

# Hydrolysis of Nitrophenyl and Dinitrophenyl Sulfate Esters<sup>1</sup>

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Received May 6, 1968

The pH-rate profile for the hydrolyses of *o*-, *m*-, *p*-nitrophenyl and 2,4- and 2,5-dinitrophenyl sulfates is characterized by a plateau in the pH 4–10 region preceded by a more rapid acid-catalyzed reaction and followed by feeble base catalysis. A linear free-energy plot for  $\log k_0$  (see ref 11) against the  $pK_a$  of the corresponding phenol with a slope of  $-1.2$  was obtained. Sodium chloride, sulfate, and fluoride and copper(II) sulfate and silver perchlorate only slightly affect  $k_0$  for 2,4-dinitrophenyl sulfate, but sodium perchlorate significantly decreases it. Acetonitrile decreases  $k_0$  for the same ester; dioxane in concentrations up to 80% has the same effect, but, when it reaches 90%, the rate is increased by a factor of 70; and dimethyl sulfoxide and *N,N*-dimethylformamide increase it exponentially. The effects of electrolytes, acetonitrile, and dimethyl sulfoxide on the molar activity coefficients of 2,4-dinitrophenyl sulfate and its hydrolysis transition state have been separated by distribution experiments. Sodium chloride slightly "salts in," and sodium sulfate and perchlorate, and the dipolar aprotic solvents "salt out" 2,4-dinitrophenyl sulfate, but all these salts and acetonitrile destabilize the transition state while dimethyl sulfoxide has little effect on it. Linear free-energy correlations have been obtained between the acid-catalyzed rate constants,  $k_{\psi}$ , and the dissociation constants of the leaving groups for all three acids at all concentrations and temperatures investigated. The slopes of these plots are between 0.22 and 0.26 indicating that the acid-catalyzed hydrolysis of these sulfate esters is relatively insensitive to the electron-withdrawing power of the leaving group. The catalytic effectiveness of the acids is  $H_2SO_4 > HClO_4 > HCl$ . Plots of  $\log k_{\psi} + H_0$  against  $H_0 + C_{H^+}$  are linear, but their slopes are different for the different acids. This behavior is rationalized by assuming that the acids, in addition to their proton-donating power, exert specific electrolyte effects on both the initial and the transition states of these hydrolyses.

Recently, considerable interest has been shown in mechanistic studies concerning the hydrolysis of sulfate esters<sup>2–5</sup> owing to their biochemical importance.<sup>6</sup> The spontaneous perchloric acid,<sup>3</sup> base,<sup>2</sup> and amine<sup>2</sup> catalyzed hydrolyses of *p*-nitrophenyl sulfate and carboxyl group participation in salicyl sulfate hydrolysis<sup>4</sup> have been reported. Lack of sufficient data has frustrated attempts to compare the mechanisms of aryl sulfate hydrolyses with those of the much more widely investigated monoaryl phosphates.<sup>7</sup> It has been suggested that a study of the hydrolysis of sulfate esters containing good leaving groups might substantiate the proposed unimolecular mechanism.<sup>2</sup> Although 2,4- and 2,5-dinitrophenyl sulfates have such good leaving groups, their preparation and consequently kinetic investigations of their hydrolysis have so far eluded the attention of chemists and biochemists alike. We, therefore, have undertaken a systematic investigation of the mechanisms of hydrolysis of both mono- and dinitrophenyl sulfates and report the results of a study of their neutral and acid-catalyzed hydrolyses.

## Experimental Section

**Materials.**—*p*-Nitrophenyl sulfate potassium salt (Eastman) was recrystallized from 90% ethanol.

*o*-Nitro-, *m*-nitro-, 2,4-dinitro-, and 2,5-dinitrophenyl sulfates were prepared by a modified procedure of Burkhardt and Wood.<sup>8</sup> Chlorosulfonic acid (35 mmol, 2.32 ml) was added dropwise with stirring to a solution of dimethylaniline (12.5 mmol, 11.73 ml) in carbon disulfide (12.5 ml) at  $-16$  to  $-21^\circ$ . The mixture was then warmed to  $35$ – $40^\circ$ ; the appropriate dry phenol (25 mmol) was added with stirring; and the mixture was stirred for 1–1.5

hr at  $35$ – $40^\circ$  and for approximately 14 hr at room temperature. After the mixture was cooled to  $0^\circ$ , it was poured rapidly with stirring into cold 4 *M* KOH (50 ml). The precipitate was filtered immediately, washed at least twice with cold 95% ethanol, and dried *in vacuo*. The potassium salts of *o*- and *m*-nitrophenyl sulfates were recrystallized from 90% ethanol. The labile dinitrophenyl sulfates were purified by the addition of dry acetonitrile to the solid, centrifugation, and rotary evaporation of the solution followed by the same procedure but using a minimum amount of cold aqueous ethanol. Rapid rotary evaporation of the solvent at  $10$ – $15^\circ$  and drying *in vacuo* gave shiny white crystals. The purity of all the sulfates was established to be not less than 99% by complete hydrolysis of known quantities in aqueous buffer solutions at pH 10.00, assaying the amount of phenoxide ion liberated, and by their ir and nmr spectra.

Deionized distilled water was used to make up the buffer solution and the standard acid and alkali solutions. The pH of the buffer solutions was adjusted by addition of hydrochloric acid or sodium hydroxide at  $25.00^\circ$  using an Orion Model 801 pH meter. The concentrations of the acid solutions were determined by titration with standard 0.10 or 1.00 *M* NaOH (BDH) using Laemoid as the indicator. The alkali solutions were standardized by titration with standard 1.00 *M* HCl using Laemoid as the indicator. 1,4-Dioxane was purified by the method of Fieser<sup>9</sup> and stored in polyethylene bottles in a refrigerator. Spectrograde dimethyl sulfoxide, *N,N*-dimethylformamide, and acetonitrile were used without further purification and stored over molecular sieve. The aqueous organic solutions were made up by using the appropriate volumes measured at room temperature.

**Kinetics.**—The hydrolysis was followed spectrophotometrically by determining either the phenoxide ion or the phenol concentration. The phenoxide ion formation was followed in the higher pH region and in alkaline solutions. At lower pH values and in the acid region advantage was taken of the fact that the extinction coefficients of the nitro- and dinitro-substituted phenol sulfates are very much smaller than those of the corresponding phenols. For a few runs in strong acid solutions, the formation of phenoxide ion was followed by adjusting the pH of the individual samples to 9.0 by the addition of buffer solutions. The rate constants for these runs agreed within 3% with those obtained by direct measurement of phenol formation. The following wavelengths ( $m\mu$ ) were used for following the phenoxide ion and phenol formation, respectively: *o*-nitrophenyl sulfate, 410, 290; *m*-nitrophenyl sulfate, 380, 350; *p*-nitrophenyl sulfate, 403, 320; 2,4-dinitrophenyl sulfate, 360, 320, and 2,5-dinitrophenyl sulfate, 440, 270. The Beer-Lambert law was obeyed over

(1) (a) For a preliminary report, see E. J. Fendler and J. H. Fendler, *Chem. Commun.*, 1261 (1967). (b) Supported in part by the U. S. Atomic Energy Commission.

(2) S. J. Benkovic and P. A. Benkovic, *J. Amer. Chem. Soc.*, **88**, 5504 (1966).

(3) J. L. Kice and J. M. Anderson, *ibid.*, **88**, 5242 (1966).

(4) S. J. Benkovic, *ibid.*, **88**, 5511 (1966).

(5) R. W. Hay and J. A. G. Edmonds, *Chem. Commun.*, 967 (1967).

(6) K. S. Dodgson, B. Spencer, and K. Williams, *Biochem. J.*, **64**, 216 (1958); H. Boström, K. Bernstein, and M. W. Whitehouse, *Biochem. Pharmacol.*, **13**, 413 (1964).

(7) J. R. Cox, Jr., and O. B. Ramsay, *Chem. Rev.*, **64**, 317 (1964).

(8) G. N. Burkhardt and H. Wood, *J. Chem. Soc.*, 141 (1929).

(9) L. F. Fieser, "Experiments in Organic Chemistry," 3rd ed., D. C. Heath and Co., Boston, Mass., 1957, p 284.

the range of concentrations employed for all the sulfates. Kinetic runs at 14.90, 25.00, and 45.00° were followed directly in the thermostated cell compartment of a Beckman DU-2 spectrophotometer. Those at 75.00 and 100.00° were carried out in sealed tubes which were placed in a thermostat, individually withdrawn at the required times, quickly cooled, and analyzed spectrophotometrically at the appropriate wavelength. For the hydrolyses in sodium hydroxide solutions, alkali resistant glass (Corning No. 7280) was used. The temperature in the thermostats and inside the cell compartment was measured by an NBS thermometer and maintained to be  $\pm 0.02^\circ$ . Examples of typical kinetic runs are shown in Figure 1.

**Partitioning Experiments.**—The measurement of the distribution of 2,4-dinitrophenyl sulfate between water and an immiscible organic solvent, at a constant temperature and in the presence and absence of salts or of other media, gives the effect of the electrolytes or of the media on the molar activity coefficient of the sulfate ester.<sup>10</sup> Water and cyclohexane, water and hexane, cyclohexane and dimethyl sulfoxide, and hexane and acetonitrile are almost completely immiscible; the salts are not extracted into the organic layer; and the density differences of these solvents readily allows them to be separated quickly and cleanly after shaking. The hydrolysis of 2,4-dinitrophenyl sulfate at 25.00° was negligible compared with the distribution time. Even in 75% dimethyl sulfoxide, representing the fastest hydrolysis rate, the half-life for the hydrolysis of 2,4-dinitrophenyl sulfate is approximately 30 min and generally the distribution was carried out in less than 2 min. Typically a known concentration of 2,4-dinitrophenyl sulfate was made up by weight in a buffer or electrolyte solution (25.00 ml), and the concentration of this solution was redetermined by measuring the absorption at 320 m $\mu$  of a suitable dilution using the appropriate blank solution. These two independently determined concentrations usually agreed within  $\pm 3\%$ . A 10.00-ml portion of the aqueous 2,4-dinitrophenyl sulfate was vigorously mixed with 10.00 ml of cyclohexane or the same volume of hexane in a thermostated separatory funnel at 25.00°. After the two layers had separated, the concentration of 2,4-dinitrophenyl sulfate was measured spectrophotometrically in each layer at 320 m $\mu$  using the appropriate blank solution. The distribution coefficient,  $r$ , is defined as [2,4-dinitrophenyl sulfate] in cyclohexane or in hexane/[2,4-dinitrophenyl sulfate] in water or in aqueous media. The subscript  $o$  refers to water and  $s$  to salt solutions or other media. The ratio  $r_s/r_o$  is equal to the ratio  $f_s/f_o$ , where  $f_s$  is the molar activity coefficient of 2,4-dinitrophenyl sulfate in the presence of electrolytes or other media, and  $f_o$  is that in water. Six independent values for  $r_o$  were determined, and they agreed within  $\pm 5\%$ . Furthermore, 2,4-dinitrophenyl sulfate was distributed between 3.75  $M$  NaClO<sub>4</sub> and cyclohexane, and in a separate experiment hexane was used instead of cyclohexane. Excellent agreement was obtained between the values found in these two experiments (Table I).

TABLE I

ACTIVITY COEFFICIENTS OF 2,4-DINITROPHENYL SULFATE AND ITS HYDROLYSIS TRANSITION STATE IN THE PRESENCE OF ELECTROLYTES, ACETONITRILE, AND DIMETHYL SULFOXIDE<sup>a</sup>

Medium	$f_s/f_o$	$f_s^*/f_o^*$
1.25 $M$ NaClO <sub>4</sub>	1.38	1.92 <sup>b</sup>
2.50 $M$ NaClO <sub>4</sub>	1.19	2.75 <sup>b</sup>
3.75 $M$ NaClO <sub>4</sub>	1.37	4.25 <sup>b</sup>
3.75 $M$ NaClO <sub>4</sub> <sup>c</sup>	1.38	4.24 <sup>b</sup>
0.75 $M$ NaCl	0.94	1.05 <sup>b</sup>
1.50 $M$ NaCl	0.91	1.00 <sup>b</sup>
2.25 $M$ NaCl	0.82	0.97 <sup>b</sup>
0.75 $M$ Na <sub>2</sub> SO <sub>4</sub>	1.73	1.70 <sup>b</sup>
25.00% CH <sub>3</sub> CN	22.40	23.40
50.00% CH <sub>3</sub> CN	147.00	214.00
75.00% CH <sub>3</sub> CN	200.00	372.00
25.00% DMSO	1.85	0.80
50.00% DMSO	6.23	1.30
70.00% DMSO	8.67	0.87

<sup>a</sup> Using cyclohexane unless otherwise stated; correlated with rate constants at 25.00° unless otherwise stated. <sup>b</sup> Rate constants measured at 45.00°. <sup>c</sup> Using hexane.

(10) F. A. Long and W. F. McDevit, *Chem. Rev.*, **51**, 119 (1952).

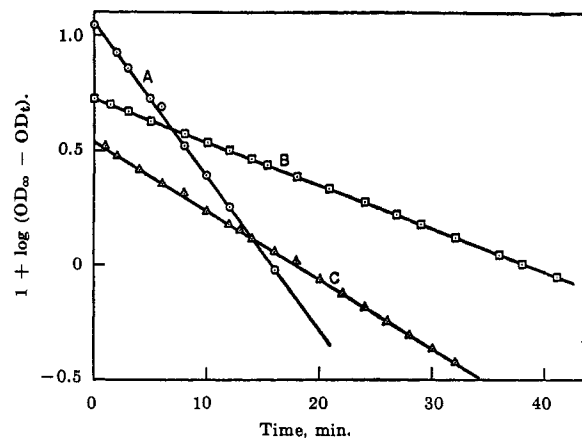


Figure 1.—Plot of  $1 + \log(OD_\infty - OD_t)$  against time for the neutral hydrolysis of sulfate esters. A = 2,4-dinitrophenyl sulfate; pH 5.90, 75.00°. B = *o*-nitrophenyl sulfate; pH 8.00, 100.00°; time scale in 10<sup>2</sup>. C = 2,5-dinitrophenyl sulfate; pH 5.90, 100.00°.

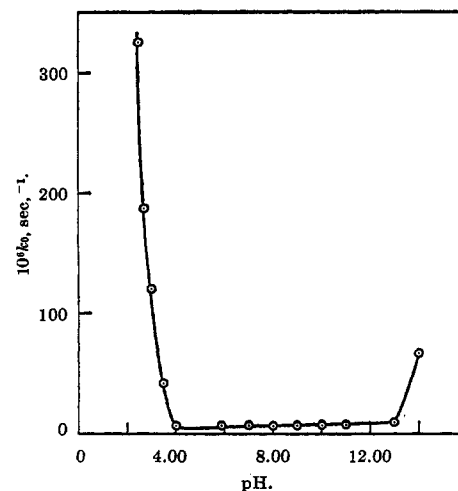


Figure 2.—Variation of  $k_0$  with pH for *o*-nitrophenyl sulfate at 100.00°.

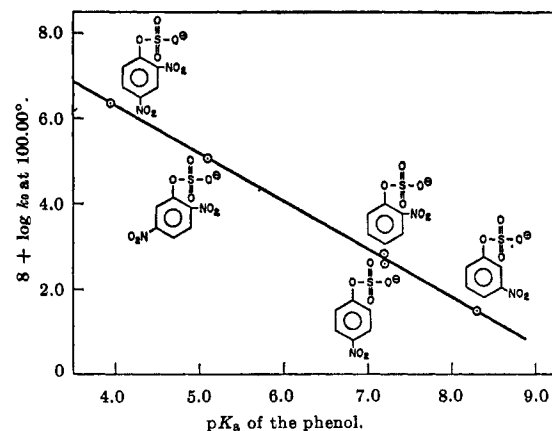


Figure 3.—Plot of  $8 + \log k_0$  at 100.00° against  $pK_a$  of the corresponding phenol.

## Results

The first-order rate constants,  $k_0$ , for the neutral<sup>11</sup> hydrolysis of nitrophenyl and dinitrophenyl sulfates are given in Table II. The pH-rate profile for *o*-nitrophenyl sulfate at 100.00° is in Figure 2. Figure 3

(11) In this paper, the neutral hydrolysis refers to the hydrolysis of the sulfate esters, in the plateau region of the pH-rate profile, *i.e.*, from pH 4 to 12, and is symbolized by  $k_0$ .

TABLE II  
HYDROLYSIS OF NITROPHENYL AND DINITROPHENYL SULFATES IN THE pH REGION

pH	Buffer <sup>a</sup>	10 <sup>3</sup> k <sub>ψ</sub> , sec <sup>-1</sup>						
		o-Nitrophenyl sulfate		m-Nitrophenyl sulfate	2,4-Dinitrophenyl sulfate		2,5-Dinitrophenyl sulfate	
		100.00°	75.00°	100.00°	75.00°	45.00°	100.00°	75.00°
1.00	0.10 M HCl	1307.0		948.0		326.0	3200.0	
2.50	0.01 M KH <sub>2</sub> PO <sub>4</sub>	306.0				269.0	1680.0	
2.70	0.01 M KH <sub>2</sub> PO <sub>4</sub>	178.0						
3.00	0.01 M KH <sub>2</sub> PO <sub>4</sub>	120.7		72.5			1220.0	
3.50	0.01 M KH <sub>2</sub> PO <sub>4</sub>	40.2					1250.0	
4.00	0.01 M KHC <sub>3</sub> H <sub>4</sub> O <sub>4</sub>	6.78						
4.32	0.01 M KHC <sub>3</sub> H <sub>4</sub> O <sub>4</sub>						1180.0	150.0
5.90	0.01 M KHC <sub>3</sub> H <sub>4</sub> O <sub>4</sub>	6.80		0.31	3700.0	295.0	1180.0	148.0
6.00	0.01 M KH <sub>2</sub> PO <sub>4</sub>	7.10		0.32	3680.0			149.00
7.00	0.01 M KH <sub>2</sub> PO <sub>4</sub>	6.85	0.659	0.32	3720.0			
8.00	0.01 M Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	7.17		0.31		279.0		
9.00	0.01 M Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	6.80	0.642	0.32		278.0		
10.00	0.01 M Na <sub>2</sub> B <sub>4</sub> O <sub>7</sub>	7.45				272.0	1160.0	
11.00	0.01 M K <sub>2</sub> HPO <sub>4</sub>	7.20	0.644			273.0		
13.00	0.10 M NaOH	8.40					1510.0	
14.00	1.0 M NaOH	68.10						

<sup>a</sup> The pH of buffers were adjusted at 25.00°.

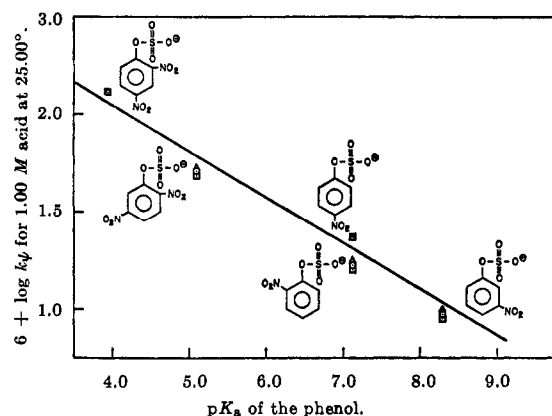


Figure 4.—Plot of  $6 + \log k_{\psi}$  at 1.00 M acid against  $pK_a$  of the corresponding phenol at 25.00°:  $\circ$ , HClO<sub>4</sub>;  $\square$ , HCl;  $\Delta$ , H<sub>2</sub>SO<sub>4</sub>.

shows the linear free-energy relationship between the dissociation constant of the leaving group (nitro or dinitrophenol) and the rate constants for the neutral hydrolysis. The Arrhenius parameters for the neutral hydrolysis are collected in Table III. The effects of salts on the neutral hydrolysis of 2,4-dinitrophenyl sulfate at 45.00° are summarized in Table IV, and Table V gives the solvent effects on the hydrolysis of the same compound. The effects of electrolytes, acetonitrile, and dimethyl sulfoxide on the molar activity coefficient of 2,4-dinitrophenyl sulfate and on that of its hydrolysis transition state are collected in Table I.

The first-order rate constants,  $k_{\psi}$ , for the acid-catalyzed hydrolysis of nitrophenyl and dinitrophenyl sulfates are given in Table VI. Good linear free-energy correlations have been obtained between  $k_{\psi}$  and the dissociation constants of the leaving groups for all three acids at all the concentrations and temperatures investigated. A typical plot for a 1.00 M acid at 25.00° is given in Figure 4. The slopes of these plots are 0.22–0.26. Plots of  $\log k_{\psi}$  against  $H_0$ <sup>12</sup> generally gave

(12) Values for  $H_0$  were taken from M. A. Paul and F. A. Long, *Chem. Rev.*, **57**, 1 (1957), and when available from more recently determined values such as those which have been reported by M. J. Jorgensen and D. R. Hartier, *J. Amer. Chem. Soc.*, **85**, 878 (1963), and K. Yates and H. Wai, *ibid.*, **86**, 5408 (1964).

TABLE III  
ARRHENIUS PARAMETERS FOR THE NEUTRAL HYDROLYSIS OF NITROPHENYL AND DINITROPHENYL SULFATES

Sulfate	E, kcal/mol	$\Delta S^\ddagger$ , eu <sup>a</sup>
o-Nitrophenyl	24.7	-17.4
p-Nitrophenyl	18.5 <sup>b</sup>	-18.5 <sup>b</sup>
2,4-Dinitrophenyl	18.8	-18.0
2,5-Dinitrophenyl	19.4	-17.4

<sup>a</sup> Calculated at 75.00°. <sup>b</sup> See ref 2.

TABLE IV  
SALT EFFECTS ON THE NEUTRAL HYDROLYSIS OF 2,4-DINITROPHENYL SULFATE AT 45.00°

	Concn of salt, M	10 <sup>3</sup> k <sub>ψ</sub> , sec <sup>-1</sup>
NaCl	0.00	27.9
	1.00	25.7
	2.00	25.0
	3.00	24.8
	4.00	8.19
NaClO <sub>4</sub>	1.00	20.3
	2.00	15.2
	3.00	11.00
	4.00	8.19
	5.00	5.78
Na <sub>2</sub> SO <sub>4</sub>	1.00	28.0
CuSO <sub>4</sub>	0.1	33.0
AgClO <sub>4</sub>	0.1	35.0
NaF	0.5	29.5
	1.0	32.2

good straight lines whose slopes are given in Table VII. The plot for o-nitrophenyl sulfate is illustrated in Figure 5. The scatter between the different acids might be due to the different electrolyte effects of the acids on the sulfate esters or on their hydrolysis transition states. To test this point we replotted our experimental data as suggested by Bunnett<sup>13</sup> and later modified by Bunnett and Olsen.<sup>14</sup> Plots of  $\log k_{\psi} + H_0$  against  $-\log a_{H_2O}$  are curved and are different for the different acids; some of them show a minimum. Figure 6 shows these plots for o-nitrophenyl sulfate. In their modified treatment Bunnett and Olsen suggest that the slope,  $\phi$ , of plots of  $\log k_{\psi} + H_0$  against  $H_0 +$

(13) J. F. Bunnett, *ibid.*, **83**, 4956 (1961), and accompanying papers.

(14) J. F. Bunnett and F. P. Olsen, *Can. J. Chem.*, **44**, 1917 (1966).

TABLE V

## NEUTRAL HYDROLYSIS OF 2,4-DINITROPHENYL SULFATE IN AQUEOUS ORGANIC SOLVENTS

Medium	Volume % organic solvent	$10^4 k_{\psi}$ , sec <sup>-1</sup> , at 25.00°	$10^4 k_{\psi}$ , sec <sup>-1</sup> , at 45.00°	$E$ , kcal/mol	$\Delta S^{\ddagger}$ , eu, at 25.00°
CH <sub>3</sub> CN-H <sub>2</sub> O	0	4.00	27.9	18.8	-18.0
	25	3.85	27.4	18.6	-18.5
	50	2.74	21.0	19.2	-16.0
	75	1.86	13.1	18.4	-15.5
Dioxane-H <sub>2</sub> O	40	5.94	50.0	20.0	-10.0
	60	4.60	49.0	22.3	-5.2
	80	3.50	42.0	24.9	0.1
	90	260.00		25.9 <sup>a</sup>	14.0 <sup>a</sup>
DMSO-H <sub>2</sub> O	25	9.20	62.1	18.0	-18.0
	50	18.00	142.0	20.0	-12.0
	75	38.7	302.0	19.4	-10.5
	85	143.7	1130.0	19.5	-6.5
DMF-H <sub>2</sub> O	25	8.62	90.8	22.2	-3.7
	50	17.6	183.0	22.1	-3.2

<sup>a</sup> Calculated from  $10^4 k_{\psi} = 76 \text{ sec}^{-1}$  at 14.90°.

TABLE VI

ACID-CATALYZED HYDROLYSIS OF NITROPHENYL AND DINITROPHENYL SULFATES<sup>a</sup>

	Concn of acid, <i>M</i>	$10^4 k_{\psi}$ , sec <sup>-1</sup>				
		<i>o</i> -Nitrophenyl sulfate	<i>m</i> -Nitrophenyl sulfate	<i>p</i> -Nitrophenyl sulfate	2,4-Dinitrophenyl sulfate	2,5-Dinitrophenyl sulfate
HCl	1.03	1.58	0.91	2.35	13.3	5.09
	1.03 <sup>b</sup>	17.8	12.0	43.5	135.0	45.0
	2.06	4.44	3.26	6.30	29.7	9.08
	3.06	11.2	6.47	18.0	64.7	23.3
	4.12	24.5	15.0	39.4	109.0	52.9
	5.15	48.6	34.3	85.5	276.0	98.7
	5.15 <sup>b</sup>		387.0			
	6.18	126.5	79.5	184.0	651.0	293.0
HClO <sub>4</sub>	7.12	258.0	201.0			
	1.00	1.70	0.958	2.35	12.7	5.17
	1.00 <sup>b</sup>	22.2	13.0	45.6	126.0	53.6
	2.00	4.16	3.06	7.25	27.7	11.5
	3.00	9.92	5.67	15.2	63.6	24.5
	4.00	24.0	12.8	35.7	142.0	52.1
	5.00	60.1	28.0	68.2	300.0	105.0
	5.00 <sup>b</sup>		297.0			
H <sub>2</sub> SO <sub>4</sub>	6.00	191.0	78.7	228.0	862.0	307.0
	7.08	759.0				
	1.00	1.76	0.98	2.36	13.2	5.27
	1.00 <sup>b</sup>	20.1	11.6	44.2	151.0	49.3
	2.00	4.33	2.94	9.58	44.0	10.4
	3.00	11.2	7.13	18.5		23.4
	4.00	33.6	20.3	51.7	225.0	69.0
	5.00	92.4	54.1	138.0		182.0
5.00 <sup>b</sup>		456.0				
	6.00	252.0	151.0		1226.0	743.0

<sup>a</sup> At 25.00°, unless specified otherwise. <sup>b</sup> At 45.00°.

TABLE VII

 $\phi$  VALUES<sup>a</sup> AND SLOPES OF LOG  $k_{\psi}$  vs.  $-H_0$  PLOTS FOR THE ACID-CATALYZED HYDROLYSIS OF NITROPHENYL AND DINITROPHENYL SULFATES

	<i>o</i> -Nitrophenyl sulphate	<i>m</i> -Nitrophenyl sulphate	<i>p</i> -Nitrophenyl sulphate	2,4-Dinitro- phenyl sulphate	2,5-Dinitro- phenyl sulphate	
$\phi$	{ HCl HClO <sub>4</sub> H <sub>2</sub> SO <sub>4</sub>	{ -0.07 -0.03 -0.20	{ -0.03 -0.39 -0.20	{ -0.05 -0.39 -0.20	{ -0.10 -0.46 -0.32	{ -0.10 -0.38 -0.14
Log $k_{\psi}$ vs. $-H_0$ slope at 25.00°	{ HCl HClO <sub>4</sub> H <sub>2</sub> SO <sub>4</sub>	{ 0.95 0.86 0.86	{ 0.94 0.86 0.85	{ 0.96 0.85 0.83	{ 0.98 0.85 0.86	{ 1.10 0.73 0.73

<sup>a</sup>  $\phi$  = slope of plots of log  $k_{\psi} + H_0$  vs. log  $C_{H^+} + H_0$  at 25.00° in the 1.00-6.00 *M* acid range.

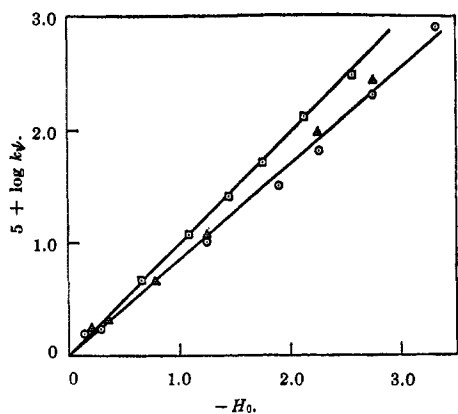


Figure 5.—Plot of  $5 + \log k_\psi$  against  $-H_0$  for *o*-nitrophenyl sulfate at 25.00°:  $\circ$ , HClO<sub>4</sub>;  $\square$ , HCl;  $\triangle$ , H<sub>2</sub>SO<sub>4</sub>.

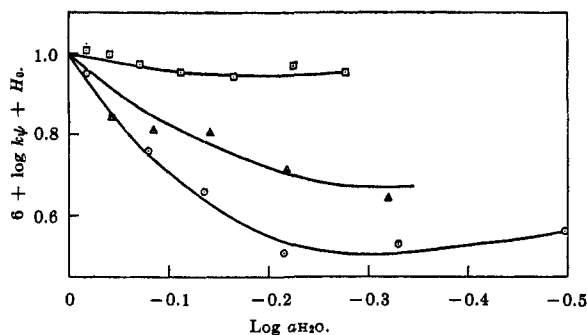


Figure 6.—Plot of  $6 + \log k_\psi + H_0$  against  $\log a_{H_2O}$  for *o*-nitrophenyl sulfate at 25.00°:  $\circ$ , HClO<sub>4</sub>;  $\square$ , HCl;  $\triangle$ , H<sub>2</sub>SO<sub>4</sub>.

$\log C_{H^+}$  indicates the effect of activity coefficient ratios on the reaction rate.<sup>14</sup> Figure 7 shows such plots for *o*-nitrophenyl sulfate. Corresponding plots for the other sulfate esters are similar. The slopes of these plots are given in Table VII. The energies and entropies of activation are collected in Table VIII.

TABLE VIII  
ENERGIES AND ENTROPIES OF ACTIVATION FOR THE  
ACID-CATALYZED HYDROLYSIS OF NITROPHENYL AND  
DINITROPHENYL SULFATES

Sulfate	Solvent	$E$ , kcal/mol	$\Delta S^\ddagger$ , eu at 25.00°
<i>o</i> -Nitrophenyl	1.03 M HCl	22.9	-5.7
	1.00 M HClO <sub>4</sub>	23.9	-5.5
	1.00 M H <sub>2</sub> SO <sub>4</sub>	21.6	-9.0
<i>m</i> -Nitrophenyl	1.03 M HCl	27.8	1.0
	5.15 M HCl	22.4	-0.4
	1.00 M HClO <sub>4</sub>	25.2	1.6
	5.00 M HClO <sub>4</sub>	22.3	-1.4
	1.00 M H <sub>2</sub> SO <sub>4</sub>	23.4	-1.0
<i>p</i> -Nitrophenyl	5.00 M H <sub>2</sub> SO <sub>4</sub>	20.1	-7.0
	1.03 M HCl	22.6	-2.0
	1.00 M HClO <sub>4</sub>	22.2	-6.0
2,4-Dinitrophenyl	1.00 M H <sub>2</sub> SO <sub>4</sub>	23.1	-1.5
	1.03 M HCl	21.8	-1.5
	1.00 M HClO <sub>4</sub>	21.6	-5.0
2,5-Dinitrophenyl	1.00 M H <sub>2</sub> SO <sub>4</sub>	22.9	-1.3
	1.03 M HCl	21.0	-8.0
	1.00 M HClO <sub>4</sub>	21.2	-6.0
	1.00 M H <sub>2</sub> SO <sub>4</sub>	21.9	-7.0

Errors, standard deviations, in individual rate constants are not greater than  $\pm 4\%$ ; those in  $E$  are approximately  $\pm 0.7$  kcal mol<sup>-1</sup>; and those in  $\Delta S^\ddagger$  are  $\pm 2$  eu. We consider values for the molar activity

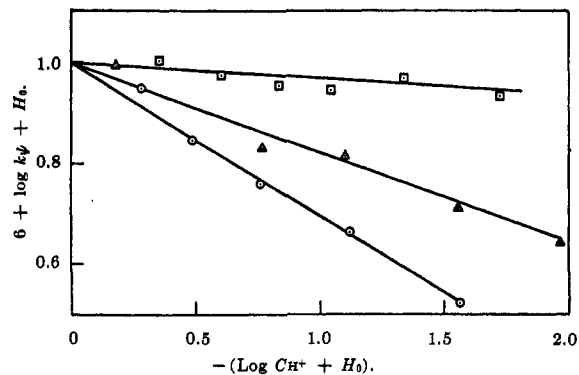


Figure 7.—Plot of  $6 + \log k_\psi + H_0$  against  $-(\log C_{H^+} + H_0)$  for *o*-nitrophenyl sulfate at 25.00°:  $\circ$ , HClO<sub>4</sub>;  $\square$ , HCl;  $\triangle$ , H<sub>2</sub>SO<sub>4</sub>.

coefficients of 2,4-dinitrophenyl sulfate to be accurate within  $\pm 10\%$ , although the errors are smaller for the electrolytes. Errors for the transition-state activity coefficient ratios are inevitably compounded, but even for acetonitrile, representing the most complex system, the results are correct within  $\pm 25\%$ .

## Discussion

**Neutral Hydrolysis.**—The pH-rate profile for the hydrolysis of aryl sulfate esters involves a plateau, pH 4–12, preceded by a more rapid acid-catalyzed reaction and followed by an exponential curve (see Figure 2) due to the incursion of base catalysis.<sup>15</sup> Superficially this hydrolytic behavior is very similar to that which has been observed for the hydrolysis of alkyl,<sup>7</sup> aryl,<sup>16,17</sup> and acyl<sup>18,19</sup> phosphate dianions.

The present results on the hydrolysis of nitrophenyl and dinitrophenyl sulfate anions will be discussed with respect to the hypotheses that (a) the rate-determining step involves unimolecular sulfur-oxygen bond fission with the elimination of SO<sub>3</sub>, (b) the hydrolysis proceeds by bimolecular nucleophilic attack of water on sulfur, and (c) water molecules participate in the transition state by ion-dipole or dipole-dipole interactions or by hydrogen bonding to such an extent that the molecularity of the reaction is a matter of its academic definition.

The sensitivity of the rate of hydrolysis to changes in substituents in the leaving group ( $\rho$ ) has been found to be a useful mechanistic probe in studies of phosphate ester hydrolysis.<sup>16,17,19</sup> We have found that a plot of  $\log k_0$  for the sulfate anion hydrolysis against the  $pK_a$  of the corresponding phenol is linear with a slope of  $-1.2$  (Figure 3). Such a relatively large substituent effect is consistent with a unimolecular mechanism, since in this case the only requirement for hydrolysis is sulfur-oxygen bond breaking. However, for the hydrolysis of phosphate monoanions, which exhibits many characteristics of a unimolecular reaction but

(15) The powerful base catalysis at high pH values might involve a change from a unimolecular to a bimolecular mechanism involving attack by hydroxide ion on both carbon and sulfur.<sup>2</sup> In addition, these processes could be complicated by specific electrolyte effects of the alkali metal hydroxide. Clearly our data on the base-catalyzed hydrolysis are insufficient to elucidate the base-catalyzed mechanism in greater detail.

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