ia</i>	4.7	2.3	1.6	60.87	422.9	483.8	1.926
<i>Ib</i>	4.7	2.3	1.5	59.52	467.8	527.3	2.131
<i>Ic</i>	4.7	2.3	1.4	57.98	524.8	582.8	2.391
<i>IIa</i>	4.5	2.25	1.6	60.63	408.7	469.3	1.861
<i>IIb</i>	4.5	2.25	1.5	59.28	451.7	510.9	2.057
<i>IIc</i>	4.5	2.25	1.4	57.75	508.1	565.9	2.315

TABLE V

Dipole Moments of Aniline and Its Derivatives at 20°C

Compound	Dipole moment D		Compound	Dipole moment D	
	benzene ^a	dioxane ^b		benzene ^a	dioxane ^b
$C_6H_5NH_2$	1.52	1.75	$o-NH_2C_6H_4NHC(=O)CH_3$	—	3.10
$o-NH_2C_6H_4COOCH_3$	1.24	1.54	$o-NH_2C_6H_4CF_3$	2.52	2.81
$o-NH_2C_6H_4CONH_2$	—	2.44	$m-NH_2C_6H_4CF_3$	3.51	3.69

^aMean deviation ± 0.04 D; ^bmean deviation ± 0.05 D.

Calculation of W_{BH} and S_{BH}

para Derivatives. The calculation of the energy of the electrostatic field of an elementary charge e distributed symmetrically on a sphere of radius R is based on the equation

$$dW = \frac{1}{2}eE^2 dV, \quad (12)$$

where dV means space element of an isotropic dielectric in a field of intensity E .

A longitudinal cross section of a cavity in the form of a prolate ellipsoid, a model of protonated *p*-derivatives, is shown in Fig. 2. The charge center is in the origin of an orthogonal coordinate system, the center of the ellipsoid is on the x -axis, which is identical with the rotation axis. The

longer and shorter half-axes are denoted as a and b , respectively; m denotes distance of the center of the ellipsoid from the origin. The distance of the center of the charge from the peak of the ellipsoid (depth) is then $d = a - m$. The inner space of the ellipsoid consists of three compartments, V_1 , V_2 and V_3 . The energy in the spherical layer V_1 is given by

$$W_1 = (e^2/8\pi\epsilon_i) (1/R - 1/r_m), \quad (13)$$

where ϵ_i denotes permittivity of the space inside the cavity and r_m smallest length of the radius vector, r , connecting the charge center with the surface of the ellipsoid. The x coordinate of the intersection of r_m with the ellipsoid surface is equal to

$$\alpha = b^2 m / (b^2 - a^2) < 0. \quad (14)$$

If $\alpha > m - a$, then

$$r_m = b \left(\frac{b^2 m^2}{a^2 - b^2} + \frac{2b^2 m^2}{a^2(a^2 - b^2)} - \frac{m^2}{a^2} + 1 \right)^{1/2}. \quad (15)$$

If $\alpha \leq m - a$, the space V_1 touches the ellipsoid surface only in one point, the peak of the ellipsoid. Then the space V_3 vanishes and the value of r_m in Eq. (13) is given by

$$r_m = a - m. \quad (16)$$

The energy of the electrostatic field in the space V_2 is given by

$$W_2 = \frac{e^2}{16\pi\epsilon_i} \left[-\frac{1}{r} + \frac{\alpha}{2r^2} + \frac{1}{2r^2} \sqrt{(\beta + \gamma^2 r)} - \frac{\gamma}{2\sqrt{-\beta}} \arctg \sqrt{-(\beta + \gamma^2 r)/\beta} \right]_{r_{in}}^{a+m}, \quad (17)$$

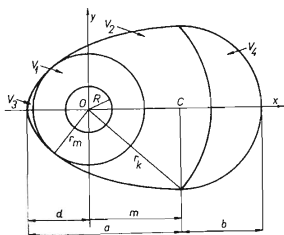


FIG. 4

Cavity in the Form of Half-Ellipsoid and Half-Sphere

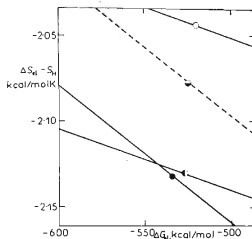


FIG. 5

Dependence of $\Delta S_{e1} - S_H$ on ΔG_{e1} of Dissociation of Aniline Derivatives

○ *ortho* Derivatives, ● *meta* derivatives, ○● *para* derivatives for models *Ib*; ○● *meta* derivatives for model *IIIb*. The points denote also the value of $\Delta G_{e1} = -W_{BH}$.

where $a + m$ and r_m are integration limits, the latter being defined by Eq. (15) or (16), α is defined by Eq. (14), $\beta = b^4 m^2 / (a^2 - b^2)^2 - b^2(a^2 - m^2) / (a^2 - b^2)$ and $\gamma = a^2 / (a^2 - b^2)$. The expression for the electrostatic energy W_3 in the space V_3 (if it exists) differs from (17) by the upper integration limit, $a - m$, and by a negative sign before the term $\alpha / 2r^2$. The total electrostatic energy in the cavities, W_i , in kcal/mol is given by

$$W_i = (N/4184) (W_1 + W_2 + W_3), \quad (18)$$

where N means Avogadro number.

The energy of the electrostatic field outside the cavities, W_e , was (in contrast to the internal space) calculated approximately. First, an expression for the mean values of E^2 on the outer surface of the ellipsoid was derived. Then the real outer field was replaced by a spherically symmetrical field, originating from a hypothetical sphere of the same volume as the ellipsoid. The value of E^2 on the outer surface of this sphere was supposed to be equal to the previously calculated mean. Thus, we obtain (in kcal/mol):

$$W_e = \frac{N}{4184} \frac{A^3 e^2 \epsilon_w}{8\pi \epsilon_i^2 S} \left[\left(\frac{\epsilon_i^2}{\epsilon_w^2} - 1 \right) I_1 + I_2 \right]. \quad (19)$$

Here S denotes surface area of the ellipsoid, A radius of the hypothetical sphere, ϵ_w permittivity of water, and

$$I_1 = \int_0^S r^{-4} (1 + \operatorname{tg}^2 \psi_1)^{-1} dS, \quad I_2 = \int_0^S r^{-4} dS, \quad (20), (21)$$

where ψ_1 denotes angle between the radius vector r and the line normal to the ellipsoid (Fig. 4). The functions to be integrated were expressed as functions of x with the aid of the equation of an ellipse, the integration limits being changed to $m - a$, $a + m$. The integrations were then performed numerically; the integration range was divided into 1000 steps. The electrostatic energy of 1 mol of ions is

$$W_{\text{BH}} = W_i + W_e \quad (22)$$

and the electrostatic entropy

$$S_{\text{BH}} = -\partial W_{\text{BH}} / \partial T. \quad (23)$$

Since W_i is assumed independent of temperature, we obtain by differentiating Eq. (19)

$$S_{\text{BH}} = \frac{N}{4184} \frac{A^3 e^2}{8\pi \epsilon_i^2 S} \left[\left(\frac{\epsilon_i^2}{\epsilon_w^2} + 1 \right) I_1 - I_2 \right] \frac{\partial \epsilon_w}{\partial T}. \quad (24)$$

ortho Derivatives. Fig. 2 shows a cross section of a spherical cavity of radius b . The geometry and symbolics are analogous to the preceding case, hence the depth of the charge center is $d = b - m$. The energy W_1 in the space V_1 can be calculated from Eq. (13) on setting $r_m = b - m$; the energy of the space V_2 is given by

$$W_2 = -\frac{e^2}{16\pi \epsilon_i} \left[\frac{1}{r} + \frac{1}{2m} \ln r + \frac{1}{4r^2} \left(\frac{b^2}{m} - m \right) \right]_{b-m}^{b+m}. \quad (25)$$

The total internal energy W_i is again given by Eq. (18). The energy of the field outside the cavity was again calculated approximately by replacing the real electrostatic field by a spherically symmetrical field with the E^2 value on the outer surface of the sphere equal to the calculated mean. Then

$$W_e = \frac{N}{4184} \frac{b^2 e^2 \epsilon_w}{16\pi \epsilon_1^2} \left[\left(\frac{\epsilon_1^2}{\epsilon_w^2} - 1 \right) I_1 + I_2 \right], \quad (26)$$

where I_1 and I_2 are given by Eqs (20) and (21) into which the equation of a circle is introduced and the limits are changed to $m - b$, $b + m$. (They were calculated analogously as in the case of an ellipsoid.) On differentiating Eq. (26) we obtain

$$S_{BH} = \frac{N}{4184} \frac{b^2 e^2}{16\pi \epsilon_1^2} \left[\left(\frac{\epsilon_1^2}{\epsilon_w^2} + 1 \right) I_1 - I_2 \right] \frac{\partial \epsilon_w}{\partial T}. \quad (27)$$

meta Derivatives. Their model is a cavity in the form of one half of a prolate rotational ellipsoid, its other half being replaced by one half of a sphere (Fig. 5). The half-axes are again a and b , the shorter one (b) is equal to the radius of the sphere. The charge is placed in the same manner as in the ellipsoid (p -derivatives), so that again $d = a - m$, where m means distance of the common center of the half-ellipsoid and half-sphere from the origin. The energy in the spaces V_1 and V_3 (provided that the latter exists) is calculated analogously as in the case of an ellipsoid, in the space V_2 from Eq. (17), where the upper integration limit is replaced by $r_k = a^2 + m^2$. The energy in the space V_4 is calculated from Eq. (25), where the lower limit is replaced by r_k . From the energies W_1 through W_4 thus obtained, the total internal energy W_i is calculated analogously as shown by Eq. (18). The energy of the external field, W_e , was again calculated approximately on the basis of the same assumptions as in the case of the p -derivatives:

$$W_e = \frac{N}{4184} \frac{A^3 e^2 \epsilon_w}{2\epsilon_1^2 (S_{ep} + S_{sp})} \left\{ \frac{1}{2\pi} \left[\left(\frac{\epsilon_1^2}{\epsilon_w^2} - 1 \right) I_1 + I_2 \right] + \frac{b^2}{3} \left[\left(\frac{\epsilon_1^2}{\epsilon_w^2} - 1 \right) I_3 + I_4 \right] \right\}. \quad (28)$$

The quantity S_{BH} is given by

$$S_{BH} = \frac{N}{4184} \frac{A^3 e^2}{2\epsilon_1^2 (S_{ep} + S_{sp})} \left\{ \frac{1}{2\pi} \left[\left(\frac{\epsilon_1^2}{\epsilon_w^2} + 1 \right) I_1 - I_2 \right] + \frac{b^2}{3} \left[\left(\frac{\epsilon_1^2}{\epsilon_w^2} + 1 \right) I_3 - I_4 \right] \right\} \frac{\partial \epsilon_w}{\partial T}. \quad (29)$$

Here S_{ep} and S_{sp} denote surface areas of the whole ellipsoid and sphere whose halves form the cavity, A radius of a hypothetical sphere of the same volume as the cavity, I_1 through I_4 pairs of integrals of the type (20) and (21). I_1 and I_2 involve the equation of an ellipse and their limits are $m - a$, m ; I_3 and I_4 involve the equation of a circle and their limits are m , $m + b$. The integrals are calculated analogously as in the case of p -derivatives.

Remarks to the calculations. All partial derivatives are understood at constant pressure. The relative dielectric permittivity of the space inside the cavities, ϵ_{ri} , is set equal to 2, relative permittivity of water¹⁵ $\epsilon_{rw} = 78.36$ at 25°C and $\partial \ln \epsilon_{rw} / \partial T = -4.588 \cdot 10^{-3} \text{ K}^{-1}$. The values of W_{BH} and S_{BH} in Tables II–IV are therefore valid only at 25°C. Besides SI units, also the thermochemical kcal (4184 joule) and for dipole moments debye ($3.344 \cdot 10^{-30}$ msA) are used. Numerical calculations were made on an IBM 1320 computer and the program was written in Fortran IV.

DISCUSSION

meta and *para* Derivatives of aniline show (within a natural scatter) the same linear dependence of ΔS^0 on ΔG^0 for dissociation; its slope calculated from newer experimental data⁶ is $-6.9 \cdot 10^{-4} \text{ K}^{-1}$. The described model leads according to Eq. (11) also to linear dependences of ΔS_{e1} on ΔG_{e1} including the group of *ortho* derivatives. Their slopes, $\vartheta = \partial \ln \epsilon_{rd} / \partial T$, in Table I are all negative; the average slope corresponding to the *para* and *meta* substituents, $-5.8 \cdot 10^{-4} \text{ K}^{-1}$, is close to the mentioned experimental value.

The hitherto unexplained drop in ΔS^0 with increasing ΔG^0 is according to our model produced mainly by electrostatic contributions of ion-dipole interaction. Its significant role follows from the fact that the site of protonation is here one pole of a permanent molecular dipole. The identity of the sign of this pole with that of the charge of a hydrogen ion is, however, not a decisive factor. In the opposite case, *e.g.* with aliphatic amines, both the sign of the right-hand side of Eq. (3) and the sign of the experimental coefficient B in Eq. (4) would change; the result would be again a drop in ΔS_{e1} with increasing ΔG_{e1} . That the value of ϑ for *meta* derivatives differs from *ortho* and *para* derivatives is due apparently mainly to inaccuracy of the assumption (9). In total, however, the values of ϑ for the individual groups of derivatives differ from one another much less than the values of the starting coefficient B (Table I), obviously a positive feature of this part of the model.

The values of W_{BH} and S_{BH} (Tables II–IV) are most strongly influenced by the choice of the depth d of the charge center. The dimensions of the cavities are given by the rather well-defined shape of the aromatic molecule which, as a rule, does not change appreciably even by protonation. Small changes of the dimensions are not important: the series of models *I* enables to arrive at the same conclusions as the series *II* involving somewhat smaller cavities. Both series are well suited for aniline derivatives with a simple substituent such as a halogen or methyl. The radius R of the sphere on which the elementary charge is symmetrically distributed was with respect to the dimensions of the cavities set equal to 0.8 \AA . Since $W_i \ll W_e$ (Tables II–IV), the resulting value of W_{BH} would not be appreciably affected by small changes of R . Moreover, S_{BH} is quite independent of R . In all cases, the values of W_{BH} and S_{BH} increase considerably with decreasing d , *i.e.* the more asymmetrical is the position of the charge in the cavity. Besides, at $d = 1.4\text{--}1.5 \text{ \AA}$ the order of the W_{BH} and S_{BH} values according to their magnitude for the groups of *o*-, *m*- and *p*-derivatives changes. Hence, the choice of the depth, d , of the charge center is of basic importance.

Regardless of nonelectrostatic contributions, the order according to magnitude of the W_{BH} values for the individual groups should be with respect to Eq. (2) just opposite to the order of the corresponding values of A in Eq. (4). The coefficient A is namely equal to ΔG^0 at zero dipole contribution. The difference in A between *o*-

and *p*-derivatives cannot be considered significant with regard to a larger scatter of *o*-derivatives; however, *m*-derivatives show much lower *A* values. The corresponding higher W_{BH} values for *m*-derivatives as compared with *o*- and *p*-derivatives are obtained with models for which $d \geq 1.5 \text{ \AA}$.

From the electrostatic contribution of the second dissociation constant, the *d* values for aliphatic diamines were calculated by Tanford¹⁶ in the range 1.1–1.4 Å; a higher value calculated from a much greater difference of $\text{p}K_{\text{a}}$ seems to be more plausible. The calculation is based on a concept of two elementary point charges in the double-protonated form and the quantity *d* is considered a sort of a conventional minimum distance between the charge in the cavity and free water molecules in the neighbouring medium. It is therefore influenced, *e.g.*, by the size of the hydration sphere of the charged group; this sphere must be at least partly included in the inner medium of the cavity. With regard to an apparently stronger hydration of the protonated aromatic amino group⁶, it is more suitable to use somewhat larger values of *d* than given by Tanford, especially for the concept of elementary charge distributed on a sphere of finite dimensions, as with the models under discussion.

On the basis of this consideration and the above-mentioned comparison of W_{BH} values with coefficients *A*, we chose for further discussion models with $d = 1.5 \text{ \AA}$, *i.e.* series *Ib* and *IIb* (Tables II–IV) as decisive. In the case of an application of a similar model to aqueous hydrogen ions, it would be necessary to consider a symmetrical position of the elementary charge in a relatively small cavity characterized by a somewhat higher ϵ_i value than in the case of aminium ions¹⁷. Since it is not possible to assume at the same time that *R* is smaller by an order of magnitude, W_{H} would turn out to be rather smaller than W_{BH} . The term ϑW_{H} in Eq. (11) is therefore in our models negligible against S_{BH} and it is possible to derive linear dependences of $\Delta S_{\text{e}1} - S_{\text{H}}$ on $\Delta G_{\text{e}1}$ from the calculated values of S_{BH} , W_{BH} and ϑ . They are shown in Fig. 5 for the models of the three kinds of derivatives denoted as *IIb*.

In a shifted coordinate system, the mentioned dependences are identical with the relation between $\Delta S_{\text{e}1}$ and $\Delta G_{\text{e}1}$. In spite of a different slope, the *meta* and *para* derivatives give the very similar dependences. Owing to the unperfectness of the model, mainly vertical distances of the points denoting $\Delta G_{\text{e}1} = -W_{\text{BH}}$ for the studied groups of derivatives are much too large. The straight line for the *ortho* derivatives is with respect to the two other ones shifted markedly toward higher values of $\Delta S_{\text{e}1}$.

In reality, the *ortho* derivatives show both positive and negative deviations (depending on the substituent) of the measured ΔS^0 value with respect to the other ones. Negative deviations can be attributed to a specific interaction (which cannot be expressed by an electrostatic model) between the protonated amino group and the neighbouring reactive substituent^{5,6,13}. On the other hand, positive deviations (higher ΔS^0) occur especially with derivatives bearing a relatively inert substituent in the *ortho* position, such as a halogen, alkyl or alkoxy group^{1,4,5}. In such a case, the electrostatic factors following from the spatial arrangement expressed by the

described model can play a role. On the basis of this model, higher values of ΔS^0 for *ortho* derivatives can be explained in terms of a higher electrostatic contribution. The electrostatic factors, however, even in the case of an inert substituent apparently overlap with interactions between an ion or unprotonated molecule and aqueous medium⁶, so that the real increase ΔS^0 is for each of the individual *ortho* derivatives under discussion different^{4,6}. A certain disadvantage of the models *Ib* is that the cavity of the *meta* derivatives is too slender and not quite suitable if the substituent is voluminous. Therefore, Fig. 5 was supplemented by model *IIIb* (Table III) suitable for *meta* derivatives bearing such a substituent. Then the positive value of ΔS_{el} is much larger and approaches *ortho* derivatives. The measured value of ΔS^0 for dissociation, e.g. for an ester of *m*-aminobenzoic acid¹⁸ shows indeed a marked positive deviation analogous to *ortho* derivatives (Part I, ref.¹³, Fig. 1).

It can be concluded that the described model in spite of its considerable simplification and some inadequacies at least shows the significant role of electrostatic factors even in the mechanism of isoelectric dissociation of aniline derivatives.

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