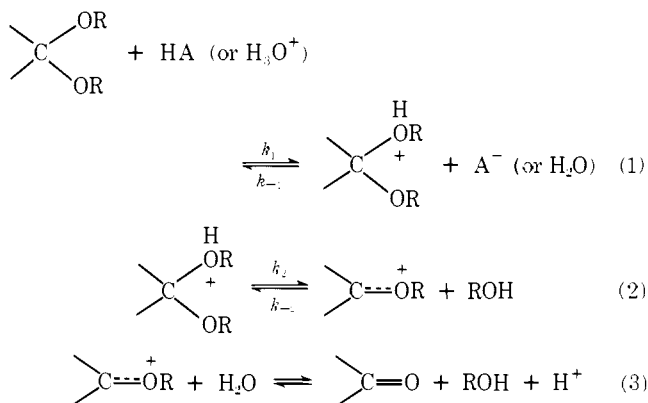# Kinetic Hydrogen Isotope Effects in the Concerted Mechanism for the Hydrolysis of Acetals, Ketals, and Ortho Esters[1]

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Abstract: The hydrolysis of many ortho esters, and some acetals and ketals, is general acid catalyzed, and in some examples these generate linear Brønsted plots over substantial ranges of catalyst acidity. This suggests that the reaction coordinate is primarily a reorganization of heavy atoms since proton transfer from one oxygen to another has been shown to generate strongly curved Brønsted plots. However, the isotopic fractionation factor for the catalytically active proton in these transition states is substantially less than 1.0; in several examples it is less than 0.5. Such values have been thought to require that the reaction coordinate be largely a motion of the hydrogen giving the low fractionation factor. This dilemma has been resolved by the observation and rationalization of fractionation factors as low as 0.28 for stable, hydrogen bridge-bonded complexes, AHA⁻. A similar, bounded coordinate is now suggested for the catalytically active protons in question. This permits the reaction coordinate to be pictured as shown in Figure 1.

A generally accepted mechanism for the hydrolysis of acetals, ketals, and ortho esters is shown in eq 1–3. For most of the

$$\begin{array}{c}\diagdown \\ \diagup \end{array}\!\!C\!\!\begin{array}{c}\diagup OR \\ \diagdown OR \end{array} + \text{ HA (or } H_3O^+) $$

$$\underset{k_{-1}}{\overset{k_1}{\rightleftharpoons}} \begin{array}{c}\diagdown \\ \diagup \end{array}\!\!C\!\!\begin{array}{c} \diagup OR \\ \overset{+}{} \\ \diagdown OR\end{array}\!\!\!\overset{\displaystyle H}{} + \text{ A}^- \text{ (or } H_2O) \quad (1)$$

$$\begin{array}{c}\diagdown \\ \diagup \end{array}\!\!C\!\!\begin{array}{c} \diagup OR \\ \overset{+}{} \\ \diagdown OR\end{array}\!\!\!\overset{\displaystyle H}{} \underset{k_{-2}}{\overset{k_2}{\rightleftharpoons}} \begin{array}{c}\diagdown \\ \diagup \end{array}\!\!C\!\!=\!\!\overset{+}{OR} + ROH \quad (2)$$

$$\begin{array}{c}\diagdown \\ \diagup \end{array}\!\!C\!\!=\!\!\overset{+}{OR} + H_2O \rightleftharpoons \begin{array}{c}\diagdown \\ \diagup \end{array}\!\!C\!\!=\!\!O + ROH + H^+ \quad (3)$$

substrates studied the rate-determining step involves C–O bond cleavage[2,3] (eq 2). The first step involves an acid–base equilibrium, and the mechanism is classified as A-1. However, a number of examples have been found to show general acid catalysis.[2,4] This might imply that the first step, involving proton transfer (eq 1), is rate determining. It has been argued by some authors, however, that the mechanism is not pure A-S$_E$2 but a concerted process in which proton transfer is accompanied by C–O bond breakage.[2,4] The observed solvent hydrogen isotope effects have posed a barrier to the adoption of this view. For reactions which show general acid catalysis, rate constants in H$_2$O are regularly larger than those in D$_2$O, often substantially so. This may be regarded as evidence that the reaction coordinate has a substantial hydrogenic component which would tend to exclude heavy atom participation. A subsidiary problem concerns the role of the protonated ether (the product of the reaction shown in eq 1). If the reaction coordinate is largely a displacement of heavy atoms, it may include a stretching of the C–O bond of the substrate, eliminating the need for the protonated ether intermediate as a discrete intermediate.

In Table I representative examples are presented for each mechanistic type. For the A-1 mechanism k_{H_2O}/k_{D_2O} generally has a value[5] from 0.29 to 0.43, and entries 1 and 2 fall within that range. When proton transfer is rate determining (A-S$_E$2), both primary and secondary hydrogen isotope effects

can contribute to k_{H_2O}/k_{D_2O}. Proton transfers from hydronium ion are subject to both effects and k_{H_2O}/k_{D_2O} is usually around 3.[6] If the proton is transferred from a molecular acid, i.e., a carboxylic acid, only the primary effect is important and k_{H_2O}/k_{D_2O} values around 7 are common.[6] Entries 5 and 6 are typical examples of an A-S$_E$2 reaction catalyzed by H$_3$O$^+$ and chloroacetic acid, respectively. Table I also gives some examples of acetal hydrolyses (entries 3 and 4) which do not, easily, fall into either class: where k_{H_2O}/k_{D_2O} is smaller than expected for an A-S$_E$2 mechanism, but too large for an A-1 mechanism. Anticipating our conclusions, these reactions have been characterized as "concerted".

Equilibrium and kinetic hydrogen isotope effects can, usefully, be expressed as functions of isotopic fractionation factors.[7] A suggested transition state structure for the concerted reaction is given in Figure 1. When H$_3$O$^+$ is the catalyst, the solvent isotope effect is given by

$$\frac{k_{H_2O}}{k_{D_2O}} = \frac{\phi_{L_3O^+}^3}{\phi_1 \phi_2^2} \quad (4)$$

where $\phi_{L_3O^+}$ is l, the fractionation factor for the aquated hydronium ion, and has the value 0.69; ϕ_1 is the fractionation factor for the transferring proton, and ϕ_2 is the fractionation factor for the nontransferred protons. Now ϕ_2 can be approximately related to l by eq 5 where χ is a measure of the residual charge on the H$_3$O$^+$ oxygen atoms.[6]

$$\phi_2 = l^\chi \quad (5)$$

If it can be assumed that the residual charge on the H$_3$O$^+$ oxygen is directly related to the degree of charge development when a molecular acid is the catalyst, then χ is $1 - \alpha$, where α is the conventional Brønsted exponent.[6] Substitution of these quantities into eq 5 and rearranging, an equation for ϕ_1 can be obtained:

$$\phi_1 = \frac{k_{D_2O}}{k_{H_2O}} (l^{1+2\alpha}) \quad (6)$$

If the catalyst is a carboxylic acid, then the solvent isotope effect is given by eq 7 and ϕ_1 is given by k_{D_2O}/k_{H_2O} since ϕ_{RCOOH} is approximately 1.0.[5]

$$\frac{k_{H_2O}}{k_{D_2O}} = \frac{\phi_{RCOOH}}{\phi_1} \quad (7)$$

Table II gives ϕ_1 calculated by the foregoing methods for acetal, ketal, or ortho ester hydrolyses which appear not to fall

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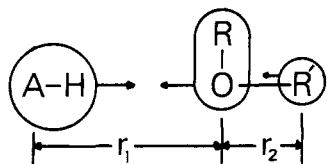
Figure 1. The transition state for general-acid-catalyzed hydrolysis of ortho esters, certain acetals, and ketals, and possibly hemiacetals and aldehyde hydrates. The arrows indicate the direction and approximate relative magnitude of the important nuclear motions of the transition state. The arrow attached to R' is somewhat shorter than that attached to OR, so that r_2 is increasing.

Table I. Kinetic Solvent Isotope Effects and Reaction Mechanism for Hydrolysis Reactions in Water[a]

no.	substrate	cat.	mech	k_{H_2O}/k_{D_2O}
1	ethyl orthoformate	H^+	A-1	0.34
2	acetaldehyde dimethyl acetal	H^+	A-1	0.37
3	2-(4-nitrophenoxy)-tetrahydropyran	HCOOH	concerted	3.45
4	benzaldehyde methyl phenyl acetal	CH_3COOH	concerted	2.13
5	ethyl vinyl ether	H^+	A-S_E2	3.2[b]
6	ethyl vinyl ether	$ClCH_2CO-OH$	A-S_E2	6.2[b]

[a] Taken from ref 3 unless otherwise noted. [b] M. M. Kreevoy and R. Eliason, *J. Phys. Chem.*, **72**, 1313 (1968).

into the A-1 category, and for a number of comparison reactions. (The examples given in Table II are not intended to be all inclusive but merely representative.) For reactions occurring by the A-S_E2 mechanism (entries 1 and 2), the ϕ_1 values are quite small, which is characteristic for these reactions. The other ϕ_1 values are consistently larger than those for true A-S_E2 reactions. For some of the calculated ϕ_1's α has not been measured directly, and in these cases reasonable estimates for α were made. While ϕ_1 is responsive to variations in α, no reasonable choices of α would generate ϕ_1 values in the range characteristic of A-S_E2 reactions. While the ϕ_1 values are higher than those associated with A-S_E2 reactions, they are all less than unity, many substantially so.

The reaction coordinate for the concerted mechanism, pictured in Figure 1, must involve considerable heavy atom motion as a result of the C–O bond being broken. It has been argued[8] that, for proton transfers between oxygen atoms, the proton lies in a completely bounded potential well. According to this view the asymmetric stretching motion of an O···H···O system would be an oscillation with a restoring force and zero-point energy. The reaction coordinate of the transition state, which by definition is unbounded, would consist entirely of heavy atom motion. In another approach[3] it was suggested that the proton could move as the heavy atom reorganization progressed, but only in coordination with the heavy atom motion, the implication being that the reaction coordinate of the transition state has a small fraction of hydrogenic character, and, correspondingly, the O–H stretching mode has a heavy atom component.[9] Since the unbounded reaction coordinate has no restoring force and the bounded O–H stretching mode is not purely hydrogenic, there may be a small reduction in the zero-point energy associated with the hydrogen when such a transition state is formed. However, the expected reduction would be quite small. In the linear motions of gaseous HF there is a 5% reduction in the zero-point energy associated with the hydrogen due to the incorporation of hydrogenic motion into the unbounded translation.[10] In any event, if the concerted mechanism is correct, the low values of ϕ_1, cited in Table·II, cannot be attributed to the hydrogenic character of the (unbounded) reaction coordinate.

On the other hand, a simple proton transfer is unlikely to be rate determining because $k_{-1}(H_2O)$ would then have to be smaller than k_2, and there is thought to be almost no energetic barrier to spontaneous proton transfer between oxygens,[11] although we recognize that several limited exceptions to this generalization are now well established, among them carbonyl addition and related reactions.[32] Further, if such a simple proton transfer *were* rate determining, a sharply curved Brønsted plot would be expected with α going from 1.0 to 0.0 over a range of a few units in the pK of the acids used if ΔpK for the reaction was near zero.[11] No such phenomenon has been observed for these reactions.[12,13] However, the ΔpK values for these reactions are most likely far removed from zero. In this event an α value near one of the extremes, either 1.0 or 0.0, would be expected. As can be seen in Table II, α generally has a value around 0.5. Thus, the evidence from isotope effects and

that from Brønsted plots appears to be in conflict. The purpose of this paper is to show how these results can be reconciled.

If the transferring proton is in a potential well, what is the shape of this surface? It appears that the best model for the hydrogenic potential function of hydrogen-bonded systems[14] and of proton transfers between water molecules[15] or ammonia molecules[16] is one that has a double minimum and a shallow central maximum that may or may not project above the first allowed vibrational level. Such a proton would have a strongly reduced zero-point energy;[17] thus, a major part of the zero-point energy difference between hydrogen and deuterium would be lost on going from the starting state to the transition state, even though the principal hydrogenic mode is still bounded. In principle, the hydrogen isotope effect could be estimated by a knowledge of the zero-point energies for each state. In practice, only some limits can be given, as the exact shape of the potential energy surface in the transition state is not known. However, the experimental results fall nicely within these limits.

Recently a correlation has been made between experimental isotopic fractionation factors for AHA^- hydrogen bonded complexes and those calculated from a family of one-dimensional quartic-quadratic potential functions.[17] Since this simple model reproduced the general magnitude and the qualitative trends of the observations remarkably well, it was thought that a similar model could be used for the concerted mechanism. The energy levels for a one-dimensional quartic-quadratic potential function can be obtained by scaling dimensionless values given by Laane.[18] If water is the reference substance, and if it can be represented by one member of the family of potential functions, then the fractionation factors $\phi_{1,n}$ can be approximated by eq 8 at one-dimensional, zero-point, energy level of approximation.[19]

$$\phi_{1,n} = \exp\frac{hc}{kt}$$
$$\times (ZPE_{H,n} - ZPE_{D,n} - ZPE_{H_2O} + ZPE_{D_2O}) \quad (8)$$

The appropriate zero-point energy (ZPE) is that taken from ref 17 and is expressed in cm^{-1}. The other symbols in eq 8 have their usual significance. This simple model predicts isotopic fractionation factors as low as 0.16, the minimum fractionation factors corresponding to a central maximum that just reaches to the first allowed vibrational state.[17] The most obvious corrections to these estimates tend to raise the predicted values, but fractionation factors as low as 0.28 have been *observed* for *stable*, hydrogen-bonded complexes.[16] Thus, the observable result can be very similar to what would be expected for rate-determining proton transfer with an unbounded hydrogenic coordinate. However, the (unbounded) reaction coordinate for this proton transfer is actually a heavy atom motion.

The remaining question is, "What sort of heavy atom motion actually dominates the reaction coordinate in the transition

Table II. Calculated Fractionation Factors, ϕ_1, for Hydrolysis Reactions[a]

no.	substrate	catalyst	k_{H_2O}/k_{D_2O}	α[b]	ϕ_1	solvent
1	ethyl vinyl ether	H_3O^+	3.2[c]	0.66[c]	0.13	water
2	ethyl vinyl ether	$ClCH_2COOH$	6.2[c]	0.66[c]	0.16	water
3	ethyl orthocarbonte	H_3O^+	0.71	0.68	0.67	water
4	ethyl orthocarbonate	CH_3COOH	1.41	0.68	0.71	water
5	ethyl orthoacetate	H_3O^+	0.53	0.65	0.80	water
6	phenyl orthoformate	H_3O^+	1.03	0.5[d]	0.46	40% dioxane
7	phenyl orthoformate	H_3O^+	0.75	0.5[d]	0.63	65% dioxane
8	acetone di-2,2,2-trichloroethyl ketal	H_3O^+	0.56	0.53	0.85	65% dioxane
9	2-(4-nitrophenoxy)tetrahydropyran	H_3O^+	0.75	0.69	0.55	50% dioxane
10	2-(4-nitrophenoxy)tetrahydropyran	HCOOH	3.45		0.29	water
11	2-(2,2,2-trichloroethoxy)tetrahydropyran	H_3O^+	0.63	0.5[e]	0.76	water
12	2-(2,2,2-trifluoroethoxy)tetrahydropyran	H_3O^+	0.78	0.5[e]	0.61	water
13	benzaldehyde methyl phenyl acetal	H_3O^+	1.01	0.60	0.44	water
14	2,5,5-trimethyl-1,3-dioxolone	H_3O^+	0.60	0.7[f]	0.68	water
15	2-methoxyethyl orthoformate	H_3O^+	0.48	0.93	0.72	water
16	2-chloroethyl orthoformate	H_3O^+	0.51	0.37	1.03	water
17	acetaldehyde ethyl 2,2,2-trichloroethyl acetal	H_3O^+	0.49	0.53	0.95	65% dioxane
18	2-(4-chlorophenoxy)tetrahydropyran	H_3O^+	0.50	0.7[g]	0.82	50% dioxane

[a] All data taken from ref 2 unless otherwise noted. [b] In some cases a value of α for the substrate in question could not be obtained. In these cases an α value for a similar substrate was used and the source is noted. [c] From M. M. Kreevoy and R. Eliason, *J. Phys. Chem.*, **72**, 1313 (1968). [d] From diethyl phenyl orthoformate in 50% dioxane: ref 2, Table VII. [e] From 2-(4-nitrophenoxy)tetrahydropyran in water: ref 2, Table VII. [f] From 2-(4-methoxyphenyl)-4,4,5,5-tetramethyl-1,3-dioxolane in water: ref 2, Table VII. [g] From 2-(4-nitrophenoxy)tetrahydropyran in 50% dioxane: ref 2, Table VII.

state?" The two coordinates that suggest themselves are r_1, the distance between the acetal or ortho ester carbon and the oxygen being protonated. Jencks[20] has pointed out that the basicity of the acceptor site is a dramatic function of this latter distance. The incorporation of r_2 into the reaction coordinate for the proton transfer and the sensitivity of the basicity of the acceptor site to r_2 appear to be the reasons for the ease of breaking the carbon–oxygen bond rather than the starting state basicity of the acceptor oxygen being critical for the selection of the rate-determining step.[21] The transition state basicity of the acceptor oxygen can be adjusted, without too much energetic cost, by adjusting r_2.

Delpuech et al. analyzed the $NH_4^+ \cdots NH_3$ system theoretically using ab initio LCAO–MO–SCF calculations with a Gaussian basis set.[16] They found that as the nitrogen atoms approached an energy minimum was reached at an N–N distance of 2.78 Å. However, the energy barrier to proton exchange was 6.1 kcal/mol. By squeezing the nitrogens together to 2.59 Å at a "cost" of 1.2 kcal/mol, the total barrier for exchange was reduced to 2.9 kcal/mol, which they reckoned would be below the lowest lying vibrational energy level. This would account for the lack of activation energy for the exchange process.[16] This implies that for the systems we are dealing with here, it may be profitable overall to reduce r_1 below the value it would spontaneously adopt in order to reduce the net barrier. The proton transfer can be further facilitated by making the donor and acceptor sites equally basic. Flanigan and de la Vega[22] have examined the case of an asymmetric potential curve for the $H_3O^+ \cdots {}^-OH$ system. Even with an energy separation of over 30 kcal/mol between the upper and lower minima and with a central barrier height over 6 kcal/mol, the proton cannot "leak" from one well to the other. The system must put the proton into an energy level higher than the barrier before it can go from one well to the other. Conversely, a proton in the lower well could not move to the upper well except by going over the top of the barrier. However, proton tunneling occurs readily for near-symmetric systems.[23] In the present case the pK_a difference between a protonated ether and a carboxylic acid is equivalent to around 10 pK units or about 15 kcal/mol.[24] If the donor site is H_2O, the difference is even smaller. Equal basicity of the two sites can be approached by increasing r_2. This would enable the proton to move freely from one potential well to another.

If r_2 does, indeed, increase to give a more symmetrical hydrogenic potential function to the transition state, it could then either return momentarily to a normal value giving the protonated acetal or ortho ester as the first intermediate, or it could continue to increase giving the stabilized carbocation as the first intermediate. Such a first intermediate would still be stabilized by weak interaction between the carbocation and the recently departed oxygen lone pair, as well as by a hydrogen bond between its proton and the conjugate base of the original catalyzing acid. If the hydrogen bond is broken more easily than the residual carbon–oxygen "solvation bond", then the breaking of the latter would be rate determining for reactions in which the proton transferring process was not. Just such a transition state has recently been proposed by Young and Jencks for most acetal hydrolyses.[25] Such a mechanism would fit the A-1 classification. Even if the original conjugate base of the proton were still present at the final separation of the carbon and oxygen atoms, it would hardly be more than a "spectator",[26] and its presence could be very hard to demonstrate. Such a path seems to us intuitively more attractive than the re-formation of an ordinary carbon–oxygen bond after the proton is transferred. In any event, the suggested structure of the transition state for the general-acid-catalyzed reactions does not hinge on the answer to this question. It is shown in Figure 1. In all variants of the mechanism the oxycarbonium ion is a real intermediate.[25,27]
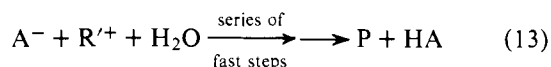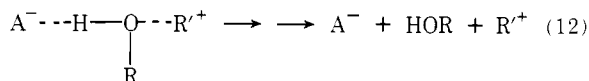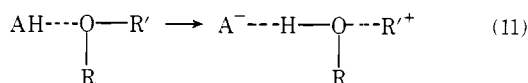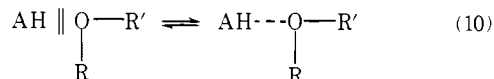
Quantum mechanical tunneling through an energy barrier is a function of the mass of the particle doing the tunneling.[8,28] Consequently, tunneling is more important for hydrogen than for deuterium than for tritium. When tunneling is an important factor in proton transfer reactions, k_H/k_D ratios $\gg 1$ are usually obtained. However, this need not be apparent in the overall rates in the present cases as most of the free energy of activation, $\Delta G^{\ddagger}$, would go into reducing r_1 and/or increasing r_2 to allow a facile proton, deuteron, or triton transfer in the transition state.

In summary, we propose the following mechanism for general-acid-catalyzed acetal, ketal, and ortho ester hydrolysis reactions. The first two steps consist of the formation of a reaction complex[19,29] (eq 9 and 10)
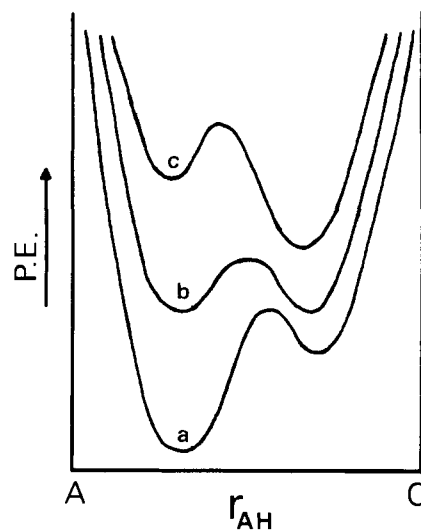
$$\text{AH} + \underset{\overset{|}{R}}{\text{O}}\text{—R}' \rightleftharpoons \text{AH} \parallel \underset{\overset{|}{R}}{\text{O}}\text{—R}' \qquad (9)$$
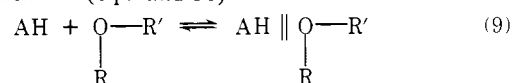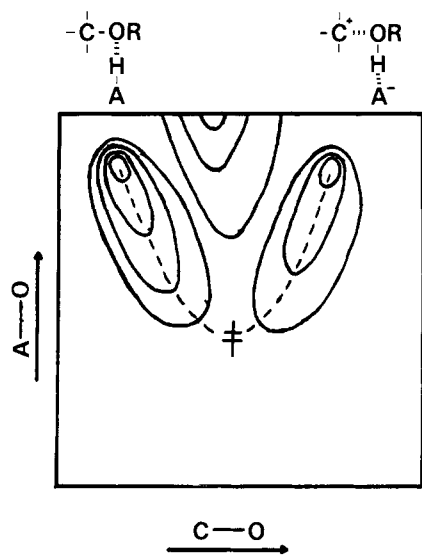
Figure 2. Contour diagram for the concerted mechanism for general-acid-catalyzed hydrolysis. The dashed line indicates the reaction pathway.

Figure 3. One-dimensional potential energy curves for the concerted mechanism for general-acid-catalyzed hydrolysis. A and O refer to the catalyzing acid and the alkoxy oxygen, respectively. The abscissa is the acid–hydrogen internuclear distance. (a) is a plot of the reaction complex starting state. (b) is the transition state, and (c) is the product complex state after proton transfer.

$$AH \parallel \underset{R}{O}\!-\!R' \rightleftharpoons AH\!-\!-\!\underset{R}{O}\!-\!R' \qquad (10)$$

$$AH\!-\!-\!-\!\underset{R}{O}\!-\!R' \longrightarrow A^-\!-\!-\!H\!-\!\underset{R}{O}\!-\!-\!R'^+ \qquad (11)$$

$$A^-\!-\!-\!H\!-\!\underset{R}{O}\!-\!-\!R'^+ \longrightarrow \longrightarrow A^- + HOR + R'^+ \qquad (12)$$

$$A^- + R'^+ + H_2O \xrightarrow[\text{fast steps}]{\text{series of}} \longrightarrow P + HA \qquad (13)$$

where AH is any acid, R is a small hydrocarbon group, and R' is the remaining portion of the acetal, ketal, or ortho ester. The rate-determining step is given by eq 11, and the remaining steps are all rapid, leading to product (P). A plausible potential energy contour diagram[30] for the rate-determining step is given in Figure 2. The vertical axis is the A···O distance and we have assumed that the proton always locates itself between these two basic centers. The horizontal axis is the C–O distance and represents C–O bond breaking. The proton in the reaction complex finds itself in a deep potential well next to A and unable to move to the potential well associated with O without a substantial input of energy (Figure 3a). As the C–O bond begins to stretch the A···O distance compresses. This compression and stretching continues to the transition state (marked with ‡). The proton now finds itself in a nearly symmetrical double minimum potential well with a shallow central maximum (Figure 3b). The proton can now move between A and O with relative ease and requires little if any activation energy.[16,22,23] The proton, however, would still be bounded and still have zero-point energy, although the difference in zero-point energy between H and D would be small. As the C–O distance continued to expand, the A···O distance would also increase and the process would continue to the product of this step. During this process the proton finds itself trapped in the energy minimum that has developed next to the oxygen (Figure 3c). In this mechanism the reaction coordinate consists almost entirely of heavy atom motion. The proton is always bounded and retains zero-point energy. A very similar mechanism has recently been proposed by Young and Jencks for the general-acid-catalyzed breakdown of ketone bisulfites.[31]

Most acetal and ketal hydrolyses appear to show specific hydronium ion catalysis and their mechanism has been regarded as A-1.[3-5] However, the compounds which appear to use the A-1 mechanism are sufficiently similar to those that we have discussed that it would be attractive to bring them under the same mechanistic umbrella. To do so we would have to postulate that a step like that shown in eq 12 is rate determining.[25] Such a rate-determining step would give rise to general acid catalysis, but with a value of α very close to unity, so that catalysis by acids other than H_3O^+ might be very hard to find.[7] It would very nicely rationalize certain other observations about acetal hydrolysis. The procarbonyl fragment of the transition state for this reaction always appears to resemble $R_1R_2C \overset{+}{\doteq} OR'$,[3] although the Leffler–Hammond principle[33] would suggest that it should range from that extreme protonated substrate. Steric crowding or strain in the starting state seems to lead to general acid catalysis, as does resonance stabilization of the procarbonyl fragment.[4] All of these structural characteristics would make it harder to reverse the reaction, shown in eq 11, and therefore tend to make that step rate determining, as we postulate that it is for ortho ester hydrolysis. Finally the placement of functional groups in lysozyme[4,25] becomes easily understandable. They are exactly where they need to be if the steps shown in eq 11 and 12 are to be facilitated.

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Vinylic Cations from Solvolysis. 26.[1] Solvolysis of 9-(α-Chlorovinyl)anthracene and Selectivity of the Derived Ion
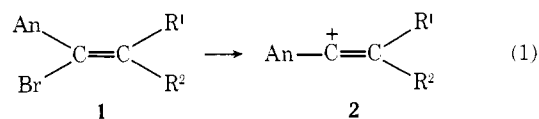
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Abstract: The solvolysis of 9-(α-chlorovinyl)anthracene (3) in 80% EtOH, 90% acetone, and AcOH gives both solvolysis and elimination products. The Winstein–Grunwald *m* value is 0.77 in 80% EtOH at 120 °C and *k*(AcOH)/*k*(AcOD) = 0.91 in the buffered acids. The reaction shows a common ion rate depression and the observed selectivity (mass low) constants decrease with an increase in solvent nucleophilicity: α(AcOH) > α(90% Me₂CO) > α(80% EtOH). The products are formed mainly from the free α-(9-anthryl)vinyl cation 20. The α value for the solvolysis of 9-(α-chloroethyl)anthracene (4) is only slightly higher than that for 3, while *k*(4)/*k*(3) = 6.9 × 10⁴ in 90% acetone. The effect of the α-9-anthryl group as an activating group for both the Sₙ1 and the AdₑE routes and the role of steric effects on these reactions and on the Sₙ1 vs. El routes of α-arylvinyl cations are discussed. Complications in evaluating α for 20 due to the uncertainty in the nature of the capturing nucleophiles and to the El reaction are revealed, the importance of the bulk of the α-aryl group in determining the selectivity of β,β-unsubstituted vinyl ions is discussed, and the selectivities of the structurally related vinylic (20) and trigonal (25) α-(9-anthryl)-substituted ions are compared.

An unusual feature of the solvolysis of several α-arylvinyl systems is the appearance of common ion rate depression.[3-6] In terms of the Ingold–Winstein solvolysis scheme,[7] the products in these cases are formed, at least in part, from a "free" vinyl cation intermediate.[7b,c] Such external ion return[7b] and selectivity are usually associated with a long lifetime of the intermediate,[7] and its appearance for the allegedly high-energy,[8] and hence short-lived, vinyl cations seems surprising. The selectivity of α-anisylvinyl cations was ascribed by us partially to the charge-stabilizing effect of the α-anisyl group, but mainly to steric effects arising from the geometry of the diagonal vinyl cation.[3-6] The vacant orbital in trigonal cations is in a plane perpendicular to the plane of the substituents, and reaction with the leaving group or with the solvent is from the least hindered direction. In contrast, the vacant orbital of a vinyl cation is in the plane of the substituents, and both the solvent and a capturing nucleophile approach the ion from the most hindered direction. Consequently, increase in the bulk of the vinylic substituents will increase the steric hindrance to capture of the ion by a nucleophile, resulting in increased lifetime and selectivity of the ion.

This explanation was borne out in previous studies on the solvolysis of α-anisyl β,β-disubstituted vinyl bromides 1 (eq 1). The selectivities, as measured by the competitive capture of the ion 2 by Br⁻ vs. capture by the solvent in 2,2,2-trifluoroethanol, or by AcO⁻ in AcOH, increase regularly with an increase in the bulk of R¹ and R² in the order R¹, R² = H < R¹, R² = Me < R¹, R² = Ar < R¹R²C = anthronylidene.[6]

$$\underset{\textbf{1}}{\overset{An}{\underset{Br}{>}}C=C\overset{R^1}{\underset{R^2}{<}}} \longrightarrow \underset{\textbf{2}}{An-\overset{+}{C}=C\overset{R^1}{\underset{R^2}{<}}} \qquad (1)$$

A test of this "steric hypothesis" by changing the bulk of the α substituent was not yet performed. Since the β,β-unsubstituted system 1, R¹ = R² = H, shows no selectivity either in aqueous ethanol or in AcOH,[4] an obvious experiment will be a search for selectivity in the solvolysis of β,β-unsubstituted systems where the α-aryl group is bulkier than anisyl. Ortho substitution increases the bulk of the α-aryl substituents. However, the few ortho-α-aryl substituted β,β-unsubstituted systems studied so far were investigated mainly[9] in the highly nucleophilic aqueous ethanol, or occasionally at very low concentrations of the leaving group in AcOH,[9] i.e., under conditions which are unfavorable for the observation of selectivity.

A closely related problem concerns the reactivity–selectivity relationship. There is presently an apparent controversy between the operation of the reactivity–selectivity principle (higher reactivity of the species results in lower selectivity)[10] for several solvolysis reactions and the "constant selectivity" rule observed by Ritchie for capture of stable carbocations by nucleophiles.[11] In addition, we found that some of our slowly formed vinyl cations 2 show higher selectivity even than that of the rapidly formed benzhydryl cation.[12] In order to delineate the effects responsible for this deviation from the two "selec-