3558 measured reflexions) and 0.079 (for 2418 measured reflexions) for the two structures, respectively (see paragraph at end of the paper regarding supplementary material).

Registry No. I·2II, 85429-08-9; III·2IV, 95911-69-6.

Supplementary Material Available: A listing of atomic coordinates of the H atoms, thermal parameters, bond lengths and angles, and stereodiagrams (15 pages). Structure factor tables may be obtained from the author by request. Ordering information is given on any current masthead page.

Sulfoquinones in the Hydrolysis of Aryl Esters of *o*- and *p*-Hydroxyarenesulfonic Acids in Alkaline Aqueous Solutions of Dioxane[21]

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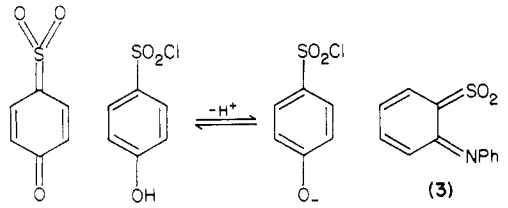
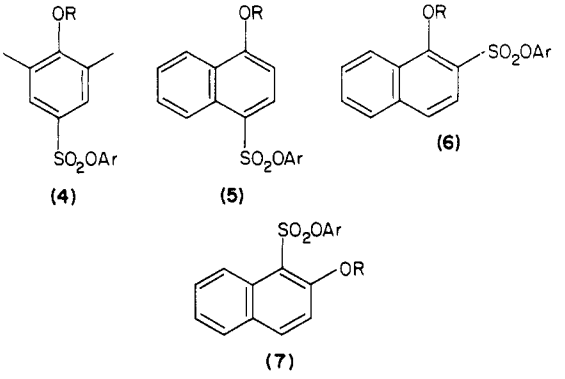
The alkaline hydrolysis of *o*- and *p*-hydroxyarenesulfonate esters of acidic phenols proceeds via an E1cB mechanism. Sulfoquinone (IUPAC name thioquinone dioxide) intermediates (e.g., **8**) constitute the best hypothesis to account for the observed kinetic results which obey the rate law k_{obsd} (hydrolysis) = $(k_a + k_b[OH^-])/(1 + [H^+]/K_a)$. There is a negligible deuterium oxide solvent isotope effect on k_a and the entropy of activation is slightly positive. Apparent bimolecular rate constants for hydroxide ion attack on the un-ionized hydroxyl esters (k_aK_a/K_w) are many orders of magnitude larger than the bimolecular rate constants for hydroxide ion attack on the corresponding *methoxy* esters which possess the BAc2 mechanism. Amines trap an intermediate to give more amide than is predicted from the second-order rate law for amine attack on the ionized hydroxy ester. The k_b term most likely arises from bimolecular attack of the hydroxide ion on the ionized hydroxy ester. The hydrolysis of *o*-hydroxyarenesulfonate esters undergoes strong competition from the "Smiles" rearrangement.

Zincke and Brüne proposed that a sulfoquinone[1a] intermediate analogous to (**1**) was formed in the alkaline hydrolysis of 4-hydroxybenzenesulfonyl chlorides.[1b] These authors based their conclusions on the observation of a yellow color which, however, was subsequently shown by Hall[2] to be due to the ionized form of the phenolic group (**2**). A nitrogen analogue of an *o*-sulfoquinone (**3**) has been postulated by Burgess[3] to account for transformations of benzothiazete 1,1-dioxides.



(1) (2) (3)

We decided to reinvestigate the possibility of a sulfoquinone intermediate because it would be related to a family of intermediates including sulfene ($R_2C{=}SO_2$)[4] and sulfonylamine ($RNSO_2$)[5] demonstrated in mechanisms of sulfonyl group transfer. Such a study would extend our knowledge of control of mechanism in acyl group transfer. The best conditions for observing a sulfoquinone in ester hydrolysis would be where the ester has a very good leaving group because the elimination–addition mechanism of ester hydrolysis possesses a large negative sensitivity to the pK of the leaving function. We investigated the hydrolysis and aminolysis of the arene derivatives (**4–7**) as the quinone analogues of the sulfoquinones from these species are known to be quite stable.[6]



(4) (5) (6)

(7)

R=H or Me; Ar = C_6H_3-2,4-di-NO_2 or C_6H_3-2-Cl-4-NO_2

The "Smiles" rearrangement competes with the sulfonyl group transfer in the case of the *o*-hydroxyarenesulfonate esters (eq 1)[7] where the leaving phenyl groups are activated

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‡ University Chemical Laboratory.

(1) (a) We use the original nomenclature[2] although an IUPAC[1c] name for the general species (thioquinone dioxide) might be preferred. (b) Zincke, T.; Brüne, R. *Chem. Ber.* **1980**, *41*, 902. (c) Rigaudy, J.; Klesney, S. P. "IUPAC Nomenclature of Organic Chemistry"; Pergamon Press: Oxford, 1979; Sections A–H.

(2) Hall, W. L. *J. Org. Chem.* **1966**, *31*, 2672.

(3) Ao, M. S.; Burgess, E. M. *J. Am. Chem. Soc.* **1971**, *93*, 5298.

(4) (a) Davy, M. B.; Douglas, K. T.; Loran, J. S.; Steltner, A.; Williams A. *J. Chem. Soc.* **1977**, *99*, 1196. (b) Williams, A.; Douglas, K. T.; Loran, J. S. *J. Chem. Soc. Chem. Commun.* **1974**, 689. (c) King, J. F.; Beatson, R. P. *Tetrahedron Lett.* **1975**, 973. (d) Thea, S.; Guanti, G.; Williams, A. *J. Chem. Soc. Chem. Commun.* **1981**, 535.

(5) (a) Williams, A.; Douglas, K. T. *J. Chem. Soc. Perkin Trans. 2* **1974**, 1727. (b) Douglas, K. T.; Williams, A. *J. Chem. Soc. Chem. Commun.* **1973**, 356.

(6) Ulrich, H.; Richter, R. "Methoden der Herstellung und Umwandlung von Chinonen"; G. Thiem: Verlag, 1977; Part 1, Vol. 7/3a, pp 730–733.

(7) Ingold, C. K. "Structure and Mechanism in Organic Chemistry"; Cornell University Press: Ithaca, NY, 1953; pp 806–807.

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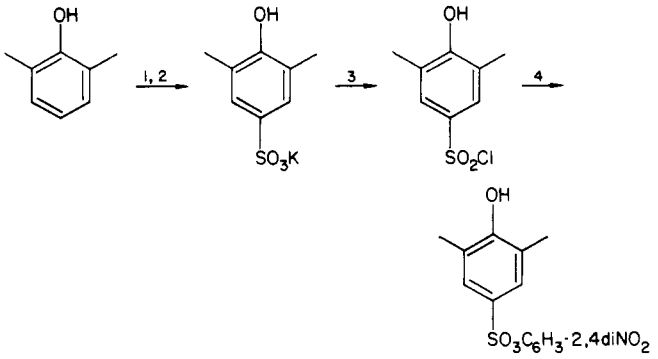
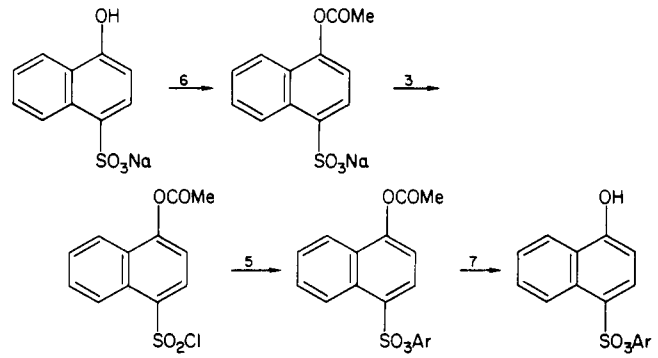
Scheme I[a]



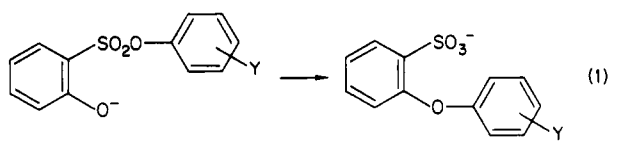
[a] Reagents: 1, $H_2SO_4 \cdot H_2O$; 2, KCl; 3, $SOCl_2$/dimethylformamide; 4, 2,4-dinitrophenol/triethylamine.

Scheme II[a]



[a] Reagents: as in Scheme I; 5, ArOH/triethylamine; 6, acetic anhydride/NaOH; 7, hot HCl/ethanol.

by powerful electron-attracting groups (Y). This complication can be easily overcome, unless the competition is too powerful, by using product analysis for the phenol which will yield the percent reaction passing through the "non-Smiles" route.



(1)

The phenol leaving group is chosen because of its versatility in leaving ability and also because of its ease of analysis.

Experimental Section

Materials. The substrates were prepared by standard laboratory methods which are not reported in detail. We outline the synthetic routes and give the analytical data for the products of interest. 2',4'-Dinitrophenyl 3,5-dimethyl-4-hydroxybenzenesulfonate was prepared from the 2,6-dimethylphenol via the corresponding sulfonyl chloride[2] as in Scheme I. The 2,4-dinitrophenyl and 2-chloro-4-nitrophenyl esters of 1-hydroxynaphthalene-4-sulfonic acid were obtained from the sodium salt of the acid according to Scheme II. The 2-chloro-4-nitrophenyl ester of 2-hydroxynaphthalene-1-sulfonic acid was obtained from the potassium salt of the acid by a route similar to that of Scheme II. The 2-chloro-4-nitrophenyl ester of 1-hydroxynaphthalene-2-sulfonic acid was obtained by an analogous route although the hydrolysis of the 1-acetoxy group with ethanolic HCl gave a poor yield. It was impossible to prepare the 2,4-dinitrophenyl ester of this acid by the hydrolysis of the acetoxy group.

The methyl ethers of the hydroxy esters were obtained by methylation of the sodium or potassium salt of the hydroxysulfonic acid with dimethyl sulfate. The acid chloride was then obtained by using $SOCl_2$/dimethylformamide and the ester formed from the chloride by using the Schotten-Baumann technique (reagent 5 in Scheme II).

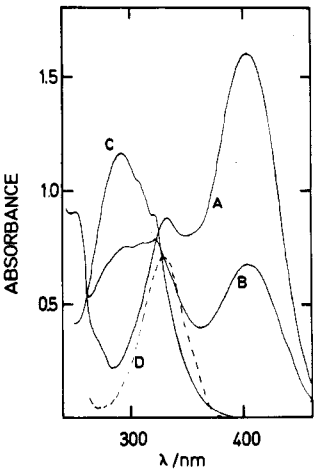
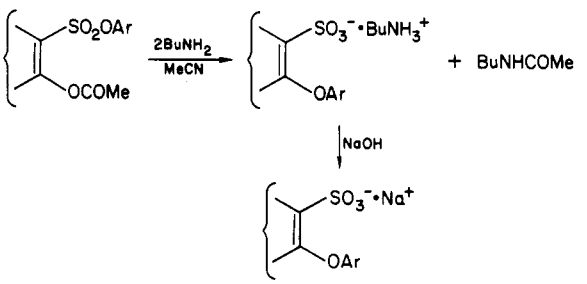


Figure 1. UV spectra of the hydrolysis products of 2-chloro-4-nitrophenyl 1-hydroxynaphthalene-2-sulfonate in 0.1 M KOH, 20% dioxane–water (v/v), 50 °C, ionic strength maintained at 1 M with KCl. (A) 1-Hydroxynaphthalene-2-sulfonate (Na salt) at 8.8×10^{-5} M + 2-chloro-4-nitrophenol (8.7×10^{-5} M). (B) Product of hydrolysis of the ester at 8.9×10^{-5} M. (C) The "Smiles" rearrangement product 1-(2-chloro-4-nitrophenoxy)-naphthalene-2-sulfonic acid (Na salt) at 8.8×10^{-5} M. 1-Hydroxynaphthalene-2-sulfonate (Na salt) at 8.8×10^{-5} M.

Scheme III



The structures of the substrates and the intermediate species were confirmed by IR and ^1H NMR spectroscopy and the analytical and physical data are recorded in a supplementary table.

Buffer materials were analytical reagent grade or were redistilled or recrystallized from bench grade products. Dioxan was purified by passage of the analytical grade material through an activated alumina column and the absence of peroxides tested by use of KI solution. Water was deionized and then glass distilled. ^{18}O-Enriched water and deuterium oxide (99.7% deuterium) were purchased from Prochem Ltd.

Methods. Kinetics were measured by the following general procedure. The substrate solution (usually 25 μL in dioxane) was added on the tip of a glass rod to buffer (2.5 mL) in a 1-cm pathlength silica gel placed in the thermostatted compartment of a spectrophotometer (Perkin-Elmer 554 or Gilford 2400S). The absorbance change at 400 nm was recorded on a potentiometric recorder. First-order rate constants were obtained from plots of $A_t - A_\infty$ vs. time. The UV spectrum of the product solution was scanned and the pH measured with a Radiometer PHM 62 pH meter calibrated to ±0.02 pH units with Merck standard buffers. The buffers employed are given in the tables. Except for hydroxide buffer the concentrations of the buffer species were kept mostly at 0.01 M because of buffer concentration effects. Some amine buffers gave substantial effects and where these were used the rate constant at zero buffer concentration was obtained by extrapolation. In some experiments the buffering was carried out

mechanically by using a machine similar to the one already described.[8]

The ortho esters gave substantial "Smiles" rearrangement products and the kinetics of the overall reaction were dissected into "Smiles" and ester attack components by product analysis of the phenolate product; the "Smiles" ether does not absorb at 405 nm, the optimal wavelength for phenolate absorption. A typical experiment is illustrated in Figure 1 for the hydrolysis of the 2-chloro-4-nitrophenyl ester of 1-hydroxynaphthalene-2-sulfonic acid (at 8.9×10^{-5} M in KOH buffer). The resultant spectrum (B) in Figure 1 is compared with standard solutions of the ether (C), the acid and phenol (A), and the acid (D). The extinction coefficient of the 2-chloro-4-nitrophenol at 405 nm in alkaline solutions is ϵ_{405} 17 558. There is an isosbestic wavelength at 324 nm for the reaction ester → acid + phenolate ion + ether. Thus the rate constant for attack at the ester (k_1) is given by the equation $k_1 = k_{obsd} \times$ [phenolate]/[starting ester] and the "Smiles" rate constant (k_2) by $k_2 = k_{obsd} - k_1$. The value of k_{obsd} ($= k_1 + k_2$) for the parallel reactions may be obtained from observing ester decay, ether formation, or phenolate release.

Product analysis by TLC was carried out routinely (Merck silica gel precoated plates); the products, both acid and ether, were sulfonic acids and did not move on the plates. Phenols and the amides from the trapping experiments (vide infra) were easily identified.

2′,4′-Dinitrophenyl 4-hydroxy-3,5-dimethylbenzenesulfonate (0.2 g) in dioxane (2.5 mL) was diluted to 10 mL with water and the pH maintained at 8.76 by the addition of KOH (1 M). The temperature was kept at 25 °C and after 1 h the solution acidified to pH 1.94 with concentrated HCl. The phenol was extracted with chloroform and identified as a single spot on TLC (eluent $Et_2O/CHCl_3$ 1:5). The water layer was evaporated and analyzed by ^1H NMR (D_2O). Comparison with an authentic solution indicated the presence of only 4-hydroxy-3,5-dimethylbenzenesulfonic acid as the organic component. The products of the naphthalene and other benzenesulfonate esters were analyzed by the UV method described for the kinetics.

Trapping experiments were performed with *N*-methylaniline on the hydrolysis of 2′-chloro-4′-nitrophenyl 1-hydroxynaphthalene-2-sulfonate in carbonate buffers at pH 10.30. The rate constant for phenol release was measured for a series of *N*-methylaniline concentrations. The rate constant for the reaction leading to 2-chloro-4-nitrophenol was obtained as shown above and the rate law (eq 2) observed. The rate law was used

$$k_1 = 1.90 \times 10^{-4} + 3.30 \times 10^{-4}[\text{PhNHMe}] \quad (2)$$

$$[\text{amide}]/[\text{phenolate}] = 3.30[\text{PhNHMe}]/(1.90 + 3.30[\text{PhNHMe}]) \quad (3)$$

to calculate the theoretical amount of amide product relative to the total phenol produced by eq 3. The amount of amide formed was obtained experimentally from UV absorbance measurements at 367 nm. The amide was prepared separately from the reaction of *N*-methylaniline and the sulfonyl chloride to serve as a UV standard. Figure 2 illustrates the spectrum of the "synthetic" reaction products where complete hydrolysis (B) accounts for the phenolate production; spectrum A is for the "synthetic" mixture where the *N*-phenyl-*N*-methyl-1-hydroxynaphthalene-2-sulfonamide completely accounts for the production of the phenolate ion. In the spectra of the synthetic mixtures (Figure 2) we kept the product ratios nominally at 60% ether and 40% phenolate as this was essentially the ratio observed in the hydrolytic process. The superior spectral change at 264 nm was not employed because of interference from the absorption of the aniline buffer. Extraction of the acidified product solution with $CHCl_3$ and evaporation of the extract gave a solid which showed phenol and anilide spots of TLC (eluent CH_2Cl_2). No products due to attack of the aniline on the aromatic nucleus of the leaving group were revealed by UV spectroscopy.

Trapping of the intermediate was also investigated by using the 4-hydroxybenzenesulfonate (4, R = H) and ammonia buffers. Various other amines were tried first (imidazole, pyridine, benzylamine, and morpholine) but these gave nuclear substitution

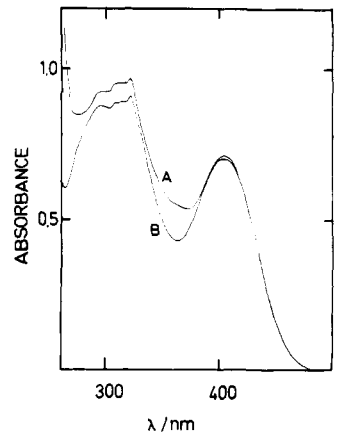


Figure 2. UV spectra of the products of aminolysis of the 2-chloro-4-nitrophenyl ester of 1-hydroxynaphthalene-2-sulfonate in carbonate buffer at pH 10.0, 20% dioxane–water (v/v), 50 °C, ionic strength maintained at 1 M with KCl. (A) The "Smiles" rearrangement product: 1-(2-chlor-4-nitrophenoxy)-naphthalene-2-sulfonic acid (Na salt) at 5.96×10^{-5} M + 2-chloro-4-nitrophenol (3.97×10^{-5} M) + *N*-phenyl-*N*-methyl-1-hydroxynaphthalene-2-sulfonamide at 3.97×10^{-5} M (this represents complete reaction of the intermediate with *N*-methylaniline—there is a 60% yield of "Smiles" product). (B) Products of *hydrolysis* of the above ester under the above conditions: "Smiles" product (5.96×10^{-5} M) + 2-chloro-4-nitrophenol (3.97×10^{-5} M) + 1-hydroxynaphthalene-2-sulfonic acid (Na salt, 3.97×10^{-5} M).

(as judged from the UV spectra of the products) which would have complicated the analysis. The reaction was followed kinetically by using concentrations from 0.1 to 1 M in total ammonia buffer (fraction base = 0.8, 20% dioxane–water (v/v), ionic strength kept at 0.2 M with KCl, pH 10.00). The product was acidified to pH 2 and extracted with $CHCl_3$ and the extract evaporated and then taken up in 5 mL of dioxane. An aliquot of this solution (25 μL) was dissolved in 2.5 mL of EtOH (0.056 M HCl) and the absorbance measured at 241 nm. Test runs were carried out with known amounts of the potential amide product and these showed that the sample lost 45% during the extraction. This value is used to calibrate the method. HPLC was also used to analyze the product of the extraction. The HPLC column (reversed phase, Lichrosorb RP8 10 μm, 25 cm × 4.5 mm) was calibrated with a standard solution of the amide prepared separately and used in conjunction with a Pye-Unicam LC-XPD pump, LC–UV detector, LC-XP Dialamix, and PM-8251 single-pen recorder. Peak areas were estimated by weighing cutouts of photocopies of the traces. The eluent was a 40% methanol–water solution. TLC analysis also indicated that amide was produced in the reaction. Although the assay method involving extraction is relatively crude it is sufficient for the purposes of the trapping experiment (see the Results section).

Trapping with ^{18}O-enriched water was carried out with **4** (R = H). A solution of the ester in dioxane (0.1 g in 2 mL) was added slowly with stirring to water (8 mL, 5.79% ^{18}O-enriched) kept at pH 10.0 with carbonate buffer (0.1 M) at 25 °C. TLC was used to check that the reaction was complete and then the solution was acidified and extracted with $CHCl_3$. The $CHCl_3$ extract was dried (Na_2SO_4) and evaporated, and the residue subjected directly to mass spectral analysis (AEI MS 902 spectrometer, carried out under the direction of Dr. J. F. J. Todd). The 2,4-dinitrophenol molecular ion was identified in the recorder trace and the ratio (M + 2)/M obtained from the peak heights.

Molecular orbital calculations were carried out at the Computer Centre, ICI Organics Division, Blackely. (We are grateful to Drs. J. A. Morley and P. Bamfield for their help.) We used a CNDO/54 programme parameterized for sulfur d orbitals. Bond lengths used are given in a supplementary table and are taken from standard works.[9] The trigonal angle was assumed to be 120° for all atoms.

(8) Thea, S.; Williams, A. *J. Chem. Soc. Perkin Trans. 2* **1981**, 72.

(9) Tables of interatomic distances and configurations of molecules and ions: "Supplement Special Publication No. 18"; The Chemical Society: London, 1965; S3s–S23s.

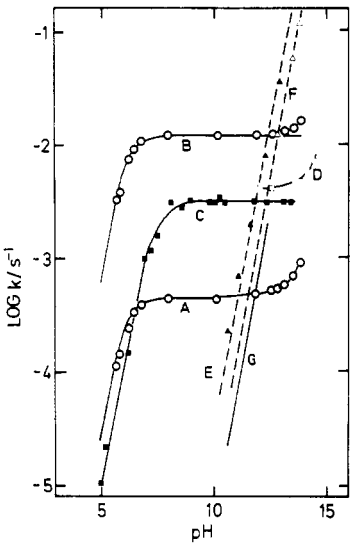


Figure 3. Dependence on pH of the reaction of sulfonate esters for 20% dioxane–water (v/v). (A) The hydrolytic component of the reaction of 2-chloro-4-nitrophenyl 2-hydroxynaphthalene-1-sulfonate at 50 °C and ionic strength maintained at 1 M with KCl. (B) The "Smiles" rearrangement reaction of the above ester under the same conditions. (C) The hydrolysis of 2,4-dinitrophenyl 3,5-dimethyl-4-hydroxybenzenesulfonate at 25 °C and ionic strength maintained at 0.2 M with KCl. (D) The hydrolysis of the above ester at 1 M ionic strength. (E) The hydrolysis of 2,4-dinitrophenyl benzenesulfonate at 25 °C 1 M ionic strength. (F) The hydrolysis of 2-chloro-4-nitrophenyl 2-methoxynaphthalene-1-sulfonate at 50 °C and ionic strength at 1 M. (G) The rate constants calculated for the hydrolysis of the 2,4-dinitrophenyl ester of 3,5-dimethyl-4-hydroxybenzenesulfonate at 25 °C (see text). The lines are calculated from the equations given in the text by using the parameters from Table I.

Calculations were made of nonbonding energies for selected atom pairs by using parameters from Derissen and Smit[10] and the "Hill" function. Interatomic distances were calculated by standard trigonometry with the bond lengths and angle above.

Ionization constants were obtained for substrates by measuring the UV spectrum as a function of pH and the pK determined from a plot of pH vs. log FA/FB (eq 4); FA and FB are the fractions of acid and base species respectively. The absorption at a suitable wavelength (given in Table I) was used to obtain FA and FB. Extrapolation of the absorbance reading to zero time was necessary in many cases as the compounds decomposed at the higher pH's. Linear regressions were performed with a Texas Instruments T1-51 III calculator.

$$\mathrm{pH} = \mathrm{p}K - \log \mathrm{FA/FB} \quad (4)$$

Results

The hydrolysis of *p*-hydroxyarenesulfonates exhibited excellent pseudo-first-order kinetics over at least 90% of the reaction. The products were simply the acid and phenol except when certain amines were used as buffer species in nucleophilic aromatic substitution. The effect of the latter buffers was not investigated except that extrapolation of the rates to zero buffer concentration gave the hydrolytic rate constant (k_1). The pH dependence of k_1 obeyed eq 5; k_a is k_s for the "Smiles" component (k_2).

$$k_1 \text{ (or } k_2) = (k_a + k_b[\mathrm{OH^-}])/(1 + [\mathrm{H^+}]/K_a) \quad (5)$$

The aqueous degradation of *o*-hydroxyarenesulfonate esters also obeyed good pseudo-first-order kinetics but the products indicated substantial "Smiles" rearrangement as a competitor for the hydrolytic path. The overall rate constant was dissected into k_1 and k_2 and k_1 fitted eq 5. In most cases the k_b term was never important as the hydroxide ion concentration was not sufficiently high. The pH dependence of both k_1 and k_2 are illustrated in Figure 3 for selected hydroxy sulfonates.

The ionization constants measured spectrophotometrically for the hydroxyarenesulfonates agree, within very close limits, with those measured kinetically (Table I) indicating that the hydrolysis and "Smiles" reaction are governed by a rapid equilibrium.

The ester substrates with no ionizable hydroxyl functions hydrolyzed in alkali according to the rate law $k_1 = k_{OH}[OH^-]$. The parameters for all the esters are recorded in Table I.

The rate constant for the "Smiles" rearrangement obeys eq 5 with $k_b = 0$. The incursion of a small (ca. 20%) increase in k_2 at high pH cannot be explained as it is not thought possible that hydroxide ion could catalyze the reaction of an already ionized species. It is possible that the increase is due to a specific anion effect. Values of k_s (analogous to k_a) for the "Smiles" rate constant are recorded in Table I.

N-Methylaniline trapping gives roughly twice as much anilide product (Table II) than is predicted from the kinetic eq 2 for second-order attack of aniline on the ionized ester (**6**, R = H, Ar = $C_6H_32Cl_4NO_2$). The use of ammonia as a trap for the hydrolysis of **4** (R = H) indicates *no increase* in overall rate constant although amide product is formed in significant amounts in increasing ammonia concentrations. At 25 °C and pH 10.00 the rate constant for 2,4-dinitrophenol release varied randomly about a mean of 3.09×10^{-3} s^{-1} with maximum deviations of ±3.6%. The value agrees well with the k_a reported in Table I for this compound derived from a much more extensive set of data. The yield of amide for 1 M buffer has therefore an *upper* limit of 3.6% which is well outside the error limits of the yields found experimentally (9.3% by UV and 7.0% by the HPLC analysis) allowing for a loss of 45% found for control samples under *exactly* the same conditions.

The effect of temperature on the kinetic parameters is recorded in Table III. The temperature effect on the ionization was also measured for two substrates: **5** (R = H, Ar = C_6H_3-2,4-di-NO_2) had $\Delta H_0 = 6.1 \pm 0.4$ kcal/mol and $\Delta S_0 = -9.1 \pm 1.4$ cal/mol deg at 25 °C; **6** (R = H, Ar = C_6H_3-2-Cl-4-NO_2) had $\Delta H_0 = 2.05 \pm 0.09$ kcal/mol and $\Delta S_0 = -16.0 \pm 0.3$ cal/mol deg at 25 °C. These values are not very different from those previously determined for phenols in water solution.[11,12]

The value of k_a in deuterium oxide solvent was measured (R = H, Ar = C_6H_3-2-Cl-4-NO_2) after allowing for the "Smiles" component ($k_a = 1.7 \times 10^{-4}$ s^{-1} under conditions given in Table I). The value of $k_a^{H_2O}/k_a^{D_2O} = 1.12$.

Oxygen-18 labeling with **4** (R = H) gave an (M + 2)/M ratio of 1.230% for the product phenol. Cleavage at the ArO–SO_2 bond should yield natural 2,4-dinitrophenol ((M + 2)/M = 1.224%) whereas Ar–O fission should yield enriched material calculated from the excess ^{18}O-enrichment in water of 5.796% to be (M + 2)/M = 7.026%. The small natural enrichment in oxygen and the ^{13}C-enrichment in natural carbon were taken into account in the calculations.

Discussion

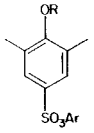
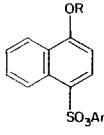
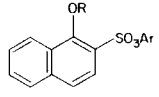
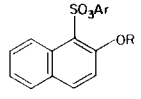
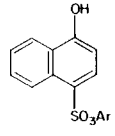
Attack at Ester. The *apparent* bimolecular rate constants (k_aK_a/K_w) for attack of hydroxide ion on the *neutral*

(10) Derissen, J. L.; Smit, P. H. *Acta Crystallogr., Sect. A* **1978**, *A34*, 842.

(11) Boulton, P. D.; Hall, F. M.; Reece, I. H. *J. Chem. Soc. B* **1966**, 717; *Ibid.* **1967**, 709.

(12) (a) Bolton, P. D.; Hall, F. M.; Reece, I. H. *Spectrochim. Acta* **1966**, *22*, 1149. (b) Rochester, C. H. *Trans. Faraday Soc.* **1966**, *62*, 355. (c) Rochester, C. H.; Rossall, B. *Ibid.* **1969**, *65*, 1004.

Table I. Kinetic Parameters for the Hydrolysis of Sulfonate Esters[a,r]

ester		mp, °C	λ, nm[e]	pK (kin)[c]	k_a, s^{-1}	k_s, s^{-1} [d]	k'', M^{-1} s^{-1} [b]	N[h]	pH[m]	T, °C
				2,4-Dinitrophenyl Ester						
	R = R[f]	143–144	294	7.40 (7.40)	3.2×10^{-3}		4.7×10^{4}	17[n]	4.5–14.5	25
							4.15×10^{-3} [t]	6	12–14.5	25
	R = Me[f]						0.24[g]			25
	R = H	156–157	345	6.50 (6.45)	2.6×10^{-2}		3.5×10^{6}	18	3.1–13.6	25
	R = Me	140–141					0.089	4	12.3–13.6	25
4-acetamidobenzenesulfonate		187–189					1.5	13	9–12	25
benzenesulfonate[f]		118.5–119.5[s]					2.0	6	10.6–13.9	25
4-benzamidobenzenesulfonate		174–175					1.3	13	11–14	25
				2-Chloro-4-nitrophenyl Esters						
	R = H[p]	143–144	371	4.88 (4.80)	1.9×10^{-4}	2.80×10^{-4}	2.0×10^{5}	8	5.1–12.9	50
	R = Me	108–109					0.30	4	11.9–13.6	50
	R = H[q]	135–136	350	6.14 (6.10)	4.5×10^{-4}	1.3×10^{-2}	2.6×10^{4}	13	5.6–13.9	50
	R = Me	117–118					0.12	3	12.9–13.9	50
		174	366	6.58 (6.60)	3.30×10^{-4}		6.7×10^{3}	7	5.1–12.9	50

[a] Except where stated the ionic strength was maintained at 1 M with KCl. All solvents were 20% dioxane–water (v/v). [b] This is either k_{OH}, the true bimolecular rate constant for attack of hydroxide ion ion the ester, or $k_a K_a / K_w$, the apparent second-order rate constant for the neutral hydroxy ester. For the mixed solvents at 25 °C pK_w = 14.62 and at 50 °C pK_w = 13.89; we assume that the influence of the ionic strength on pK_w is negligible. (Harned, H. S.; Fallon, L. D. *J. Am. Chem. Soc.* **1939**, *61*, 2374.) [c] Values in parenthesis represent the pK determined from the kinetics by fitting to eq 5. [d] The rate constant for the "Smiles" rearrangement of the conjugate base of the hydroxy ester. [e] Wavelength used to determine the pK spectrophotometrically. [f] Ionic strength maintained at 0.2 M with KCl. [g] Calculated from the rate constant for alkaline hydrolysis of the 2,4-dinitrophenyl benzenesulfonate (k_{OH}^{H}) using the relationship: $\log k_{OH}^{calc}/k_{OH}^{H} = 2.24\Sigma\sigma$ according to Palm, V. A.; Vizgert, R. V. *Dokl. Akad. Nauk. SSSR* **1962**, *142*, 1091. [h] Number of data points. [m] The pH was regulated with the following buffer species: KOH, carbonate, succinic acid, acetic acid, boric acid, tris(hydroxymethyl)aminomethane. The pH stat was also used for selected points. Some amine buffers were also employed for the 3,5-dimethyl-4-hydroxybenzenesulfonate ester hydrolyses (see text). [n] In some cases the value of the rate constant at zero buffer concentration was obtained from extrapolation. [p] A value for k_b, 4.1×10^{-3} M^{-1} s^{-1} may be estimated for this ester at 1 M ionic strength (KCl). [q] A value of 4.7×10^{-4} M^{-1} s^{-1} may be estimated for this ester for k_b. [r] Errors in the pK measurements are not greater than ±0.02 and in the kinetic parameters are no greater than 5%. [s] Lit. mp 118–119 °C. (Vizgert, R. V. *Zh. Obshc. Khim.* **1958**, *28*, 1873.) [t] Rate constant for reaction of hydroxide ion with the base form of **4** (R = H).

Table II. *N*-Methylaniline Trapping of an Intermediate in the Hydrolysis of the 2-Chloro-4-nitrophenyl Ester of 1-Hydroxynaphthalene-2-sulfonic Acid (6)[c]

[PhNHMe], M	anilide product, %[b,d] calcd[a]	obsd
9.19×10^{-3}	1.6	2.4
2.57×10^{-2}	4.3	8.6
4.78×10^{-2}	7.7	18.8

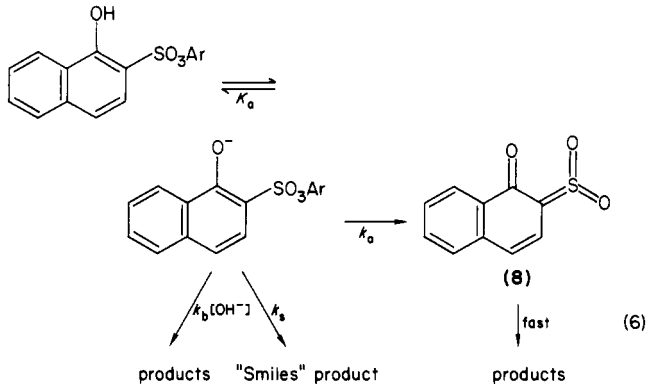
[a] Calculated according to eq 2. [b] This is as a percentage of the reaction (k_1) *not* going through the "Smiles" route. [c] Dioxane–water 20% (v/v), pH 10.30 maintained by carbonate (0.01 M), ionic strength kept at 1 M with KCl, 50.0 °C. [d] *N*-Phenyl-*N*-methyl-1-hydroxynaphthalene-2-sulfonamide had mp 85–86 °C.

Table III. Activation Parameters for Rate Constants for Reactions of *o*- and *p*-Hydroxyarenesulfonate Esters[a]

ester	rate constant[b,f]	T, °C	$\Delta H^{\ddagger}$[c]	$\Delta S^{\ddagger}$[c]
4 (R = H)	3.09×10^{-3}	25.0		
k_a	1.08×10^{-2}	35.1	21.4 ± 0.5	1.7 ± 1.6
	2.57×10^{-2}	43.1		
5 (R = H, Ar = C_6H_3-2-Cl-4-NO_2)				
	1.16×10^{-4}	41.5		
k_a	3.49×10^{-4}	50.1	24.8 ± 0.2	2.15 ± 0.63
	9.92×10^{-4}	59.1		
7 (R = H, Ar = C_6H_3-2-Cl-4-NO_2)				
	1.44×10^{-4}	40.1		
k_a	4.51×10^{-4}	50.0	24.7 ± 1.3	2.6 ± 4.2
	1.56×10^{-3}	59.6		
	4.51×10^{-3}	40.1		
k_s	1.24×10^{-2}	50.0	20.8 ± 0.6	−2.8 ± 1.7
	3.39×10^{-2}	59.6		
6 (R = H, Ar = C_6H_3-2-Cl-4-NO_2)				
	6.61×10^{-5}	41.5		
k_a	1.91×10^{-4}	50.1	24.20 ± 0.02	−0.89 ± 0.05
	5.37×10^{-4}	59.1		
	8.99×10^{-5}	41.5		
k_s	2.78×10^{-4}	50.1	24.8 ± 0.5	1.8 ± 1.7
	7.73×10^{-4}	59.1		
	1.89×10^{5}	50.1		
k_aK_a/K_w[d]	3.75×10^{5}	60.0	14.5 ± 0.1	10.3 ± 0.3
	5.82×10^{5}	66.4		
5 (R = H, Ar = C_6H_3-2,4-di-NO_2)				
	1.00×10^{-2}	16.5		
k_a	2.66×10^{-2}	25.0	19.0 ± 0.1	−2.0 ± 0.4
	7.57×10^{-2}	34.8		
	1.94×10^{6}	16.5		
k_aK_a/K_w[e]	3.55×10^{6}	25.0	11.7 ± 0.1	10.8 ± 0.3
	6.90×10^{6}	34.8		

[a] Dioxane–water 20% (v/v), ionic strength maintained at 1 M with KCl. [b] Except where stated the reactions were carried out with 0.01 M KOH buffer solutions which exhibited pH 11.89 at 50 °C. [c] $\Delta H^{\ddagger}$ is given as kcal/mol, and $\Delta S^{\ddagger}$ as cal/mol deg both at 25 °C. The standard states for the second-order rate constants are 1 M. [d] Succinate buffer (0.01 M) at pH 4.31 at 50.1 °C. [e] Succinate buffer (0.01 M) at pH 4.39 at 25.0 °C. [f] Units for k_a and k_s are s^{-1} and for k'' are $M^{-1}\ s^{-1}$.

hydroxy esters are dramatically enhanced (10^5 to 10^7-fold) over the unambiguous bimolecular rate constants for hydroxide ion attack on the methoxy esters (Table IV). The mechanism for the k_a term cannot therefore be a BAc2 type as in the methoxy esters and the simplest hypothesis is that an E1cB process (eq 6) occurs. In the case of the ortho esters this will involve an *o*-sulfoquinone intermediate (e.g., **8**) and a *p*-sulfoquinone (such as **1**) is postulated for the para esters.

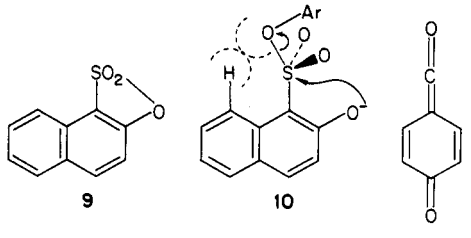


The ortho ester reaction possesses a second degradative route namely the "Smiles" rearrangement (k_s in eq 6) easily dissected from the overall kinetics by product analysis. The positive entropy of activation for k_aK_a/K_w (Table III) is good evidence that the mechanism is *not* a bimolecular process which should have a considerable *negative* entropy. The entropies of activation for the k_a term are near zero and are mostly slightly positive in good agreement with a bona fide unimolecular reaction.[13]

A mechanism involving O–Ar fission is eliminated by labeling experiments indicating no enrichment in the hydroxyl group of the product 2,4-dinitrophenol from **4** (R = H). The deuterium oxide solvent isotope effect of 1.12 for k_a for the ortho ester (**6**, R = H, Ar = C_6H_3-2-Cl-4-NO_2) indicates that a general base catalysis of water attack is not responsible for the reaction.[14]

Trapping with amine nucleophiles indicates that more amide product is formed than is expected from the kinetic equation; this is consistent with a mechanism involving rate-limiting intermediate formation.

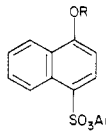
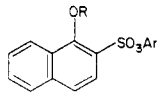
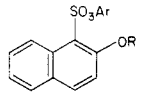
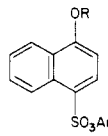
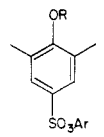
A *p*-sulfoquinone appears to be the simplest intermediate to explain the *p*-hydroxy ester hydrolysis. It is conceivable that a benzothioxetane *S*,*S*-dioxide (e.g., **9**) could account for the results for the ortho esters but this is unlikely as the rate constants for k_a are within one order of magnitude the same as that for the para series. Moreover, the ester **7** (R = H, Ar = C_6H_3-2-Cl-4-NO_2) would have difficulty in the expulsion of the leaving group to form **9** owing to unfavorable peri interactions (**10**) which would not be felt in the corresponding expulsion from the 1-hydroxynaphthalene-2-sulfonate (**6**).



Parallel studies have indicated a similar type of intermediate (**11**) for the hydrolysis of 4-hydroxybenzoates[15]

(13) Schaleger, L. L.; Long, F. A. *Adv. Phys. Org. Chem.* **1963**, *1*, 1.
(14) Johnson, S. L. *Adv. Phys. Org. Chem.* **1967**, *5*, 237.
(15) (a) Thea, S.; Guanti, G.; Petrillo, G.; Hopkins, A.; Williams, A. *J. Chem. Soc. Chem. Commun.* **1982**, 577. (b) Thea, S.; Guanti, G.; Kashefi-Naini, N.; Williams, A. *Ibid.* **1983**, 529. (c) Cevasco, G.; Guanti, G.; Thea, S.; Williams, A. *Ibid.* **1984**, 783. (d) Cevasco, G.; Guanti, G.; Hopkins, A.; Thea, S.; Williams, A. *J. Org. Chem.* **1985**, *50*, 479. (e) Thea, S., Cevasco, G., Guanti, G., Kashefi-Naini, N., Williams, A. *Ibid.* **1985**, *50*, 1867.

Table IV. Comparison of the Ratio of k_aK_a/K_W (R = H) to k_{OH} (R = Me) for the Hydrolysis of Hydroxy- and Methoxyarenesulfonate Esters and the Binding Energy Differences for the Intermediates[e]

substrate	T, °C	k_a, s^{-1}	k_aK_a/K_Wk_{OH}	pK	$E^{1/2}$, mV[b]	E_{bind}[c]	$E_{nonbond}$[d]
			2-Chloro-4-nitrophenyl Esters				
	50	3.3×10^{-4}		6.58	-710	7.94	10.47
	50	1.9×10^{-4}	6.5×10^5	4.88	-560	0	0
	50	4.5×10^{-4}	2.1×10^5	6.14	-560	7.85	15.94
			2,4-Dinitrophenyl Esters				
	25	2.6×10^{-2}	3.9×10^7	6.50	-710		
	25	3.2×10^{-3}	2.0×10^5	7.40	-670[a]		

[a] This value is for the 2,5-dimethyl-*p*-quinone. [b] Values of $E^{1/2}$ are for the quinone[6] analogous to the intermediate sulfoquinone. [c] Relative energy calculated from the CNDO/54 program. Units in kcal/mol; the energy corresponds to the "total binding" energy for the sulfoquinone intermediate. [d] Relative nonbonding energies of the sulfoquinone intermediate calculated as indicated in the text; units kcal/mol. [e] Kinetic and equilibrium data from Table I.

which is analogous to a ketene in the same way that sulfoquinone is analogous to a sulfene.

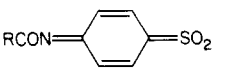
The reactivity of an E1cB mechanism will depend on the leaving ability of the phenoxide ion.[16] Table IV indicates that increasing the acidity of the phenol leaving group increases k_2. The amount of change (judged from a *two point* Brønsted slope β_L = −1.3 for the 1-naphthol-4-sulfonate esters (**5**, R = H)) might be expected for extensive S–O fission in the transition state. Smaller values are seen with nucleophilic attack (of OH^-) on aryl sulfonate esters where S–O cleavage is also thought to be relatively far advanced in the transition state (β_L ca. −0.9).[17,18] The charge development on the leaving oxygen is close to that seen in sulfene formation from aryl sulfonates (β_L = −1.5 to −2.4).[4a,d]

The relatively large increase in negative effective charge on the leaving oxygen requires a decrease elsewhere in the molecule presumably from the para or ortho oxy anion group. We therefore expect a strong dependence of k_a on the p*K* of the hydroxy ester. Such an effect is not apparent in the present examples as we believe other effects are also being felt. Ester **6** (R = H, Ar = C_6H_3-2-Cl-4-NO_2) has a relatively low p*K* (4.88) but its k_a is in the same order of magnitude as that for the corresponding ester **7** (R = H, Ar = C_6H_3-2-Cl-4-NO_2) (p*K* = 6.58) and the ester **5** (R = H, Ar = C_6H_3-2-Cl-4-NO_2) (p*K* = 6.14). Energies calculated by the CNDO program indicate that the intermediate from the 1-hydroxy 2-sulfonate ester is more stable than those from the 1-hydroxy 4-sulfonate and 2-hydroxy 1-sulfonate (Table IV). We therefore suppose that similarity of k_a for the 1-hydroxy-2-sulfonate and the other esters results from a balance between the increased stability of the intermediate (which should be reflected in the transition state) and the lower p*K* of the hydroxy function.

It is interesting to speculate on the cause of the stability differences as expressed by k_a (Table IV); we believe that some of these come from the unfavorable nonbonding interactions between the SO_2 oxygen and the peri hydrogen; nonbonding energy calculations in Table IV support this. Table IV also indicates that stability of the intermediates might also bear a relationship (apart from the nonbonding component) with the half-wave potentials for quinones.

It is expected from this work that the 4-hydroxy sulfonyl chlorides studied by Hall[2] and by Zincke and Brüne[1b] hydrolyze and react with nucleophiles through the sulfoquinone. The base form of the 4-hydroxy-3,5-dimethylbenzenesulfonyl chloride is unlikely to survive long enough in alkali to allow its detection because the 2,4-dinitrophenyl ester has a half life of only 4 min. Hall was able to determine UV spectra of such base species because he worked with ether solvent. The low p*K* of the 3,5-dibromo species presumably lowers the reactivity of the sulfonyl chloride sufficiently to enable the base species to be "seen" in water solvent.[1b]

The alkaline hydrolysis of 4-benzamido- and 4-acetamidobenzenesulfonate esters (Table I) gave k_{OH} values close to that for the benzenesulfonate ester. There seems to be no good evidence for the participation of "iminosulfoquinones" (**12**) in the present reaction although these have been postulated in some polymerization reactions.[20]



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(16) Williams, A.; Douglas, K. T. *Chem. Rev.* **1975**, *75*, 627.
(17) D'Rozario, P.; Smyth, R. L.; Williams, A. *J. Am. Chem. Soc.* **1984**, *106*, 5027.
(18) Deacon, T.; Farrar, C. R.; Sikkel, B. J.; Williams, A. *J. Am. Chem. Soc.* **1978**, *100*, 2525.
(19) We use the value of k_a for ester **5** Ar = C_6H_3-2-Cl-4-NO_2, R = H at 50 °C and calculated k_a for ester **5** Ar = C_6H_3-2,4-di-NO_2, R = H at 50 °C (0.342 s^{-1}) by using data from Table III.
(20) Contreras, J.; Jones, J. I. *Phosphorus Sulfur* **1979**, *6*, 67.

"Smiles" Reaction. The entropy of activation for k_s (Table IV) is close to zero consistent with a unimolecular process. Table I indicates that the 2-hydroxynaphthalene-1-sulfonate is about 50-fold more reactive than the 1-hydroxynaphthalene-2-sulfonate. This could be due to the lower pK of the 1-hydroxy group (4.88 as opposed to 6.14); a smaller factor could arise from peri interactions in the naphthalene-1-sulfonate not present in the naphthalene-2-sulfonate constraining the aryl group to be close to the 2-oxy anion.

(21) A preliminary report of part of this work: Thea, S.; Guanti, G.; Hopkins, A.; Williams, A. *J. Am. Chem. Soc.* **1982**, *104*, 1128.

Acknowledgment. We are grateful to CNR and Ministero della Pubblica Istruzione (Italy) and SERC (UK) for financial support. Part of this work was carried out during tenure of a Ciba-Geigy Senior Fellowship (AW). We thank C. Palmero and C. Pernigotti for their assistance with some of the experiments.

Supplementary Material Available: Tables for analytical and physical data for the substrates and details of molecular orbital and nonbonding calculations (4 pages). Ordering information is given on any current masthead page.

Stabilization Demands of Diethyl Phosphonate Substituted Carbocations as Revealed by Substituent Effects

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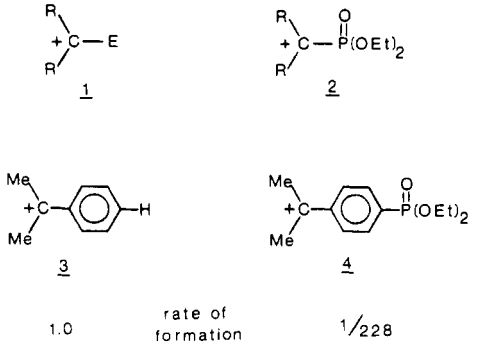
Department of Chemistry, University of Notre Dame, Notre Dame, Indiana 46556

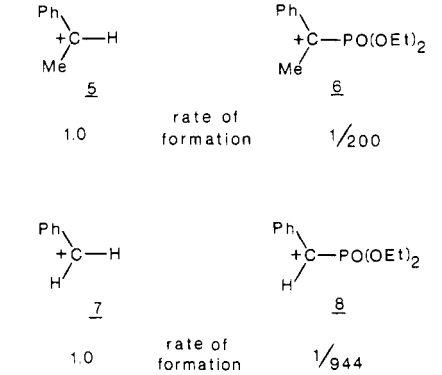
Received November 30, 1984

Trifluoroethanolyses of a series of mesylate derivatives of diethyl (1-aryl-1-hydroxymethyl)phosphonates, **9**, gave a Hammett ρ value of −10.1 in the electron donor substituent region. This value was slightly less than the value of −11.6 seen in the corresponding benzyl mesylates, $ArCH_2OMs$, **12**, in hexafluoroisopropyl alcohol. These data suggest that the demand for aryl group stabilization in the intermediate phosphoryl-substituted cation **10** does not surpass that of the α-H analogues, the benzyl cations. Some other factor must therefore account for the relative ease of formation of cations **10**, which have the electronegative diethyl phosphonate group attached directly to the cationic center. The likely factor is an offsetting cation stabilizing feature associated with the diethyl phosphonate group. The Hammett plots for both mesylates **9** and **12** show a break, with decreased ρ values (−6.1 and −5.1, respectively) being observed in the electron-withdrawing region of the plot. Solvent effect studies on **9**-*m*-F suggested that a change to "borderline behavior" is the origin of the break in the Hammett plot. A mechanistic change to the k_Δ process could be ruled out. The triflate derivative of diethyl (1-hydroxyethyl)phosphonate, **14**, gave mixtures of substitution and elimination products on solvolysis. Solvent effect studies indicated a largely nucleophilic mechanism, while isotope effect studies were in line with some cationic character in the transition state in the highly ionizing, nonnucleophilic hexafluoroisopropyl alcohol solvent. Ion pair formation or the S_N2 (intermediate) mechanism could rationalize the behavior of **14** in more highly ionizing solvents.

Our interest in electronegatively substituted carbocations of general type **1**[1,2] has led us to generate certain phosphoryl-substituted cations **2**. The diethyl phosphonate group is strongly electron withdrawing (σ = 0.52).[3] Cation **4** forms 228 times less readily than the cumyl cation **3** (σ^+ = 0.50). Surprisingly, cation **6** could be generated



quite readily (only 200 times more slowly than the α-H analogue **5**). This was unexpected since a potent electron-withdrawing group was attached directly to the cationic center of **6**. Naively, one might expect that the effect of this group would be to retard the rate to a much greater extent in **6** than in **4**, where the cationic center is insulated from the diethyl phosphonate group by a phenyl ring. This phenomenon, i.e., relatively small rate retardations on attachment of $PO(OEt)_2$ directly to a cationic center, appeared to be general. Cation **8** formed only 944 times less readily than the α-H analogue, the benzyl cation **7**.



Why does the diethyl phosphonate group, attached directly to the cationic center of **6** or **8**, have such a small rate retarding effect relative to hydrogen? A potential

(1) For a discussion of the chemistry of cation **1**, where E = COR, see: Creary, X. *Acc. Chem. Res.* **1985**, *18*, 3–8.
(2) Creary, X.; Geiger, C. C.; Hilton, K. *J. Am. Chem. Soc.* **1983**, *105*, 2851–8.
(3) Tsvetkov, E. N.; Lobanov, D. I.; Isosenkova, L. A.; Kabachnik, M. I. *J. Gen. Chem. USSR (Engl. Transl.)* **1969**, *39*, 2126–32. An earlier value of 0.60 has been reported. See: Freedman, L. D.; Jaffe, H. H. *J. Am. Chem. Soc.* **1955**, *77*, 920–1.

0022-3263/85/1950-2165$01.50/0