

# Hydrolysis of $\alpha$ -Methoxystyrenes. A Molecular Orbital-Perturbation Analysis of Substituent Effects and the Relationship between Hydration and Solvolysis Reactions

Gordon Marc Loudon\* and Carl Berke<sup>1</sup>

Contribution from the Baker and Olin Laboratories of Chemistry, Cornell University, Ithaca, New York 14850. Received January 23, 1974

**Abstract:** We have found that the rates of hydration of para-substituted  $\alpha$ -methoxystyrenes, a reaction believed to proceed through carbonium ion intermediates, show a systematic downward curvature when correlated by  $\sigma^+$  but a fair correlation against  $\sigma$  values. This behavior is not due to a change in rate-determining step, nor can it be viewed as equivalent to a curved Brønsted plot. We have examined substituent effects in the hydration reactions of various  $\alpha$ -substituted styrenes with the Yukawa-Tsuno relation, and we have found that, as the electron-donating character of the  $\alpha$  substituent is increased, an increasingly less negative  $\rho$  is accompanied by a progressively smaller  $r$  parameter; the hydrolysis of  $\alpha$ -methoxystyrenes is an extreme case of this behavior, and the small  $r$  value for this reaction leads to the observation of downward curvature in the  $\sigma^+$  correlation. The hydrolysis of  $\alpha$ -acetoxystyrenes represents a deviation from the relationship of  $\rho$  and  $r$ , and possible reasons for this observation are discussed. Extended Hückel calculations show that the relationship between  $\rho$  and  $r$  in hydration reactions is theoretically reasonable, and perturbation arguments reveal that the decreased "resonance interaction" of substituents in the para position in styrenes substituted in the  $\alpha$  position with electron-donating substituents is due to the perturbation to significantly higher energies of the lowest unoccupied molecular orbital (LUMO) of the 1-phenylethyl cation (as a model for the transition state of the hydration reaction) by the  $\alpha$  substituent. Similar perturbation arguments explain why hydration reactions are less sensitive to substituent effects than solvolysis reactions leading to the same first intermediate carbonium ion. The observation of "saturation effects" in substituent-induced perturbations is given theoretical support through these arguments.

The use of linear free energy relationships is an extremely useful tool in the exploration of mechanistic hypotheses in a wide variety of situations.<sup>2a</sup> In particular, the generalized Hammett-type eq 1, introduced by Yukawa and Tsuno,<sup>2b</sup> at least in its several reduced forms, has proved especially valuable. In this equation,  $k_{x_i}$  is the rate constant for the reaction  $i$  of the compound with substituent  $x$ ,  $k_{H_i}$  is the rate constant for the same reaction of the unsubstituted compound,  $\sigma_x$  is the Hammett<sup>3,4</sup>  $\sigma$  constant for substituent  $x$ , and  $\sigma_x^+$  is the Brown-Okamoto<sup>4,5</sup> constant for substituent  $x$ .  $\rho_i$  measures the susceptibility of reaction  $i$  to a change in substituent, and  $r_i$  measures the importance of resonance effects in reaction  $i$ . When  $r_i = 0$ , eq 1 reduces to the Hammett equation,<sup>3</sup> with parameters defined by benzoic acid ionization equilibria; when  $r_i = 1$ , eq 1 becomes the Brown-Okamoto<sup>5</sup> equation, with parameters defined for a standard *tert*-cumyl chloride solvolysis reaction. Although it seems intuitively reasonable that there should be a relationship between the magnitude of  $\rho_i$ , a measure of "electron demand" in passing from ground state to transition state, and that of  $r_i$ , such a relationship does not seem to exist, a point that has been stated<sup>2a</sup> and repeated.<sup>2b,6</sup> One of the goals of this paper is to explore this intuitive idea in greater depth and to demonstrate in both experiment

and theory that in a series closely related hydration reactions, namely, the hydration of  $\alpha$ -substituted styrenes, changes in  $\rho_i$  and  $r_i$  are related in a quite understandable fashion.

Our point of departure in this study is the mechanistic investigation of the acid-catalyzed hydrolysis of ring-substituted  $\alpha$ -methoxystyrenes. Recently, Loudon, *et al.*,<sup>7</sup> considered the hydrolysis of these compounds and observed indications that there existed a downward-curving plot of  $\log k$  for hydronium ion catalysis of this reaction *vs.*  $\sigma^+$ , although these authors expressed the reservation that the curvature in this plot might not be real because of the large experimental error in  $\log k$  resulting from the extrapolative manner in which these rates were determined. In fact, these rates were correlated rather well by  $\sigma$  values, even though the reaction is believed to proceed through carbonium ions which can be conjugatively stabilized by para substituents on the benzene ring. If the curvature in the  $\sigma^+$  correlation were real, a change in the rate-determining step might be indicated for this vinyl ether hydrolysis reaction, a point which could be established by further mechanistic investigation. Changes in the rate-determining step or changes in mechanism have been deduced for other reactions using regular deviations from linear free energy relationships.<sup>8</sup> The structural requirements for a change in the rate-determining step in vinyl ether hydrolysis, from rate-determining protonation of the double bond to rate-determining hydra-

(1) Undergraduate Research Participant, 1973.

(2) (a) P. R. Wells, *Chem. Rev.*, **63**, 171 (1963); (b) Y. Yukawa and Y. Tsuno, *Bull. Soc. Chem. Jap.*, **32**, 965, 971 (1959).

(3) L. P. Hammett, "Physical Organic Chemistry," 2nd ed, McGraw-Hill, New York, N. Y., 1971, Chapter 11.

(4) All  $\sigma^+$  and  $\sigma$  constants used herein were taken from J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," Wiley, New York, N. Y., 1963, p 204.

(5) H. C. Brown and Y. Okamoto, *J. Amer. Chem. Soc.*, **80**, 4979 (1958).

(6) Y. Okamoto and H. C. Brown, *J. Org. Chem.*, **22**, 485 (1957).

(7) G. M. Loudon, C. K. Smith, and S. E. Zimmerman, *J. Amer. Chem. Soc.*, **96**, 465 (1974).

(8) (a) B. M. Anderson and W. P. Jencks, *J. Amer. Chem. Soc.*, **82**, 1773 (1960); (b) D. S. Noyce and L. R. Snyder *ibid.*, **81**, 620 (1959); (c) D. N. Kershaw and J. A. Leisten, *Proc. Chem. Soc., London*, **84** (1960); (d) C. G. Swain and W. P. Langsdorf, Jr., *J. Amer. Chem. Soc.*, **73**, 2813 (1951); (e) G. S. Hammond, J. Peloquin, F. T. Fang, and J. G. Kochi, *ibid.*, **82**, 443 (1960); (f) D. S. Noyce and R. M. Pollack, *ibid.*, **91**, 119 (1969).

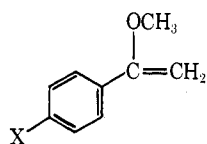
**Table I.** Summary of Kinetic Data for Hydrolysis of Para-Substituted  $\alpha$ -Methoxystyrenes at  $29.9 \pm 0.1^\circ$  in "5% Dioxane,"  $\mu = 1.0 M$ 

| Compd     | Buffer <sup>a</sup>               | pH (pD) $\pm 0.02$ | $k_{HA},^b M^{-1} \text{min}^{-1}$ | $k_H,^c M^{-1} \text{min}^{-1}$ |
|-----------|-----------------------------------|--------------------|------------------------------------|---------------------------------|
| <b>1a</b> | CH <sub>3</sub> CO <sub>2</sub> H | 4.70               | $(7.92 \pm 0.44) \times 10^{-2}$   | $(1.53 \pm 0.16) \times 10^2$   |
| <b>1b</b> | CH <sub>3</sub> CO <sub>2</sub> H | 4.70               | $(5.66 \pm 0.30) \times 10^{-1}$   | $(6.52 \pm 1.00) \times 10^2$   |
| <b>1c</b> | CH <sub>3</sub> CO <sub>2</sub> H | 4.70               | $(1.49 \pm 0.04)^d$                | $(3.76 \pm 0.34) \times 10^3$   |
| <b>1d</b> | CH <sub>3</sub> CO <sub>2</sub> H | 4.70               | $(8.55 \pm 0.17)$                  | $(1.05 \pm 0.05) \times 10^4$   |
|           | CH <sub>3</sub> CO <sub>2</sub> D | 5.18               | $(1.47 \pm 0.02)$                  | $(2.92 \pm 0.23) \times 10^3$   |
| <b>1e</b> | CH <sub>3</sub> CO <sub>2</sub> H | 4.70               | $(3.06 \pm 0.06) \times 10$        | $(2.42 \pm 0.20) \times 10^4$   |
|           | CH <sub>3</sub> CO <sub>2</sub> D | 5.18               | $(5.10 \pm 0.16)$                  | $(6.19 \pm 1.63) \times 10^3$   |
| <b>1f</b> | CH <sub>3</sub> CO <sub>2</sub> H | 4.70               | $(1.08 \pm 0.01) \times 10^2$      | $(7.37 \pm 0.45) \times 10^4$   |
|           | CH <sub>3</sub> CO <sub>2</sub> D | 5.18               | $(1.50 \pm 0.04) \times 10$        | $(2.45 \pm 0.39) \times 10^4$   |
|           | Imidazolium                       | 7.24               | $(5.26 \pm 0.30) \times 10^{-1}$   | $(1.04 \pm 0.35) \times 10^5$   |
|           | KH <sub>2</sub> PO <sub>4</sub>   | 6.60               | $(1.73 \pm 0.08) \times 10$        | $(2.04 \pm 0.81) \times 10^5$   |

<sup>a</sup> Acidic component of buffer; the mole ratio of acidic to basic buffer component was always 1.0 in these experiments. <sup>b</sup> Equation 2; all errors are standard deviations. These values were determined by multiplying slopes of  $k_\psi$  vs. [total buffer] plots by 2. <sup>c</sup> Equation 2; these values were determined by dividing intercepts of  $k_\psi$  vs. [total buffer] plots by  $[H^+]$ . Note that such "one-point" determinations of  $k_{HA}$  and  $k_H$  may contain significant absolute errors. For example, the  $k_H$  values for **1f** show large scatter. This behavior is due to the facts that (1)  $\log k_0$  vs. pH plots, although linear, have slopes slightly different from unity; (2) the values of  $k_0$  at pH 7 are much less reliable than those at pH 4.7, because of the smaller contribution of this term to the rate expression, eq 2; and (3) there may be unpredictable systematic errors as one changes buffer systems. Because we are primarily interested in accurate *relative* rates in constructing the linear free energy relationships used herein, the use of data at the lower pH, where  $k_0$  is more reliable, and the use of the same conditions for each compound should minimize such errors in the relative rates. <sup>d</sup> From ref 2.

tion of the resulting carbonium ion intermediate, have been the object of some interest recently.<sup>9,10</sup> If the curvature does not reflect a change in the rate-determining step, it would then represent a breakdown of the Brown-Okamoto equation for this series of compounds, and the reasons for this breakdown would be of theoretical interest.

We have therefore determined the rates of hydrolysis of each member of the series of para-substituted  $\alpha$ -methoxystyrenes **1a-f** under identical experimental con-



- 1a**, X = -NO<sub>2</sub>      **d**, X = -H  
**b**, X = -CO<sub>2</sub>CH<sub>3</sub>    **e**, X = -CH<sub>3</sub>  
**c**, X = -Br          **f**, X = -OCH<sub>3</sub>

ditions. We have found that there does in fact exist substantial curvature in the plot of  $\log k$  vs.  $\sigma^+$  and that this behavior does not represent a change in the rate-determining step. We shall show that this reaction can be viewed as a reaction proceeding through electron-deficient intermediates correlated by eq 1 with an unusually low, although nonzero,  $r_1$  value; this property of the reaction implies a fair correlation with  $\sigma$  values. The relationship of substituent effects in this reaction to those in related reactions has been explored using extended Hückel calculations, and the results bear on the relationship between transition states in hydration and solvolysis reactions which proceed through common intermediate carbonium ions.

### Experimental Section

**Synthetic Procedures.** The syntheses and analytical data of all compounds reported in this study have been previously presented.<sup>7</sup>

**Kinetic Procedures.** The reaction rates reported herein were determined spectrophotometrically by procedures which have been previously described.<sup>7</sup> The solvent system used in all original work reported herein is the "5% dioxane"-1 M ionic strength KCl detailed elsewhere.<sup>7</sup>

**Deuterium Isotope Exchange Experiments.** Experiments designed to investigate isotope exchange into unreacted vinyl ethers were carried out in the following manner. Approximately 10 ml of the appropriate deuterated buffer (typically 0.1 N acetic acid-*d*<sub>1</sub>, prepared from commercial glacial acetic acid-*d*<sub>1</sub>, 0.1 N potassium acetate, freshly fused and weighed in an N<sub>2</sub> atmosphere, in the "5% dioxane"-0.9 M KCl system described previously, substituting D<sub>2</sub>O for H<sub>2</sub>O) was rapidly stirred under dry nitrogen, and 30  $\mu$ l of the appropriate vinyl ether was added. This nonhomogeneous system duplicates the kinetic situation in that the relatively small amounts of vinyl ether dissolved in the solution are in an identical solvent with that used in the kinetic procedures, although the per cent of the total vinyl ether dissolved in the solvent at any one time is quite small. The assumption inherent in this experiment is that reactions at interfaces do not contribute to the observed effects. After various times on identical samples, the solvent was extracted with pentanes, and the pentanes were backwashed with 5% Na<sub>2</sub>CO<sub>3</sub> solution and then water. The pentanes were dried over anhydrous Na<sub>2</sub>CO<sub>3</sub> and concentrated in a stream of argon or dry nitrogen. The residue was analyzed by gas chromatography-mass spectroscopy (20% Carbowax 20M on neutral 60-80 mesh Chromosorb W, 8 ft  $\times$  0.25 in., column temperature 110-140 $^\circ$ , depending on the compound under investigation; Perkin-Elmer Model 270 mass spectrometer operated at 70 eV) by considering peak enhancement of the P + 1 ions; parent ions were strong in both reactants and products.

### Results

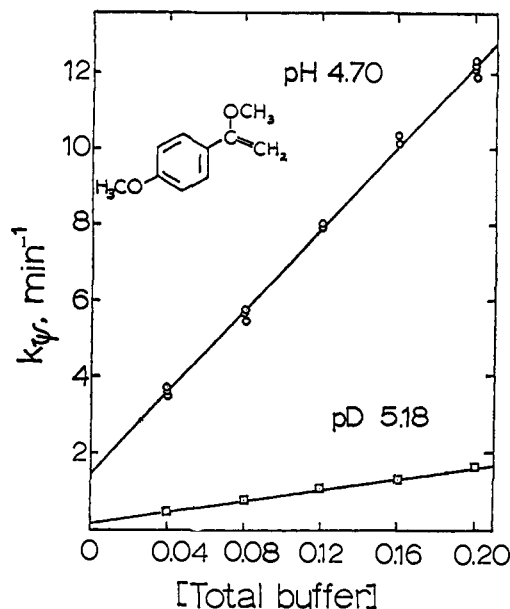
The hydrolysis of compounds **1a-f** was carried out in 1:1 acetic acid-potassium acetate buffers, [total acetate] = 0.04-0.20 M, pH  $4.70 \pm 0.02$  (pD 5.18 for deuterated buffers in this solvent system<sup>7</sup>); selected other buffer systems were also used. A summary of the kinetic data is presented in Table I, and the detailed kinetic data are provided in Table I-S (see paragraph at end of paper regarding supplementary material). We have previously established<sup>7</sup> that the rate law for hydrolysis of all compounds **1a-f** is

$$k_\psi = \sum_i k_{HA_i} [HA_i] + k_H [H^+] \quad (2)$$

in which  $k_\psi$  is the observed pseudo-first-order rate constant,  $k_{HA_i}$  and  $k_H$  are second-order rate coefficients for hydrolysis catalyzed by a general acid HA<sub>i</sub> and protons, respectively, the brackets denote concentration, and  $[H^+]$  is the proton concentration; this quantity was previously shown<sup>7</sup> to be equal to the antilog of the pH meter reading in this solvent system. As an example of eq 2, the buffer dependence of the hydrolysis of **1f** is

(9) A. J. Kresge and H. I. Chen, *J. Amer. Chem. Soc.*, **94**, 2819 (1972).

(10) J. D. Cooper, V. P. Vitullo, and D. L. Whalen, *J. Amer. Chem. Soc.*, **93**, 6294 (1971).



**Figure 1.** The buffer dependence of the pseudo-first-order rate constants for hydrolysis of **1f** in acetate buffers in both  $\text{H}_2\text{O}$  and  $\text{D}_2\text{O}$ .

shown in Figure 1. The hydrolysis of **1f** was followed at constant buffer concentration and pH, progressively substituting KCl with  $\text{KNO}_3$  in an amount equal to the maximum buffer contribution to ionic strength which was employed. The results of this experiment, shown in Table II, indicate that the buffer dependence con-

**Table II.** Effect of Neutral Salt on the Hydrolysis of *p*-Methoxy- $\alpha$ -methoxystyrene<sup>a,b</sup>

| [ $\text{KNO}_3$ ], M | $10k_\psi$ , <sup>c</sup> $\text{min}^{-1}$ |
|-----------------------|---|
| 0.00                  | 3.71  |
| 0.05                  | 3.86  |
| 0.10                  | 3.84  |
| 0.15                  | 3.90  |
| 0.20                  | 3.88  |
| Av (3.84 $\pm$ 0.04)  |   |

<sup>a</sup> pH 6.61  $\pm$  0.02; 29.9  $\pm$  0.1 $^\circ$ ; [total phosphate] = 0.0375 M; [KCl] = 0.925 M - [ $\text{KNO}_3$ ]; total ionic strength = 1.0 M. <sup>b</sup> See ref 11. <sup>c</sup> Equation 2.

tains no contribution from a specific salt effect. We demonstrated previously<sup>7</sup> that replots of slopes, of plots of  $k_\psi$  vs. [total buffer] vs. fraction in ionized form,  $f_A$ , were linear and intersected  $f_A = 0$  at the origin, a fact which further underscores the lack of a specific salt effect on the reaction.<sup>7,11</sup>

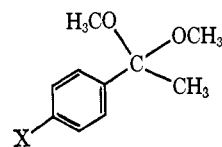
The effect of changing the buffer from one with a less nucleophilic conjugate base ( $\text{KH}_2\text{PO}_4$ ) to one with a more nucleophilic conjugate base (imidazole  $\text{H}^+$ ) at approximately constant pH was investigated to assess whether there is any significant nucleophilic contribution to the buffer catalysis.<sup>12</sup> After correcting the phosphate data to the imidazole  $\text{p}K_a$  via a Brønsted correction, using data obtained here as well as that ob-

(11) The use of  $\text{KClO}_4$ , which would have provided a more stringent test of the specific salt effect, was precluded by the insufficient solubility of this salt in the solvent system used here: see P. Salomäa, A. Kankaanperä, and M. Lahti, *J. Amer. Chem. Soc.*, **93**, 2084 (1971).

(12) W. P. Jencks and J. Carriuolo, *J. Amer. Chem. Soc.*, **83**, 1743 (1961).

tained in previous work<sup>7</sup> for phosphate and carboxylate buffers, and correcting the data for statistical effects, it was found that  $k_{\text{H}_2\text{PO}_4}/k_{\text{ImH}^+} = 8.3$ , a number consistent with the modest electrostatic effect to be expected on such carbonium ion reactions.<sup>7,13</sup>

The mechanistic considerations to be discussed below required the investigation of the hydrolysis of ketals **2a-f** under conditions identical with those used for the



- 2a**, X =  $-\text{NO}_2$       **d**, X =  $-\text{H}$   
**b**, X =  $-\text{CO}_2\text{CH}_3$     **e**, X =  $-\text{CH}_3$   
**c**, X =  $-\text{Br}$             **f**, X =  $-\text{OCH}_3$

hydrolysis of the vinyl ethers **1a-f**. The hydrolysis of these compounds was not catalyzed by buffers and could apparently be described by the relation

$$k_\psi = k_{\text{H}}[\text{H}^+] \quad (3)$$

in which  $k_\psi$  is the observed pseudo-first-order rate constant for hydrolysis, and  $k_{\text{H}}$  is the second-order rate constant for apparent hydrogen ion catalysis. The kinetic data for the hydrolysis of these compounds are presented in Table III.

**Table III.** Hydrolysis of Para-Substituted Acetophenone Dimethyl Ketals at 29.9  $\pm$  0.1 $^\circ$  in "5% Dioxane,"  $\mu = 1.0$  M

| Compd <sup>a</sup> | $k_{\text{H}}$ , <sup>b</sup> $\text{M}^{-1} \text{min}^{-1}$ |
|--------------------|---|
| <b>2a</b>          | (2.04 $\pm$ 0.04) $\times 10^3$                               |
| <b>2b</b>          | (1.20 $\pm$ 0.02) $\times 10^4$                               |
| <b>2c</b>          | (4.62 $\pm$ 0.03) $\times 10^4$                               |
| <b>2d</b>          | (1.27 $\pm$ 0.01) $\times 10^5$                               |
| <b>2e</b>          | (3.43 $\pm$ 0.03) $\times 10^5$                               |
| <b>2f</b>          | (7.62 $\pm$ 0.05) $\times 10^5$                               |

<sup>a</sup> All determinations in 1:1 acetic acid-potassium acetate buffer, pH 4.70  $\pm$  0.02. <sup>b</sup> Average of three to five determinations at [total acetate] varying from 0.04 to 0.20 M; errors are average deviations; rate constants are calculated by dividing  $k_\psi$  by  $[\text{H}^+]$ . See eq 3 for definition of constants. See also footnote c in Table I.

Measurements of deuterium exchange into unreacted vinyl ether and deuterium incorporation into product ketone were carried out for the hydrolysis of compounds **1d** and **1f**. Deuterium incorporation was monitored up to 67% completion of the reaction for **1d** and 78% completion for **1f**. In neither case was any detectable incorporation observed. On the other hand, the product acetophenone from these reactions showed 0.90 and 0.93 atom D, respectively; since light-hydrogen impurities in the solution are amplified via an isotope effect of 6-7 in these reactions, we consider these incorporations to be indistinguishable from unity.

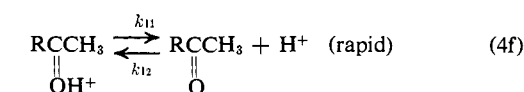
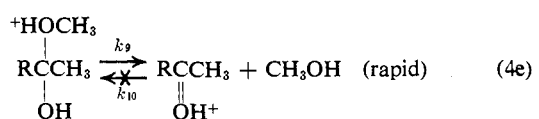
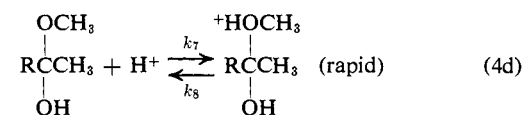
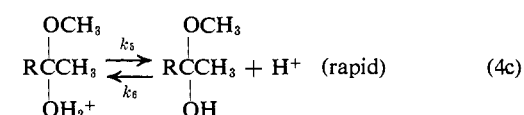
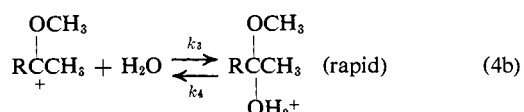
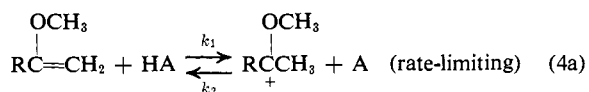
## Discussion

A plot of both  $\log k_{\text{H}}$  and  $\log k_{\text{HOAc}}$  (eq 2) vs.  $\sigma^+$  for the hydrolysis of para-substituted  $\alpha$ -methoxystyrenes is shown in Figure 2. It is to be emphasized that all data shown in this figure were obtained directly under iden-

(13) T. H. Fife, *J. Amer. Chem. Soc.*, **87**, 1084 (1965).

tical conditions, so that uncertainties in the relative rates are small (see also footnote *c*, Table I, for an elaboration of this point). It is clear that the downward curvature previously suggested<sup>7</sup> in the plot of the  $\log k_H$  values *vs.*  $\sigma^+$  is real and that a similar curvature exists in the correlation of  $\log k_{\text{HOAc}}$  with  $\sigma^+$ . Plots of these data *vs.* the Hammett  $\sigma$  constants show a fair correlation for the  $k_H$  values and a poor correlation for the  $k_{\text{HOAc}}$  values.

We proceed under the assumption that, since the reaction is believed to proceed through ring-conjugated carbonium ion intermediates,  $\sigma^+$  is the appropriate correlation parameter. We then show that if one assumes that the observed curvature in  $\sigma^+$  plots represents a change in rate-determining step, this assumption leads to behavior inconsistent with our experimental results. The mechanism accepted for vinyl ether hydrolysis is given in eq 4a-f. There are two candidates for the



rate-determining step within this scheme if the first step becomes rapid. Step 4b would be a rate-limiting carbonium ion hydration, and step 4e involves rate-limiting bond scission in the hemiketal and resembles closely the rate-limiting step in an established mechanism for ketal hydrolysis.<sup>14</sup> We know that the vinyl ether hydrolysis reaction shows excellent pseudo-first-order kinetics for all compounds and excellent isobestic points, so that it is safe to assume that no intermediates accumulate and steady-state kinetics apply. If step 4a becomes sufficiently rapid, it is readily shown that for the above mechanism in which step 4b becomes rate limiting, buffer catalysis should disappear. One would then expect to see a vanishing of the buffer dependence of  $k_{\psi}$ . This behavior is not observed. One can modify steps 4b and 4c to become a general base-catalyzed carbonium ion hydration, a reaction with precedent.<sup>15</sup>

(14) E. H. Cordes, *Progr. Phys. Org. Chem.*, **4**, 1 (1967).

(15) C. D. Ritchie, *J. Amer. Chem. Soc.*, **94**, 3275; (1972); *Accounts Chem. Res.*, **5**, 348 (1972).

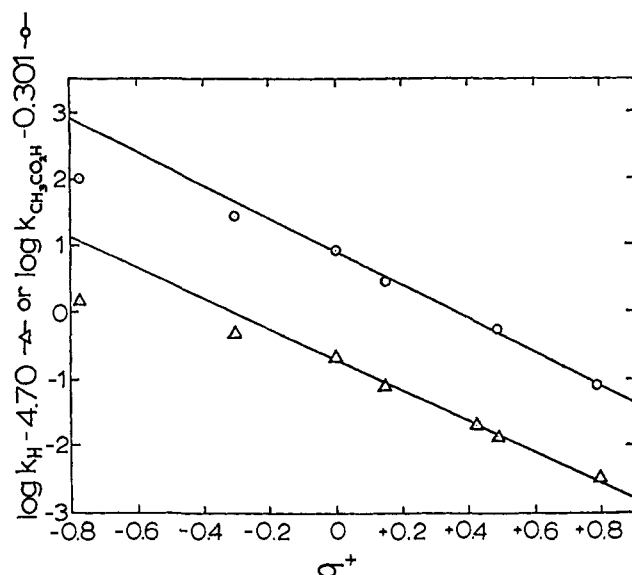
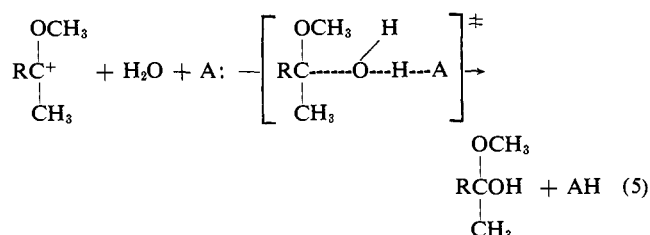


Figure 2. The  $\sigma^+$  correlation of the hydrolysis rates of compounds 1a-f for both acetic acid catalysis and hydronium ion catalysis. The additional point on the hydronium ion plot is for the *p*-carboxyl ( $\text{CO}_2\text{H}$ ) derivative (data derived from ref 7). The solid lines are the least-squares fit for the points corresponding to  $\sigma^+ \geq 0$ .



Kinetic considerations then predict "specific acid-general base" catalysis, a phenomenon indistinguishable from general acid catalysis. This is ruled out by three observations. First, the transition state in eq 5 is very close to that for the microscopic reverse of a ketal hydrolysis, if one makes the rather conservative substitution of a hydrogen by an alkyl group in the attacking nucleophile; but hydrolysis of ketals is not buffer catalyzed in this system (see Results). Second, the isotope effects which are observed in this system, tabulated in Table IV, are near the theoretical maximum

Table IV. Deuterium Isotope Effects for Hydrolysis of  $\alpha$ -Methoxystyrenes at  $29.9 \pm 0.1^\circ$ , "5% Dioxane,"  $\mu = 1.0 M$

| Compd | $k_H/k_D^{a,c}$ | $k_{\text{HOAc}}/k_{\text{DOAc}}^{b,c}$ |
|-------|-----------------|---|
| 1d    | $3.39 \pm 0.39$ | $5.75 \pm 0.19$                         |
| 1e    | $3.89 \pm 1.08$ | $5.89 \pm 0.14$                         |
| 1f    | $3.02 \pm 0.56$ | $7.24 \pm 0.50$                         |

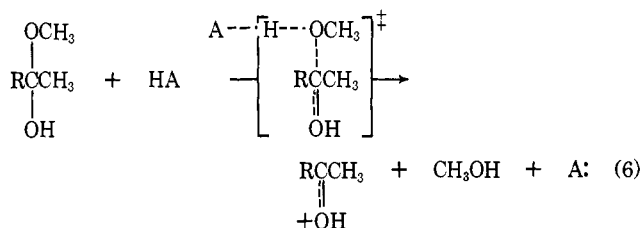
<sup>a</sup> Isotope effect for hydronium ion catalysis; see eq 2. <sup>b</sup> Isotope effect for acetic acid catalysis; see eq 2. <sup>c</sup> Errors are standard deviations.

for a proton transfer to carbon, a result which was confirmed by Kresge<sup>16</sup> in a preliminary communication. In all cases in which there has been shown to exist a general base catalyzed attack of water on an  $\text{sp}^2$ -hybridized carbon, solvent isotope effects  $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}}$  for buffer catalysis have been no greater than 3.0, and often

(16) A. J. Kresge, D. S. Sagatys, and H. L. Chen, *J. Amer. Chem. Soc.*, **90**, 4174 (1968).

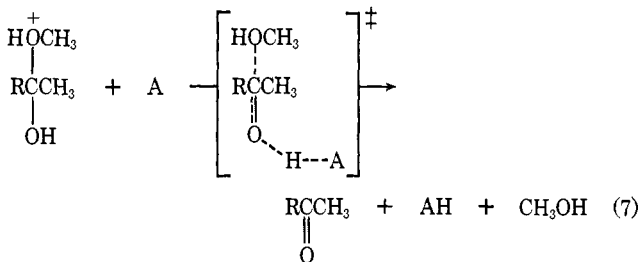
considerably less,<sup>12,15,17</sup> in accord with theoretical expectation.<sup>18</sup> In addition, the prior equilibrium protonation of the multiple bond would contribute an isotope effect  $k_{\text{H}_2\text{O}}/k_{\text{D}_2\text{O}} < 1$ , so that the observed overall isotope effect would be further reduced. Finally, there is no exchange of deuterium from solvent into unreacted  $\alpha$ -methoxystyrenes when the hydrolysis reactions are run in deuterated media, nor is there more than one deuterium incorporated into the product acetophenones.

Step 4e as written does not involve buffer components, so that it cannot represent the rate-determining step. It is possible to combine steps 4d and 4e in eq 6,



which would represent an overall general acid catalyzed reaction. Again, this transition state resembles that for a general acid catalyzed ketal hydrolysis, for which buffer catalysis is not observed in this system and for which isotope effects are uniformly small or even inverse<sup>19</sup> in cases for which buffer catalysis is observed; in this case, as before, the large observed solvent isotope effect is hard to reconcile with these facts. Finally, the lack of incorporation of solvent deuterium into unreacted starting material also rules against this mechanism.

One could modify steps 4e and 4f as shown in eq 7.



The overall reaction in this case would become a specific acid-general base catalyzed event (kinetically apparent general acid catalysis), but we are faced again with a prior protonation equilibrium which would reduce or invert the observed isotope effect, and with no explanation for the lack of incorporation of solvent deuterium into unreacted starting material.

The curvature of the  $\sigma^+$  correlations of Figure 2, therefore, finds no explanation in a change of the rate-determining step. Another possible explanation for

(17) (a) E. J. Pollock, M. C. Neveu, and M. L. Bender, *J. Amer. Chem. Soc.*, **84**, 595 (1962); see also T. St Pierre and W. P. Jencks, *ibid.*, **90**, 3819 (1968); (b) M. L. Bender, F. J. Kézdy, and B. Zerner, *ibid.*, **85**, 3017 (1963); (c) W. P. Jencks and J. Carriuolo, *ibid.*, **82**, 675 (1960); (d) B. Zerner and M. L. Bender *ibid.*, **83**, 2267 (1961); (e) B. Capon and B. C. Ghosh, *J. Chem. Soc. B*, 472 (1966); (f) A. R. Butler and V. Gold, *Proc. Chem. Soc., London*, 15 (1960); (g) B. M. Anderson, E. H. Cordes, and W. P. Jencks, *J. Biol. Chem.*, **236**, 455 (1961); (h) P. Y. Bruice and H. G. Mautner, *J. Amer. Chem. Soc.*, **95**, 1582 (1973).

(18) C. A. Bunton and V. J. Shiner, Jr., *J. Amer. Chem. Soc.*, **83**, 3214 (1961).

(19) (a) T. H. Fife and L. K. Jao, *J. Amer. Chem. Soc.*, **90**, 4081 (1968); (b) T. H. Fife and L. H. Brod, *ibid.*, **92**, 1681 (1970); (c) T. (1968); *Accounts Chem. Res.*, **5**, 264 (1972), and references cited therein.

this curvature is that the plots are reflecting curvature which has been associated with the approach to the diffusion-controlled limit in highly electron-delocalized systems by Eigen<sup>20</sup> and Bell.<sup>21</sup> Granting for the moment the reasonable assumption that the  $\text{p}K_a$  values of the carbonium ions putatively produced in this type of reaction would follow a  $\sigma^+$  correlation, one can see that the correlations of Figure 2 are then equivalent to Brønsted plots for fixed acid catalysts and varying substrate. Clearly, if the rate of a proton-transfer reaction approaches "sufficiently close" to the diffusion-controlled limit, it can no longer be influenced appreciably by a change of substituent. A number of arguments suggest that this is not the explanation for the curvature, however. First, second-order rate coefficients for hydronium ion catalysis are no greater than  $10^4 \text{ M}^{-1} \text{ sec}^{-1}$ , and the second-order rate constants for acetic acid catalysis are no greater than  $10^1 \text{ M}^{-1} \text{ sec}^{-1}$ , *i.e.*, about five and eight orders of magnitude, respectively, from the encounter limit; furthermore, the curvature is at least as great for the acetic acid catalyzed reaction as for the  $\text{H}_3\text{O}^+$  reaction. Eigen<sup>20</sup> noted empirically that in systems in which a great degree of electron delocalization is present, curvature of Brønsted plots may take place well below the diffusion limit. However, Kemp and Casey<sup>22</sup> have challenged the interpretation of the rather limited data upon which such curvature is based, noting that sets of compounds which give such curvature are composed of compounds of different structural types. Finally, there is no real basis for our assumption that the  $\text{p}K_a$  values for our carbonium ion intermediates would be correlated by  $\sigma^+$ ; in fact, the arguments made below will suggest that they should not be so correlated. Therefore, it appears unlikely that the curved  $\sigma^+$  correlation is a reflection of, or is equivalent to, a curved Brønsted plot.

We therefore reach the conclusion that a poor correlation of the hydrolysis data by the  $\sigma^+$  constants is an inherent property of this system; even though carbonium ions are formed  $\alpha$  to aromatic rings in both *tert*-cumyl chloride solvolyses and  $\alpha$ -methoxystyrene hydrations, the former reaction is evidently a poor electronic model for the latter.

**Analysis of Data by the Yukawa-Tsuno Equation (Eq 1).** In order to analyze the apparent curvature of  $\sigma^+$  correlations in terms of eq 1, we rewrite eq 1 as

$$\log(k_{xi}/k_{Hi}) = \rho_i(r_i - 1)\sigma^+_{xz} - \rho_i(r_i - 1)\sigma_x + \rho_i\sigma^+_{xz} \quad (8)$$

For electron-withdrawing substituents, it is a good approximation that  $\sigma^+ \approx \sigma$ ; to the extent that this is true, eq 8 for these substituents reduces to the Brown-Okamoto<sup>5</sup> eq 9. For the commonly used electron-

$$\log(k_{xi}/k_{Hi}) \approx \rho_i\sigma^+_{xz} \quad (9)$$

(20) M. Eigen, *Angew. Chem., Int. Ed. Engl.*, **3**, 1 (1964).

(21) R. P. Bell, "The Proton in Chemistry," Cornell University Press, Ithaca, N. Y., 1959, p 163.

(22) D. S. Kemp and M. C. Casey, *J. Amer. Chem. Soc.*, **95**, 6670 (1973). Part of this challenge rests, in fact, on the constancy of Brønsted exponents for the hydrolysis of various sets of vinyl ethers, as observed by Kresge's group.<sup>23</sup> We note that if we carry out a Brønsted correlation for each of our vinyl ethers based on the two acids  $\text{CH}_3\text{CO}_2\text{H}$  and  $\text{H}_3\text{O}^+$  (although dissimilar, the same two acids are used for each compound; *cf.* Kemp and Casey's "kinetic  $\text{p}K_a$ " method), the Brønsted exponent is  $0.46 \pm 0.02$ , with a maximum deviation of 0.04 for any one compound.

(23) A. J. Kresge, H. Chen, Y. Chiang, E. Murrill, M. Payne, and D. Sagatys, *J. Amer. Chem. Soc.*, **93**, 413 (1971).

donating substituents,  $\sigma_x^+ < \sigma_x < 0$ . Therefore, for electrophilic reactions ( $\rho_i < 0$ ) with  $r_i < 1$ , eq 8 shows that the points for these substituents will show downward deviations from the line defined by eq 9. The apparent smoothness of these deviations (which we are loosely calling curvature) is an accidental consequence of the relative values of  $\sigma_x^+$ ,  $\sigma_x$ , and  $r_i$  in the situations discussed in this paper in which these deviations are important.

When correlated by the Yukawa-Tsuno eq 1, the data for  $\alpha$ -methoxystyrene hydrolysis catalyzed by either hydronium ion or acetic acid yield a value for  $r_i$  of about 0.3, so that the apparent curvature in the  $\sigma^+$  plot is in the direction expected by the above analysis. It seemed reasonable that, within a set of hydration reactions of  $\alpha$ -substituted styrenes, as one increases the electron-donating effect of the  $\alpha$  substituent, the susceptibility of the reaction rate to substitution at the ring positions should decrease ( $\rho_i$  should be less negative), and the "demand" of the system for resonance stabilization should be smaller ( $r_i$  should decrease). A survey of available data for the hydrolysis or hydration reactions of  $\alpha$ -substituted styrenes (Table V) shows that this in-

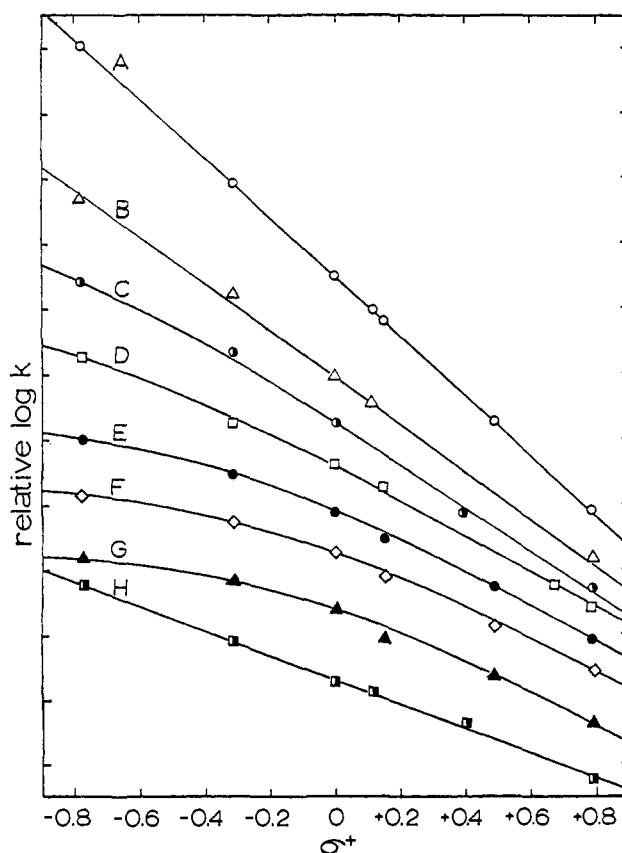
**Table V.** Correlation of Rates of Hydration Reactions Involving Carbonium Ion Intermediates by the Yukawa-Tsuno Equation (Eq 1)

| Reaction   | $-\rho^a$   | $r^a$       | $s^b$ |
|--|-------------|-------------|-------|
| Solvolysis of <i>tert</i> -cumyl chlorides ( $\sigma^+$ values), 25°                               | 4.52 ± 0.13 | (1.00)      | 0.09  |
| Hydration of styrenes, 25° <sup>c</sup>  | 3.64 ± 0.18 | 0.94 ± 0.13 | 0.11  |
| Hydration of $\alpha$ -methylstyrenes, 25° <sup>d</sup>  | 3.36 ± 0.20 | 0.74 ± 0.15 | 0.13  |
| Hydrolysis of diethyl $\alpha$ -arylvinyl phosphates, 25° <sup>e</sup>                             | 2.71 ± 0.12 | 0.66 ± 0.13 | 0.09  |
| Hydrolysis of $\alpha$ -methoxystyrenes, HOAc catalysis, 30° <sup>f</sup>                          | 2.59 ± 0.06 | 0.30 ± 0.30 | 0.04  |
| Hydrolysis of $\alpha$ -methoxystyrenes, H <sub>3</sub> O <sup>+</sup> catalysis, 30° <sup>f</sup> | 2.29 ± 0.14 | 0.26 ± 0.13 | 0.09  |
| Hydrolysis of $\alpha$ -acetoxy-styrenes, 25° <sup>g</sup>   | 1.96 ± 0.08 | 0.89 ± 0.11 | 0.05  |
| Hydrolysis of acetophenone dimethyl ketals, 30° <sup>f</sup>                                       | 2.29 ± 0.06 | 0.13 ± 0.05 | 0.04  |

<sup>a</sup> Uncertainties are standard deviations. <sup>b</sup> Standard deviation of log  $k$ . <sup>c</sup> W. M. Schubert and J. R. Keefe, *J. Amer. Chem. Soc.*, **94**, 559 (1972). <sup>d</sup> Reference 38. <sup>e</sup> R. D. Frampton, T. T. Tidwell, and V. A. Young, *J. Amer. Chem. Soc.*, **94**, 1271 (1972). <sup>f</sup> This work; the ketal hydrolysis is included as a solvolysis-like reaction for reference; see discussion in text. <sup>g</sup> Reference 8f.

tuitive judgment is borne out very well. Figure 3, which depicts  $\sigma^+$  correlations for these reactions, shows decreasing sensitivity to ring substitution (less negative slope at positive  $\sigma^+$  values) as well as increasing apparent curvature (smaller  $r_i$ ) as one proceeds down the figure in the direction of the more electron-donating  $\alpha$  substituents.<sup>24</sup> There is one glaring exception to this trend, namely the hydrolysis of  $\alpha$ -acetoxy-styrenes by the rate-determining proton-transfer mechanism (A-

(24) The data for the various reactions in Table V were obtained in general at different acidities, so that the relationship between  $\rho_i$  and  $r_i$  suggested herein may contain a modest acidity dependence. There are slight medium differences over and above the relative acidity (*i.e.*, the amount of nonaqueous component of solvent) which will also impart some scatter to this relationship. Nevertheless, the trends presented here are clear.



**Figure 3.**  $\sigma^+$  correlation of hydration and solvolysis data. Each division on the ordinate represents one log  $k$  unit, and the data for each reaction are displaced arbitrarily for convenience of presentation. The lines are drawn through the values of log  $k$  calculated by the best fit of the data to eq 1; the smoothness of the curves is not algebraically required by eq 1 but is a consequence of the relative values of  $\sigma_x^+$ ,  $\sigma_x$ , and  $r_i$ , as discussed in the text. A, *tert*-cumyl chloride solvolysis ( $\sigma^+$  values, included for reference); B, hydration of styrenes; C, hydration of  $\alpha$ -methylstyrenes; D, hydrolysis of diethyl  $\alpha$ -arylvinyl phosphates; E, hydrolysis of  $\alpha$ -methoxystyrenes, CH<sub>3</sub>CO<sub>2</sub>H catalysis; F, hydrolysis of  $\alpha$ -methoxystyrenes, H<sub>3</sub>O<sup>+</sup> catalysis; G, hydrolysis of acetophenone dimethyl ketals; H, hydrolysis of  $\alpha$ -acetoxy-styrenes. See Table V for references.

SE2 mechanism),<sup>25</sup> for which  $\rho_i$  is not sufficiently negative for the  $r_i$  value observed; stated another way, there is no curvature in the  $\sigma^+$  plot, and the slope of this plot is too shallow. This behavior may be due to the fact that the relationship between  $\rho_i$  and  $r_i$  in the other reactions is coincidence or to another reason. There is considerable uncertainty in the extrapolation used to determine the A-SE2 rates for  $\alpha$ -acetoxy-styrenes substituted with electron-withdrawing substituents, and it is quite possible that the rates for *p*-nitro- and *m*-chloro- $\alpha$ -acetoxy-styrenes still contain some contribution from the "normal" ester hydrolysis mechanism. If this is the case, the points on the  $\sigma^+$  plot for this reaction for the electron-withdrawing substituents should be displaced to lower values of log  $k$ , and a more negative  $\rho_i$  as well as curvature in this plot would be observed. Alternatively, a different mechanism, kinetically indistinguishable from the A-SE2 mechanism, may be operating for the  $\alpha$ -acetoxy-styrenes, but this seems unlikely, since the rates of this reaction and those for

(25) This hydrolysis shows a duality of mechanism; the data under discussion here are extrapolated data for hydrolysis by the A-SE2 mechanism.

diethyl  $\alpha$ -arylvinyl phosphate hydrolysis are comparable. This question is under further study.

One should be able to observe a similar relationship in  $\rho_i$  and  $r_i$  for other series of related reactions. Despite the large body of solvolysis data for variously  $\alpha$ -substituted benzylic systems, the possible variability of mechanism<sup>26</sup> and the lack of data obtained under nearly identical conditions with identical leaving groups prohibit such a comparison in solvolytic systems. Such a relationship, however, has been observed in the bromination of 1,1-diarylethylenes,<sup>27</sup> although the data are complicated by the possibility of out-of-plane rotation by one of the aryl groups. Hine<sup>28</sup> cites  $pK_{R-}$  data of triarylcarbinols as another example of this effect, albeit complicated by similar problems. In any event, the relationship between  $\rho_i$  and  $r_i$  in closely related reactions, run under similar conditions, appears to be reasonable.

A reaction which shows a small value of  $r_i$  in eq 1, or, equivalently, a downward-curving  $\sigma^+$  correlation, can be thought of as displaying a "substituent effect saturation" behavior. Hine<sup>28</sup> discussed such effects as possible sources of deviations from linear free energy relationships and noted that more cases of these effects would be known if more systems could be studied in which variations of reactivity or equilibrium constant of "more than 10<sup>26</sup>-fold" were encompassed. Clearly, in an appropriately activated system, such effects may be observed over much smaller ranges of reactivity.

Our intuition, that the reduced  $r_i$  value in eq 1 is due to decreased resonance interaction of ring substituents, can be translated into molecular orbital terms using extended Hückel theory and perturbation arguments; the results of these calculations provide both theoretical justification for these effects and an understanding of their origin.

**Extended Hückel Calculations.** Although absolute energies derived from extended Hückel theory (EHT) are generally untrustworthy, one expects that relative energies in closely related systems calculated by EHT will have considerable significance, since there have been numerous examples in which even simple Hückel theory has provided relative energies that correlate well with experimental data.<sup>29</sup> In addition, the experimental use of substituent effects is, in reality, the introduction of relatively small perturbations in chemical systems, and the results of perturbation theory should be applicable to the analysis of the results of substituent effect studies. It has been shown that reliable perturbation analyses may be made using the results from EHT calculations, since the perturbation approach often relies heavily on certain properties of "frontier orbitals"<sup>30</sup> which are relatively invariant with the calculational method used to obtain them; indeed, more complex (and costly) molecular orbital methods offer little advantage when perturbation methods are used.<sup>31, 32</sup>

(26) R. A. Sneen, *Accounts Chem. Res.*, **6**, 46 (1973).

(27) See Table V of A. F. Hegarty, J. S. Lomas, W. V. Wright, E. D. Bergmann, and J. E. Dubois, *J. Org. Chem.*, **37**, 2222 (1972).

(28) Jack Hine, "Physical Organic Chemistry," McGraw-Hill, New York, N. Y., 1962, pp 101-103.

(29) A. Streitwieser, Jr., "Molecular Orbital Theory for Organic Chemists," part II, Wiley, New York, N. Y., 1961.

(30) (a) K. Fukui, T. Yonezawa, and H. Shingu, *J. Chem. Phys.*, **20**, 722 (1952); (b) K. Fujui, C. Nagata, and H. Shingu, *ibid.*, **22**, 1433 (1954).

(31) (a) Illustrations of the application of the results of perturbation

The object of this theoretical investigation was to compare the substituent effects on the rates of  $\alpha$ -methoxystyrene protonation to those on the rates of styrene hydration (a reaction which follows  $\sigma^+$  very closely)<sup>33</sup> in order to investigate whether downward curvature in the  $\sigma^+$  correlation, which we have shown to be equivalent to a reduced  $r_i$  value in eq 1, is theoretically reasonable. The styrene hydration was chosen as our reference system in order to maintain the close structural similarity between our reference system and the investigated system upon which the claim for valid relative energies rests. The extended Hückel program which we used was the latest version of Hoffmann<sup>34</sup> with bond angles and bond lengths based on those in a standard compilation.<sup>35</sup> Conformations were such as to optimize  $\pi$  overlap and minimize steric crowding; in no case did the configurations assumed result in dangerously small values in the interatomic distance matrix. To simulate transition states in the hydration reactions we used the presumed first intermediate carbonium ions; although this procedure is an obvious oversimplification (see below for a further elaboration of this point), the comparison between reference system (styrenes  $\rightarrow$  1-arylethyl cations) and the system under study ( $\alpha$ -methoxystyrenes  $\rightarrow$  1-methoxy-1-arylethyl cations) should tend to cancel the effects of discrepancies common to both systems. Calculated values for relative activation energies,  $E_a^{0\pm}$  (which, when divided by  $-2.3RT$ , give calculated values of relative rates  $\log k_{xi}/k_{Hi}$ ), are presented in Table VI and are shown in the

**Table VI.** Calculated Relative Activation Energies for Protonation Reactions

| Para substituent                 | $\Delta E_a^{0\pm}$ (styrene),<br>kcal/mol | $\Delta E_a^{0\pm}$<br>( $\alpha$ -methoxystyrene),<br>kcal/mol |
|----------------------------------|--|---|
| -NO <sub>2</sub>                 | 2.499                                      | 1.683   |
| -CO <sub>2</sub> CH <sub>3</sub> | 1.547                                      | 0.984   |
| -H                               | [0]  | [0]   |
| -CH <sub>3</sub>                 | -1.395                                     | -0.701  |
| -OCH <sub>3</sub>                | -3.036                                     | -1.519  |

form of a  $\sigma^+$  correlation in Figure 4. The following features of these data are interesting. The limiting slope of the curve in Figure 4, indicated by the dashed line, is 0.73; the ratio of the corresponding limiting slopes of the  $\sigma^+$  correlations of  $\log k_{xi}/k_{Hi}$  for  $\alpha$ -methoxystyrene hydrolyses and styrene hydrations is 0.68; thus, the theory gives a good quantitative account of the relative sensitivity of the two reactions to sub-

theory to the understanding of hitherto unexplained chemical processes are given in L. M. Loew, Ph.D. Thesis, Cornell University, 1973, Chapter I; (b) C. F. Wilcox, L. M. Loew, and R. Hoffmann, *J. Amer. Chem. Soc.*, **95**, 8192 (1973); (c) C. F. Wilcox, L. M. Loew, R. G. Jesaitis, and S. Belin, *ibid.*, submitted for publication; (d) K. N. Houk, J. Sims, C. R. Watts, and L. J. Luskus, *ibid.*, **95**, 7301 (1973), and references cited therein.

(32) The frontier orbital method has not been beyond criticism: see M. J. S. Dewar, "The Molecular Orbital Theory of Organic Chemistry," McGraw-Hill, New York, N. Y., 1969, p 364.

(33) W. M. Schubert and J. R. Keefe, *J. Amer. Chem. Soc.*, **94**, 559 (1972).

(34) (a) R. Hoffmann, *J. Chem. Phys.*, **39**, 1397 (1963); (b) R. Hoffmann and W. N. Lipscomb, *ibid.*, **36**, 2179, 3849 (1961); **37**, 2872 (1962).

(35) "Tables of Interatomic Distances and Configurations in Molecules and Ions," *Chem. Soc., Spec. Publ., No. 11* (1958); *Suppl., No. 18* (1965).

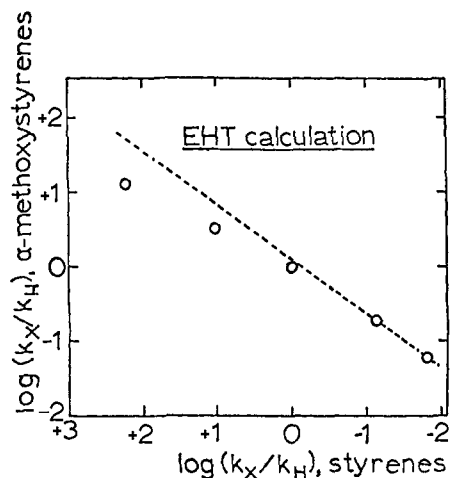


Figure 4. Graphical presentation of the data in Table VI. The points are (left to right) *p*-methoxy, *p*-methyl, *p*-hydrogen, *p*-carbomethoxy, and *p*-nitro.

stituent effects. The downward deviation of the *p*-methoxy point from the dashed line is 0.65 log units; the corresponding deviation of this point in the experimental correlation is 0.80 log units. The downward curvature is therefore reflected in the EHT results; this is particularly interesting in view of the explicit neglect of electron repulsion (which we might loosely term "field effects") which is characteristic of EHT. Evidently, as one considers increasingly stable carbonium ions in these hydration reactions, not only are the reactions inherently less sensitive to substituents but also the tendency of substituent effects to "saturate" within a given series of compounds increases. An experimental indication that this effect would also prevail for a solvolysis-like reaction is the curved  $\sigma^+$  plot for the hydrolysis of para-substituted acetophenone dimethyl ketals (line G of Figure 3).

Libit and Hoffmann<sup>36</sup> have commented rather eloquently: "The idea of substituent effects can be said to be part of the unique and beautiful logic of chemistry . . . but [realistic] calculations are so complex . . . that [one tends] to abdicate to the computer and substitutes as a goal predictability for understanding; . . . the problem is in understanding why a particular calculation came out as it did." We can understand the effects observed here from relatively simple considerations of second-order perturbation theory, which enable us to focus on two "frontier orbitals" from which the effects largely arise.

We are interested in the stabilization energy,  $\epsilon_{ij}$ , brought about on a system *j* by a perturbation (substituent) *i*;  $\epsilon_{ij}$  is essentially the substituent effect. Realizing that this effect resides largely in the interaction of the highest unoccupied molecular orbital of the substituent (HOMO), and the lowest unoccupied molecular orbital (LUMO) of the system, the so-called "frontier orbitals,"<sup>30,31</sup> then we can write immediately from second-order perturbation theory

$$\epsilon_{ij} \approx \kappa_{ij} \frac{\left( \sum_{k,l} c_i^{(k)} c_j^{(l)} \right)^2}{(E_j - E_i)} \quad (10)$$

in which  $c_i^{(k)}$  is the coefficient of the HOMO of substituent *i* at atom *k*,  $c_j^{(l)}$  is the coefficient of the LUMO

(36) L. Libit and R. Hoffmann, *J. Amer. Chem. Soc.*, **96**, 1370 (1974).

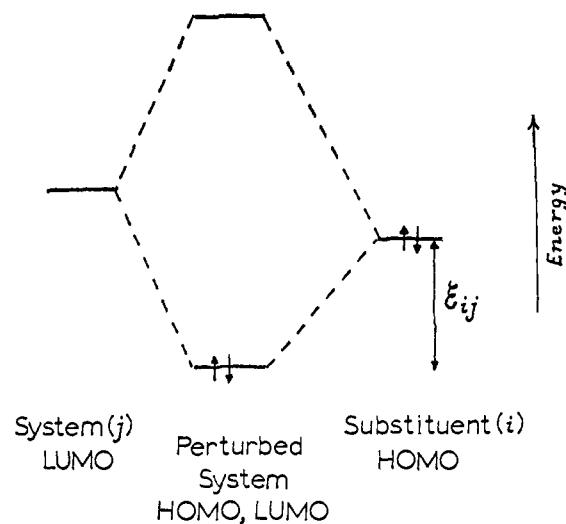


Figure 5. Schematic illustration of the results of the interaction of frontier orbitals of the system and substituent according to eq 11 or 12.

of system *j* at atom *l*, the summation is taken over only adjacent *k,l* pairs,  $E_i$  is the energy of the HOMO of substituent *i*,  $E_j$  is the energy of the LUMO of system *j*, and  $\kappa_{ij}$  is a proportionality constant. For the special cases considered here, in which only two atoms are in bonding interaction between system and substituent, we can drop the summation to obtain

$$\epsilon_{ij} \approx \kappa_{ij} \frac{(c_i c_j)^2}{E_j - E_i} \quad (11)$$

Figure 5 illustrates conceptually in energy-level terms the meaning of eq 11. We shall further assume that most of the substituent effects on the reaction rates observed in this work reside on the cations (or transition states) and that the substituent effects on the reactant states, though formally analyzable in the same way, may be neglected; our EHT calculations show that this is reasonable for the systems studied here. When considering relative substituent effects, as in Figure 4, we may write expressions like eq 11 for substituent stabilization energies  $\epsilon_{i1}$  and  $\epsilon_{i2}$  for each of two systems; here we have defined  $j = 1$  for the 1-phenylethyl cation, and  $j = 2$  for the 1-methoxy-1-phenylethyl cation. Since  $E_i$  is present in both of the resulting expressions, we can solve for  $\epsilon_{i2}$  in terms of  $\epsilon_{i1}$  and obtain

$$\epsilon_{i2} \approx \frac{\kappa_{i2} c_i^2 c_2^2}{\kappa_{i1} c_i^2 c_1^2 / \epsilon_{i1} + (E_2 - E_1)} \quad (12)$$

The term  $(E_2 - E_1) \equiv \Delta E_{21}$  is the difference in LUMO energy of the two systems; if the absolute value of this difference is small enough, we have

$$\epsilon_{i2} \approx \frac{\kappa_{i2} c_2^2}{\kappa_{i1} c_1^2} \epsilon_{i1} \quad (13)$$

or the substituent effect in one system is linearly related to that in another—thus, a "linear 'free energy' relationship." If the absolute value of  $\Delta E_{21}$  is not small enough, the relationship is no longer linear. The value of  $\Delta E_{21}$  from our EHT calculations, relative to the 1-phenylethyl cation in each case, is 5.440 kcal for the 1-methyl-1-phenylethyl cation and 17.424 kcal for 1-methoxy-1-phenylethyl cation; these numbers suggest a considera-



bly reduced substituent effect in the latter species, or transition states closely resembling it, and suggest that reactions involving this species are more likely to give a curved correlation, as observed (see Figure 3). The 1-acetoxy-1-phenylethyl cation gives a calculated value of  $\Delta E_{21} = 8.749$  kcal, in between the value for the 1-methyl and 1-methoxy cations, as intuition would dictate; this point illustrates additionally that the large deviation of  $\alpha$ -acetoxystyrene hydration rates from the  $\rho_i - r_i$  relationship is puzzling.

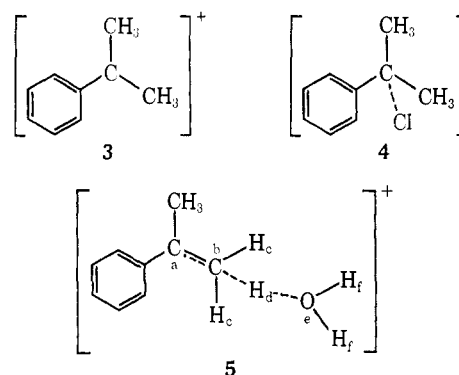
One might consider that the decreased resonance effect from the para position as electron-donating character of the substituent at the  $\alpha$  position increases would be easily rationalized by considering the net charge at the para carbon in the variously  $\alpha$ -substituted parent cations; *i.e.*, the lower the net charge, the smaller the substituent effect. In fact, the calculated net charge in the parent cations at the para position does decrease regularly as the  $\alpha$  substituent becomes more electron donating. To the extent that frontier orbital considerations are valid, "net charge" is approximated by the squared (normalized) LUMO coefficients, *i.e.*,  $c_1^2$  and  $c_2^2$  in the above equations. Clearly, a reduced value of  $c_2^2$  relative to  $c_1^2$  will reduce the substituent effect, so that this effect is certainly present; however, in the cases studied here, it is the  $\Delta E_{21}$  term which dominates. Thus, we conclude that the "curved  $\sigma^+$  correlations," or, alternatively, a small  $r_i$  value in eq 1, can be viewed to largely arise from the effect of the structural perturbation on the LUMO energy of the perturbed system.

It is to be stressed that, even within the framework of this theory, effects of the type discussed here can arise even when  $\Delta E_{21}$  is negligible in the transition state if the substituent effects on the reactant states are large; similarly, substituent effects on the reactants, explicitly ignored here, will make a contribution to the effects observed, the significance of which will depend on the system under scrutiny. Conversely, "linear 'free energy' relationships" can arise from fortuitously compensating variation of expressions like eq 12 for both reactants and transition states. The explicit neglect of such factors as solvation may not be appropriate, even for this highly relative calculation, in all cases. The frontier orbital approach does, however, offer an attractive explanation for the substituent effects observed here and illustrates that "saturation phenomena" are inherently reasonable.

The perturbation approach may be used fruitfully to answer a general question posed by Noyce and Pollack<sup>37</sup> concerning the relationship between two closely related processes, namely, solvolysis and hydration reactions. These authors noted that existing data in the literature suggested that, although a phenyl group has about the same substituent effect as two methyl groups in a solvolysis reaction (*e.g.*, *tert*-butyl chloride reacts at about the same rates as  $\alpha$ -phenethyl chloride), a phenyl group is about equal to a methyl group in hydration reactions (*e.g.*, isobutylene hydrates about equally as fast as  $\alpha$ -methylstyrene). An equivalent statement is that substituent effects on hydration reactions are likely to be less dramatic than those on solvolysis reactions leading to the same putative intermediate carbonium

(37) D. S. Noyce and R. M. Pollack, *J. Amer. Chem. Soc.*, **91**, 7158 (1969).

ion. An additional illustration of this idea in experiment is the parameters of eq 1 for *tert*-cumyl chloride solvolysis ( $\rho = -4.5$ ,  $r = 1.0$ ) *vs.* those for  $\alpha$ -methylstyrene hydration ( $\rho = -3.4$ ,  $r = 0.7$ );<sup>38</sup> both reactions lead presumably to the same first intermediate carbonium ion. Noyce and Pollack<sup>37</sup> argued from thermochemical data that properties of the reactant state in hydration reactions were not responsible for this reduced sensitivity of these processes, and, although solvolysis reactant states were not considered explicitly, these authors suspected reasonably that the transition states for these reactions, for which a variety of experimental evidence exists implicating carbonium ions as first intermediates, are really rather different in some way in the two types of reactions. Hydration reactions are studied in largely aqueous solutions, whereas solvolytic reactions are usually characterized in less polar media, so that solvent effects probably play some role in these observations. Nevertheless, the perturbation arguments below show that the observation of general acid catalysis leads one to expect a reduced substituent effect in hydration reactions. We considered the LUMO energy of the following three species, 3, 4, and 5.



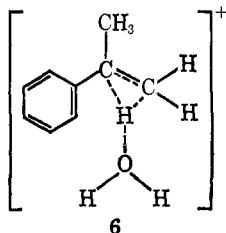
Species 3 is our reference, the *tert*-cumyl cation. Species 4 is an ion pair which might closely represent the *tert*-cumyl chloride solvolysis transition state; the carbon-containing part of this molecule was taken as identical with species 3, with coplanar carbons and C-C-C bond angles of  $120^\circ$ , and the Cl was placed 1.5 C-Cl bond lengths, or 2.66 Å, on a line from the carbon  $\alpha$  to the benzene ring and normal to the plane of the carbon system. In species 5, which represents a hydration transition state "50% along the reaction coordinate," bond lengths and angles were chosen as the average of the values of those of the hypothetical reactant state ( $\alpha$ -methylstyrene +  $\text{H}_3\text{O}^+$ ) and first intermediate (*tert*-cumyl cation +  $\text{H}_2\text{O}$ ): bond lengths  $ab = 1.43$  Å,  $bc = 1.08$  Å,  $be = 2.70$  Å,<sup>39</sup>  $d$  collinear with  $b$  and  $e$  and 1.35 Å from each,  $ef = 1.00$  Å;<sup>40</sup> bond angles  $abc = 114.75^\circ$ ,  $abe = 99.75^\circ$ ,  $def = 108.25^\circ$ . No effort was made to define the energy maximum along the reaction coordinate. These values, though reasonable, are obviously highly speculative. The LUMO energies of these species are  $E_3$ ,  $-10.52150$  eV;  $E_4$ ,  $-10.44034$  eV; and  $E_5$ ,  $-10.12229$  eV.  $\Delta F_{13}$  is thus 0.08116 eV, or 1.87 kcal, and  $\Delta E_{53}$  is 0.39921 eV, or

(38) N. C. Deno, F. A. Kish, and H. J. Peterson, *J. Amer. Chem. Soc.*, **87**, 2157 (1965).

(39) G. C. Pimentel and A. R. McClellan, "The Hydrogen Bond," W. H. Freeman, San Francisco, Calif., 1960, p 267.

(40) (a) W. S. Benedict, N. Gailar, and E. F. Plyer, *J. Chem. Phys.*, **24**, 1139 (1956); (b) W. C. Hamilton and J. A. Ibers, "Hydrogen Bonding in Solids," W. A. Benjamin, New York, N. Y., 1968, pp 115-116.

9.20 kcal. These values, and eq 12, suggest that if this result can be generalized, substituents will be less influential in hydration reactions than in solvolysis reactions giving the same intermediate and less effective in either reaction than in carbonium ion equilibria. We are aware that species **3**, **4**, and **5** are much different species relative to each other than the other species considered above; this fact, and the known limitations of EHT calculations, implies that this calculation should be regarded as suggestive. There are other transition states for hydration which might predict similar substituent effects, such as **6**, and these are not ruled out by



the calculations, of course.<sup>41</sup> Despite uncertainties

(41) (a) **5**, in fact, could be regarded as merely an extreme of a transition state leading to an unsymmetrical  $\pi$  complex. The question of  $\pi$  complexes as first intermediates has been dealt with extensively, and these species are considered unlikely in hydration reactions leading to stable carbocations in highly polar solvents, especially water: W. M. Schubert, B. Lam, and J. R. Keefe, *J. Amer. Chem. Soc.*, **86**, 4727 (1964); (b) G. M. Loudon and D. S. Noyce, *ibid.*, **91**, 1433 (1969).

that may exist in the precise description of transition states, the explicit incorporation of hydronium ion into the transition state for hydration (these reactions are believed to be general acid-catalyzed) leads to a significantly higher LUMO energy and, therefore, by eq 12, a substantially reduced substituent effect. Given the approximate validity of these models, the perturbation approach has provided an attractive means for understanding the differences in substituent effects in hydration and solvolysis reactions.

**Acknowledgment.** We are grateful to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for support of this research. We thank Professor Roald Hoffman for the use of his extended Hückel program and for helpful advice, Dr. Mihai Elian for assistance with the details of the calculations, and Professor Charles F. Wilcox, Jr., for his encouragement and his many constructive suggestions.

**Supplementary Material Available.** A table of detailed kinetic data will appear following these pages in the microfilm edition of this volume of the journal. Photocopies of the supplementary material from this paper only or microfiche (105 × 148 mm, 24× reduction, negatives) containing all of the supplementary material for the papers in this issue may be obtained from the Journals Department, American Chemical Society, 1155 16th St., N.W., Washington, D. C. 20036. Remit check or money order for \$3.00 for photocopy or \$2.00 for microfiche, referring to code number JACS-74-4508.