

An attempt was made to use the data for cell II to find  $K_1$ . The calculations involve the relations

$$-\log m_H = (\mathcal{F}/2.3026RT)(E_{II} - E^0) + \log m_2 + \log \gamma_H \gamma_{Cl} \quad (10)$$

$$pK'_1 = pK_1 + f(m_2) = -\log[m_H(m_2 - m_H)/(m_1 + m_H - m_2)] \quad (11)$$

The activity coefficients required by equation (10) are not known but can be approximated by those of hydrochloric acid in pure water. From these relations and the smoothed data for cell II, values of

$pK'_1$  were calculated for several ratios of  $m_1$  to  $m_2$ . Extrapolation of  $pK'_1$  to zero ionic strength gave  $pK_1 = -0.33$  at  $25^\circ$  regardless of which constant value of  $m_1/m_2$  was used in the extrapolation. Errors in the concentrations and electromotive forces have such a large effect on this intercept that it is not possible to place much confidence in the value given above. But it seems fair to state that these calculations indicate that the first ionization constant is certainly greater than one.

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[CONTRIBUTION FROM THE VENEREAL DISEASE EXPERIMENTAL LABORATORY, U. S. PUBLIC HEALTH SERVICE, SCHOOL OF PUBLIC HEALTH, UNIVERSITY OF NORTH CAROLINA]

## The Acid Dissociation Constants of Aromatic Phosphonic Acids. I. Meta and Para Substituted Compounds<sup>1</sup>

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The acid dissociation constants of 25 meta and para substituted benzenephosphonic acids have been determined by potentiometric titration in water and in 50% ethanol. The data show that Hammett's equation applies, and that the reaction constants are close to unity. Comparison of the reaction constants with those for the ionization of the benzoic, the arylboric, and the arylarsonic acids leads to the conclusion that  $\rho$ -values depend on the polarizabilities of the central atoms of the acid functions. Several substituent constants not in Hammett's original tabulation are evaluated, and the structures of aminophosphonic acids are discussed.

As part of a systematic study of the properties of organophosphorus compounds, we have determined the acid dissociation constants of 25 meta and para substituted benzenephosphonic acids by potentiometric titration in water and 50% ethanol. This investigation was undertaken to evaluate quantitatively the effect of substituents on the strength of such acids. From measurements of five phosphonic acids, Lesfauries and Rumpf<sup>2</sup> had concluded previously that the effect of substituents in benzoic and in benzenephosphonic acids are very similar. This conclusion suggests that Hammett's equation<sup>3</sup> applies, and that the reaction constants ( $\rho$ ) for the two series are almost the same. The data presented by the previous authors<sup>2</sup> are inadequate to test these points. It is shown in the present paper that the two assumptions are correct.

### Experimental

**Materials.**—Practically all the phosphonic acids were prepared in this Laboratory and have been reported previously.<sup>4</sup> *p*-Ethylmercapto-, *p*-ethoxy- and 3,4-methylenedioxybenzenephosphonic acids were kindly made available to us by Drs. L. D. Quinn and Arthur Roe of the Department of Chemistry, University of North Carolina.<sup>5</sup>

*m*-Carboxybenzenephosphonic acid<sup>6</sup> was prepared from *m*-carboxybenzenediazonium fluoroborate by the general

(1) Presented before the Division of Organic Chemistry at the 122nd Meeting of the A.C.S., Atlantic City, N. J., September, 1952.

(2) P. Lesfauries and P. Rumpf, *Compt. rend.*, **228**, 1018 (1949); this is the only paper in the literature concerned with the  $pK$ 's of aromatic phosphonic acids.

(3) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940, Chapter VII.

(4) G. O. Doak and L. D. Freedman, *THIS JOURNAL*, (a) **73**, 5658 (1951); (b) **74**, 753 (1952); **75**, 683 (1953).

(5) For the preparation of these compounds cf., R. W. Bost and L. D. Quinn, *J. Org. Chem.*, in press; R. W. Bost, L. D. Quinn and A. Roe, *ibid.*, in press.

(6) Previously prepared by A. Michaelis, *Ann.*, **293**, 193 (1896); m. p. 245–246°.

method described previously.<sup>4b</sup> The phosphonic acid was purified by procedure A,<sup>4a</sup> and the yield was 43%; m. p. > 300°. No phosphonic acid was obtained.

*Anal.* Calcd. for C<sub>7</sub>H<sub>7</sub>O<sub>5</sub>P: P, 15.33; neut. equiv., 67.4. Found: P, 14.89; neut. equiv., 68.0.

**Procedure.**—Approximately one millimole of the acid was dissolved in 10 ml. of the appropriate solvent and titrated with 0.25 *N* sodium hydroxide. After each addition of the alkali the pH was determined by means of a Cambridge "Electron-Ray" Research Model pH meter in conjunction with a Beckman 1190-90 glass electrode and a saturated calomel electrode. Each  $pK$  was calculated by standard methods<sup>7</sup> from 7 to 10 pH determinations. The  $pK$  values obtained in this manner agreed to  $\pm 0.05$  unit, and were averaged. Duplicate titrations were made in a few cases, and agreed to within  $\pm 0.05$  unit. Activity corrections and liquid junction potentials were neglected throughout, and hence the experimental values are non-thermodynamic dissociation constants.

### Results and Discussion

Table I lists both the first and second  $pK$  of the phosphono group ( $-\text{PO}_3\text{H}_2$ ) for the acids investigated. The  $\sigma$ -values for some of the substituents (R) are included in Table I; only values appearing in Hammett's original table<sup>3</sup> are given. From these data reaction constants ( $\rho$ ) and their standard errors were calculated by the method of least squares and are summarized in Table II. The correlation coefficients ( $r$ )<sup>8</sup> are also given in Table II, and serve as a measure of the fit of the data to Hammett's equation. The same table further gives  $-\log K^0$  derived from the equation, and the number ( $n$ ) of compounds used in the calculation of  $\rho$ . Although the aromatic phosphonic acids are much stronger acids than either the benzoic acids<sup>9</sup> or the aromatic arsonic acids,<sup>9</sup> the reaction con-

(7) Cf. S. Glasstone, "Textbook of Physical Chemistry," 2nd Ed., D. Van Nostrand Co., Inc., New York, N. Y., 1946, p. 1003.

(8) Cf. G. S. Snedecor, "Statistical Methods," 4th Ed., Iowa State College Press, Ames, Ia., 1946, Chapter VII.

(9) D. Pressman and D. H. Brown, *THIS JOURNAL*, **65**, 540 (1943).

TABLE I  
 $\rho K$  of 

R	$\rho K_{PO_3H_2}$ <sup>a</sup>		$\rho K_{PO_3H^-}$ <sup>a</sup>		$\sigma^b$
	In H <sub>2</sub> O	In 50% EtOH	In H <sub>2</sub> O	In 50% EtOH	
<i>m</i> -(NH <sub>2</sub> Me) <sup>+</sup>	1.1 <sup>c,d</sup>	..	..	..	
<i>m</i> -(NH <sub>2</sub> Et) <sup>+</sup>	1.1 <sup>e</sup>	..	..	..	
<i>p</i> -NO <sub>2</sub>	1.24	2.30	6.23	7.42	0.778
<i>m</i> -NO <sub>2</sub>	1.30	2.37	6.27	7.43	.710
<i>p</i> -SO <sub>2</sub> NH <sub>2</sub>	1.42	2.52	6.38	7.52	
<i>p</i> -COOH	1.50	2.80	..	..	
<i>m</i> -Br	1.54	2.85	6.69	7.96	.391
<i>m</i> -Cl	1.55	2.83	6.65	7.94	.373
<i>m</i> -COOH	1.55	2.83	..	..	.355
<i>p</i> -Br	<sup>e,f</sup>	2.88	6.83 <sup>f</sup>	8.01	.232
<i>p</i> -Cl	1.66	2.93	6.75	7.99	.227
<i>p</i> -COO <sup>-</sup>	..	..	6.89	8.15	
<i>m</i> -OH	1.78	3.10	7.03	8.23	
<i>m</i> -COO <sup>-</sup>	..	..	7.03	8.17	
H	1.83 <sup>g</sup>	3.15	7.07 <sup>g</sup>	8.26	0
<i>p</i> -SEt <sup>h</sup>	<sup>i</sup>	3.14	<sup>i</sup>	8.32	
<i>p</i> -NHAc	<sup>e</sup>	3.15	7.10	8.22	
<i>m</i> -NH <sub>2</sub>	..	..	7.16	8.31	-.161
<i>m</i> -NHEt	..	..	7.24	<sup>i</sup>	
<i>m</i> -NHMe	..	..	7.30	<sup>i</sup>	
<i>m</i> -NH(CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub>	..	..	7.33	<sup>i</sup>	
<i>m</i> -NHNH <sub>2</sub>	..	..	<sup>i</sup>	8.22	
3,4-CH <sub>2</sub> O <sub>2</sub> <sup>h</sup>	<sup>e</sup>	3.21	7.15	8.33	-.159
<i>p</i> -Me	1.98	3.32	7.24	8.38	-.170
<i>p</i> -OH	1.99	3.44	7.25	8.49	
<i>p</i> -OEt <sup>h</sup>	2.06 <sup>k</sup>	3.37	7.28 <sup>k</sup>	8.48	-.250
<i>p</i> -NH <sub>2</sub>	..	..	7.53	<sup>i</sup>	-.660
<i>p</i> -NHNH <sub>2</sub>	..	..	7.54	<sup>i</sup>	
<i>p</i> -NHMe	..	..	7.58 <sup>l</sup>	<sup>i</sup>	

<sup>a</sup> Each value given is the mean of 7 to 10 values which agreed to within  $\pm 0.05$  unit. All measurements were made at  $25 \pm 1^\circ$ . <sup>b</sup> All  $\sigma$ -values are taken from ref. 3. <sup>c</sup> From titration with 0.5 *N* HCl. <sup>d</sup> From the data of ref. 2 one can calculate for *p*-Me<sub>2</sub>N<sup>+</sup>HC<sub>6</sub>H<sub>4</sub>PO<sub>3</sub>H<sub>2</sub>:  $\rho K_{PO_3H_2}$  1.1. <sup>e</sup> This compound was insufficiently soluble to determine  $\rho K_{PO_3H_2}$  in water. <sup>f</sup> Lesfauries and Rumpf (ref. 2) report  $\rho K_{PO_3H_2}$  1.60,  $\rho K_{PO_3H^-}$  6.6 in water. <sup>g</sup> Lesfauries and Rumpf (ref. 2) report  $\rho K_{PO_3H_2}$  1.60,  $\rho K_{PO_3H^-}$  6.85 in water. <sup>h</sup> This compound was kindly furnished by Drs. A. Roe and L. D. Quinn (*cf.* ref. 5). <sup>i</sup> The available quantity of this compound was insufficient to determine the  $\rho K$ 's in both solvents. <sup>j</sup> This compound was not readily soluble in 50% ethanol containing one equivalent of NaOH. <sup>k</sup> Lesfauries and Rumpf (ref. 2) report for *p*-MeOC<sub>6</sub>H<sub>4</sub>PO<sub>3</sub>H<sub>2</sub> in water  $\rho K_{PO_3H_2}$  2.02,  $\rho K_{PO_3H^-}$  7.1. <sup>l</sup> Lesfauries and Rumpf (ref. 2) report for *p*-Me<sub>2</sub>NC<sub>6</sub>H<sub>4</sub>PO<sub>3</sub>H<sub>2</sub> in water:  $\rho K_{PO_3H^-}$  7.35.

stants are very nearly the same in the three classes of compounds.<sup>10</sup>

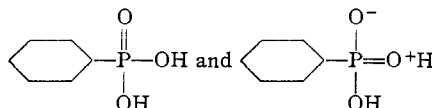
Pressman and Brown have compared the reaction constants for benzoic, arylboric and arylarsonic acids, and have concluded that the most important resonance structures of the arsonic acids do not involve a charged arsenic atom.<sup>9</sup> Application of their arguments to the phosphonic acids would lead to the conclusion that the most important contributions to the ground state come from the structures

(10) For the benzoic acids in water,  $\rho = 1.00$  by definition.  $\rho$  (RAsO<sub>2</sub>H<sub>2</sub> → RAsO<sub>2</sub>H<sup>-</sup>) = 0.953 + 0.123 and  $\rho$  (RAsO<sub>2</sub>H<sup>-</sup> → RAsO<sub>2</sub>O<sup>-</sup>) = 0.874 ± 0.079 were calculated from the data of reference 9. It is seen that the two  $\rho$ -values for the arsonic acids do not differ significantly.

TABLE II  
 REACTION CONSTANTS ( $\rho$ )

Solvent	<i>n</i> <sup>a</sup>	$\rho$ <sup>b</sup>		$\gamma$ <sup>c</sup>	$-(\log K^0)$ <sup>d</sup>
		RPO <sub>3</sub> H <sub>2</sub>	RPO <sub>3</sub> H <sup>-</sup>		
H <sub>2</sub> O	10	0.755 ± 0.028	0.995		1.836
50% EtOH	12	.986 ± .053	.986		3.132
RPO <sub>3</sub> H <sup>-</sup> → RPO <sub>3</sub> O <sup>-</sup>					
H <sub>2</sub> O	12	0.949 ± 0.042	0.990		6.965
50% EtOH	13	.885 ± .065	.972		8.197

<sup>a</sup> The number of determinations on which the calculation of  $\rho$  is based. <sup>b</sup> The error given is the standard error of the slope of the plot of  $\sigma$  vs.  $\log (K/K^0)$ . <sup>c</sup> The correlation coefficient. <sup>d</sup> The intercept of the plot of  $\sigma$  vs.  $\log (K/K^0)$ .



both of which have 10 electrons surrounding the phosphorus atom. However, we have pointed out in an earlier paper that such structures cannot be of great importance.<sup>11,12</sup> Accordingly, Pressman and Brown's argument must be revised, and an alternative interpretation will now be proposed. Substituent constants are generally considered to measure the effect of substituents on the electron distribution in aromatic compounds.<sup>3,13</sup> Since the dissociation process is identical in all the reaction series discussed here, the difference in reaction constants must depend on the effectiveness with which the electrical effects of the substituents are transmitted to the reacting hydroxy group in the various compounds. The several acid series discussed differ primarily in the nature of the central atom of the acidic group. Hence, it appears reasonable to assume that the reaction constant must depend on the polarizability of the central atom. To test this postulate we have considered the polarizabilities, as measured by the ionic refractivities, of the ions derived from the central atom in combination with all the electrons it shares. In Table III, these polarizabilities are compared with the respective reaction constants, and a good correlation is observed. Hence, it seems safe to conclude that the relative values of the reaction constants depend strongly on the polarizability of the central atom.

TABLE III

COMPARISON OF REACTION CONSTANTS AND POLARIZABILITIES

Reaction series: ionization of	$\rho$	Ion	Ionic refractivity <sup>a</sup>
ArB(OH) <sub>2</sub>	2.53 <sup>b</sup>	B <sup>5-</sup>	391
ArCOOH	1.00 <sup>b</sup>	C <sup>4-</sup>	88
ArAsO <sub>2</sub> H <sub>2</sub>	0.95 <sup>c</sup>	As <sup>3-</sup>	76
ArPO <sub>3</sub> H <sub>2</sub>	0.76	P <sup>3-</sup>	67

<sup>a</sup> Extrapolated from K. Fajans, *Z. physik. Chem.*, B24, 118 (1934). <sup>b</sup> From reference 3. <sup>c</sup> From reference 10.

(11) H. H. Jaffé and L. D. Freedman, *THIS JOURNAL*, 74, 1069 (1952).

(12) Since expansion of the valence shell in phosphorus requires promotion of electrons from the 2d level to the 3d level, structures involving a charged central atom must be more important in the phosphonic acids than in the arsonic acids. According to Pressman and Brown's reasoning, the reaction constant for the ionization should therefore be larger for the phosphonic than for the arsonic acids. However, the reverse relationship is actually observed.

(13) H. H. Jaffé, *J. Chem. Phys.*, 20, 279 (1952).

For several substituent groups appearing in Table I, no substituent constants are given in Hammett's original table.<sup>3</sup> Sigma values for these substituents were calculated by standard correlation methods<sup>8</sup> and are given in Table IV.

TABLE IV  
SUBSTITUENT CONSTANTS DERIVED<sup>a</sup>

Group	From $pK_{PO_2H_2}$		From $pK_{PO_2H^-}$	
	In H <sub>2</sub> O $\sigma$	In 50% EtOH $\sigma$	In H <sub>2</sub> O $\sigma$	In 50% EtOH $\sigma$
<i>m</i> -(NH <sub>2</sub> Me) <sup>+</sup>	0.96		....	....
<i>m</i> -(NH <sub>2</sub> Et) <sup>+</sup>	.96		....	....
<i>p</i> -SO <sub>2</sub> NH <sub>2</sub>	.54	0.61	0.65	0.73
<i>p</i> -COOH	.43	.33	....	....
<i>p</i> -COO <sup>-</sup>	....	....	.12	.06
<i>m</i> -COO <sup>-</sup>	....	....	-.02	.03
<i>m</i> -OH	.07	.04	-.02	-.03
<i>p</i> -NHAc	....	-.01	-.10	-.02
<i>p</i> -OH	-.21	-.30	-.25	-.31
<i>m</i> -NHMe	....	....	-.30	
<i>m</i> -NHEt	....	....	-.24	
<i>m</i> -NH(CH <sub>2</sub> ) <sub>3</sub> CH <sub>3</sub>	....	....	-.34	
<i>m</i> -NHNH <sub>2</sub>	....	....		-.31
<i>p</i> -NHMe	....	....	-.59	
<i>p</i> -NHNH <sub>2</sub>	....	....	-.55	

<sup>a</sup> Substituent constants for some of these groups have been reported previously by various authors or can be calculated from data in the literature. No critical discussion of these  $\sigma$ -values is given in this paper since a review of Hammett's equation is being prepared by one of us (H.H.J.) for publication in *Chem. Revs.*

Several of the substituents (R) listed in Table I are acid functions. The experimental  $pK$ 's of these groups are given in Table V. In these cases assignments of the  $pK$ 's to given functions were necessary. Fortunately, no serious overlap of the  $pK$ 's was observed, and all assignments appear unambiguous. The data in Table V permit calculation of substituent constants for the groups —PO<sub>3</sub>-

TABLE V  
 $pK$ 's OF ACIDIC FUNCTIONS

Compound <sup>a</sup>	$pK$ in H <sub>2</sub> O	$pK$ in 50% EtOH
<i>p</i> -HOOC <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> H <sup>-</sup>	3.95	5.36
<i>m</i> -HOOC <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> H <sup>-</sup>	4.03	5.29
<i>m</i> -EtN <sup>+</sup> H <sub>2</sub> C <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> H <sup>-</sup>	4.90	<sup>b</sup>
<i>m</i> -MeN <sup>+</sup> H <sub>2</sub> C <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> H <sup>+</sup>	4.71	<sup>b</sup>
<i>p</i> -HOC <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> <sup>-</sup>	9.9	~10.9 <sup>c</sup>
<i>m</i> -HOC <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> <sup>-</sup>	10.2	~12 <sup>c</sup>
<i>p</i> -NH <sub>2</sub> SO <sub>2</sub> C <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> <sup>-</sup>	10.0	~11.1 <sup>c</sup>
<i>p</i> -NH <sub>2</sub> <sup>+</sup> (CH <sub>2</sub> ) <sub>3</sub> OC <sub>6</sub> H <sub>4</sub> PO <sub>3</sub> <sup>-</sup>	9.5	<sup>b</sup>

<sup>a</sup> The dissociating acidic functions are italicized. <sup>b</sup> This compound was insufficiently soluble in 50% EtOH. <sup>c</sup> This value is approximate, since for  $pH > 10$  the measurements are unreliable.

H<sup>-</sup> and —PO<sub>3</sub><sup>-</sup>. These values, listed in Table VI, must be considered as rough estimates, since their calculation involves comparison of experi-

mental data from different laboratories. However, it may be concluded that the substituent —PO<sub>3</sub>H<sup>-</sup> is weakly electron attracting in both meta and para positions, and the substituent —PO<sub>3</sub><sup>-</sup> is electron repelling in both positions. These findings are in agreement with assumptions made by Schwarzenbach and Zurc<sup>14</sup> in order to explain the  $pK$ 's of aliphatic diphosphonic acids.

TABLE VI

Substituent	SUBSTITUENT CONSTANTS OF THE PHOSPHONO ANIONS	
	$\sigma_{meta}$	$\sigma_{para}$
PO <sub>3</sub> H <sup>-</sup>	0.25, <sup>a</sup> 0.24 <sup>b</sup>	0.17, <sup>a</sup> 0.29 <sup>b</sup>
PO <sub>3</sub> <sup>-</sup>	-0.02 <sup>c</sup>	-0.16 <sup>c</sup>

<sup>a</sup> Calculated from the acid dissociation constants, in H<sub>2</sub>O, of the COOH-group of *m*- and *p*-carboxybenzenephosphonic acids.  $\rho = 1.000$  by the definition (*cf.* ref. 3). <sup>b</sup> Calculated from the acid dissociation constants, in 50% EtOH, of the COOH-group of *m*- and *p*-carboxybenzenephosphonic acids. The  $\rho$ -value was taken from J. D. Roberts, E. A. McElhill and R. Armstrong, *THIS JOURNAL*, **71**, 2923 (1949). <sup>c</sup> Calculated from the acid dissociation constants, in H<sub>2</sub>O, of the OH group in *m*- and *p*-hydroxybenzenephosphonic acids. The  $\rho$ -value was calculated from the data of C. M. Judson and M. Kilpatrick, *ibid.*, **71**, 3110 (1949).

The first  $pK$  obtained by titration of the alkylaminobenzenephosphonic acids with alkali is nearly the same as the  $pK$  of the corresponding anilinium ions,<sup>15</sup> and hence can be assigned to the arylalkylammonium group.<sup>16</sup> The same conclusion was reached by Lesfauries and Rumpf for *p*-dimethylaminobenzenephosphonic acid.<sup>2</sup> This assignment is further supported by the infrared spectra of *m*- and *p*-aminobenzenephosphonic acids,<sup>17</sup> which do not show the characteristic amino doublet near  $3\mu$ ,<sup>18</sup> and hence do not contain a free amino group. These frequencies are also absent in the meta and para isomers of (aminophenyl)-phenylphosphinic acid, but are present in the corresponding bis-(aminophenyl)-phosphinic acids,<sup>17</sup> which must contain a free amino group. These data confirm the zwitterion structure of the aminobenzenephosphonic acids.

The last  $pK$  of *p*-( $\beta$ -aminoethoxy)-benzenephosphonic acid (*cf.* Table V) agrees closely with that of ethanolamine,<sup>19</sup> and hence is assigned to the aliphatic ammonium group. This assignment is in agreement with the conclusion of Chavanne<sup>20</sup> that the last  $pK$  of aliphatic aminophosphonic acids must be assigned to the ammonium group.

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(14) G. Schwarzenbach and J. Zurc, *Monatsh.*, **81**, 202 (1950).

(15) N. F. Hall, *THIS JOURNAL*, **52**, 4115 (1930), gives *N*-methylaniline,  $pK_a$  4.78; *N*-ethylaniline,  $pK_a$  5.14.

(16) This argument is valid since the substituent constant for the —PO<sub>3</sub>H<sup>-</sup> group is small.

(17) The infrared spectra were kindly recorded for us by Samuel P. Sadtler & Sons, Inc., Philadelphia, Pa.

(18) H. W. Thompson, *J. Chem. Soc.*, 328 (1948).

(19) N. F. Hall and M. R. Sprinkle, *THIS JOURNAL*, **54**, 3469 (1932), give  $pK_a$  9.53.

(20) V. Chavanne, *Ann. chim.*, [12] **4**, 383 (1949).