Reactions of an Allylic Carbocation with Nucleophiles in Aqueous Solvents

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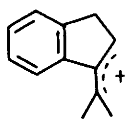
The allylic carbocation formed from 3-(2-X-propan-2-yl)indene (1-X) (X = Cl, OAc, or OH_2^+), or from 2-acetoxy-1-isopropylideneindan (2-OAc) in aqueous solvents containing *ca.* 75 vol % water reacts rapidly with nucleophiles. The selectivity is very low: β_{nuc} *ca.* 0.07 with alcohols as nucleophiles and β_{nuc} *ca.* 0.03 with substituted acetate anions. The nucleophile attacks at both ends of the allylic system but preferentially at the exocyclic carbon atom, giving the thermodynamically more stable product. Azide anion reacts with the carbocation about 50 times as fast as does water. The solvolysis of the allylic isomers (1-OAc) and (2-OAc) is accompanied by intramolecular rearrangement of the acetates as well as hydron abstraction by the leaving acetate anion, yielding the 1,2- and 1,4-elimination products. The elimination product compositions are quite different, which indicates two discrete ion-pair intermediates. It is concluded also that the isomerization proceeds by an ion-pair route, since in less polar solvents it has only been observed along with solvolysis and elimination. The experimental results for the acetates accommodate well a mechanism in which solvolysis, rearrangement, and elimination are connected *via* two contact ion-pair intermediates.

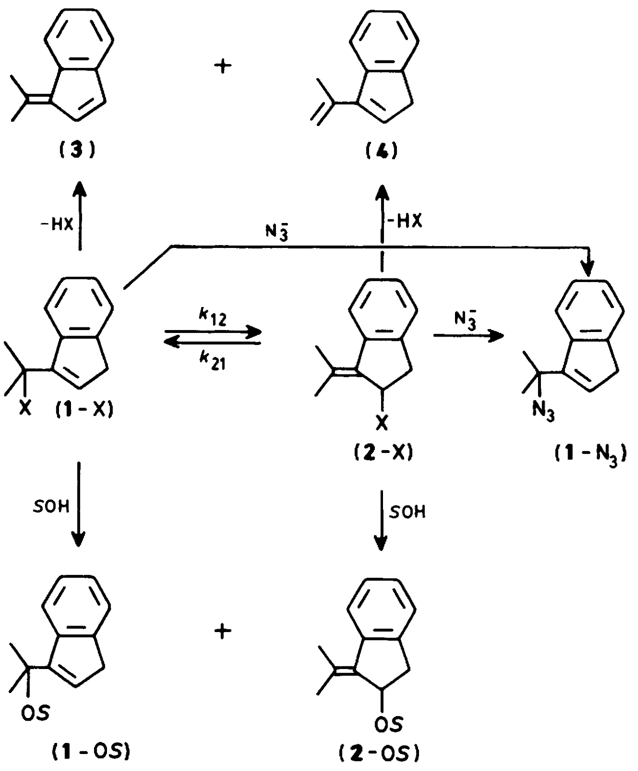
The role of ion pairs in good ionizing solvents has been examined in some detail.[1-3] The requirement that a significant fraction of the reaction takes place at the ion-pair stage and not *via* a 'free' solvent-equilibrated carbocation or directly *via* the substrate in a one-step reaction (S_N2) is probably not very often fulfilled in substitution reactions under these conditions but may be more common in elimination reactions. In this paper we describe the study of an allylic carbocation (I) and its reaction



(I)

with different kinds of nucleophile in aqueous solvent. This carbocation is rapidly formed from substrates that have a good leaving group at the exocyclic carbon atom. Its formation takes place so readily that even with a poor leaving group like acetate anion the substrate is solvolysed reasonably quickly and does not undergo any significant acyl–oxygen fission.

The carbocation is not only easily formed, it also reacts rapidly with nucleophiles, as concluded from the observation of a very low selectivity in its reactions with nucleophilic reagents. Approximate rate constants for this trapping of the carbocation have been estimated according to the method of Jencks and his co-workers.[2] Trapping at the ion-pair stage probably occurs to a small extent. Moreover, kinetic data and product compositions suggest that the allylic rearrangement of the acetates proceeds *via* two discrete ion-pair intermediates. The elimination reactions from the carbocation intermediates will be presented in more detail in the following paper.



Scheme 1.

Results

Kinetic Measurements.—The solvolysis of 3-(2-acetoxypropan-2-yl)indene (1-OAc) at constant ionic strength 0.75M ($NaClO_4$) in 10.3 mol % (*ca.* 25 vol %) acetonitrile in water at 35 °C provides as products 2-acetoxy-1-isopropylideneindan (2-OAc), 3-(2-hydroxypropan-2-yl)indene (1-OH), 2-hydroxy-1-isopropylideneindan (2-OH), 1-isopropylideneindene (3), and 3-isopropenylindene (4) (Scheme 1). A reaction starting from the isomeric acetate (2-OAc) yields much less of the olefin (4). The composition of the mixture of isomeric alcohols (1-OH) and (2-OH), which are the dominant products, is similar whether pure (1-OAc) or (2-OAc) is used as starting material (Table 1). The alcohols are very easily isomerized. Thus addition of a trace of acid to the product mixture converts almost all (2-OH) into (1-OH), the thermodynamically more stable product.

The reactions of (1-OAc) as well as of (2-OAc) were studied as a function of time by a sampling high-performance liquid chromatography (h.p.l.c.) procedure. The reactions follow the

Table 1. Product compositions obtained in reactions of (1-OAc) and (2-OAc) in 10.3 mol % CH_3CN-H_2O at 35 °C

Substrate	Salt[a]	$\frac{[(\textbf{1}\text{-OH})]^b}{[(\textbf{2}\text{-OH})]}$	$\frac{\text{Elimination}}{\text{Substitution}}$	$\frac{100[(\textbf{3})]}{[(\textbf{3})] + [(\textbf{4})]}$
(1-OAc)	$NaClO_4$	4.2	53×10^{-3}	26
(2-OAc)	$NaClO_4$	4.2	36×10^{-3}	77

[a] Concentration 0.75M. [b] (2-OH) isomerizes rapidly to (1-OH) in the presence of acids.

rate laws (1)—(3) where k_{1p} and k_{2p} denote the rate constants for the disappearance of (1-OAc) and (2-OAc), respectively, to products (P) other than the corresponding isomeric acetate.

$$d[(\textbf{1}\text{-OAc})] = -(k_{12} + k_{1p})[(\textbf{1}\text{-OAc})] + k_{21}[(\textbf{2}\text{-OAc})] \quad (1)$$

$$d[(\textbf{2}\text{-OAc})] = k_{12}[(\textbf{1}\text{-OAc})] - (k_{21} + k_{2p})[(\textbf{2}\text{-OAc})] \quad (2)$$

$$d[P] = k_{1p}[(\textbf{1}\text{-OAc})] + k_{2p}[(\textbf{2}\text{-OAc})] \quad (3)$$

The isomerization of the acetates is slow compared with reaction to give other products (P). Thus the disappearance of the starting material shows an approximatively pseudo-first-order behaviour. A simple computer simulation of the reactions, based upon the integrated expressions of equations (1)—(3), was employed to obtain more accurate rate constants. The rate constants are collected in Table 2. The equilibrium constant $K_{eq} = k_{12}/k_{21}$ obtained from the kinetic data ($NaClO_4$) is 0.35.

The presence of NaN_3 provides one more product, which was identified as the azide adduct ($\textbf{1}$-N_3). The observed rate constants do not change significantly even at high concentrations of azide anion (0.75M) when half of the product mixture consists of azide adduct. Thus a zero-order dependence of azide concentration on the total reaction rate is observed. The absence of an increase in the rate constants k_{1p} and k_{2p} implies that attack of N_3^- on the ester carbonyl group to yield the alcohols (1-OH) and (2-OH) is negligible.

Sodium acetate (0.75M), buffered with a small amount of acetic acid, was found to decrease k_{1p} and k_{2p} more than 50%. Table 2 also includes rate constants for the solvolysis of (1-OAc) with 0.75M-NaCl and -NaBr, respectively. The solvolysis of (1-OAc) in 7.7 mol % (25 vol %) trifluoroethanol in water is about twice as fast. Also in this medium the rate of solvolysis is decreased by a factor of about two by addition of NaOAc instead of $NaClO_4$.

The reaction of (1-Cl) is very rapid in water–acetonitrile and the rate was not measured. In pure methanol, a much less efficient reaction medium in which (1-OAc) does not produce any detectable solvolysis or isomerization product after two weeks in methanol at 35 °C, only some elimination product (3) is obtained; (1-Cl) reacts with a half-life of about 4 min.[4]

Selectivities from Product Ratios.—The chloride (1-Cl) yields the alcohols (1-OH) and (2-OH) accompanied by the elimination products (3) and (4) when solvolysed in water–acetonitrile. The measured product ratio, [(1-OH)]/[(2-OH)] = 3.9 in the presence of sodium acetate, is the same as obtained in reactions of (1-OAc) and (2-OAc).

The selectivity of the allylic carbocation towards different nucleophilic components of the solvent has been measured by solvolysing (1-Cl) in a mixture of 75 vol % H_2O and 6.25 vol % of each of the alcohols CF_3CH_2OH, $NCCH_2CH_2OH$, CH_3CH_2OH, and $MeOCH_2CH_2OH$ or MeOH (Table 3). The correlation between the pK_a value of a nucleophile and its reactivity towards the carbocation is shown in Figure 1. The reactivity of a given alcohol was measured as the second-order rate constant derived from the amount of ether produced and the concentration of the alcohol. Since there are reasons for not employing trifluoroethanol, water, and methanol for the regression line (see Discussion section), the correlation is based upon only three alcohols.* The Brønsted coefficient is small, β_{nuc} *ca.* 0.07. Consistently, the selectivity expressed by the ratio of the second-order rate constants, k(ethanol)/k(cyanoethanol), was found to be 1.4 in the medium 75 vol % H_2O, 12.5 vol % CH_3CH_2OH, and 12.5 vol % $NCCH_2CH_2OH$. The same value was measured for the reaction of (1-OAc) (Table 3). A slightly smaller value (1.3) was measured for the carbocation formed from ($\textbf{1}$-OH_2^+). However, this parameter was found to decrease with reaction time, behaviour also shown in the reactions of (1-Cl) when the reaction was performed in the presence of acid (the value of 1.4 probably corresponds to kinetic control; the decrease is presumably caused by some acid-catalysed solvolysis of the ether products).

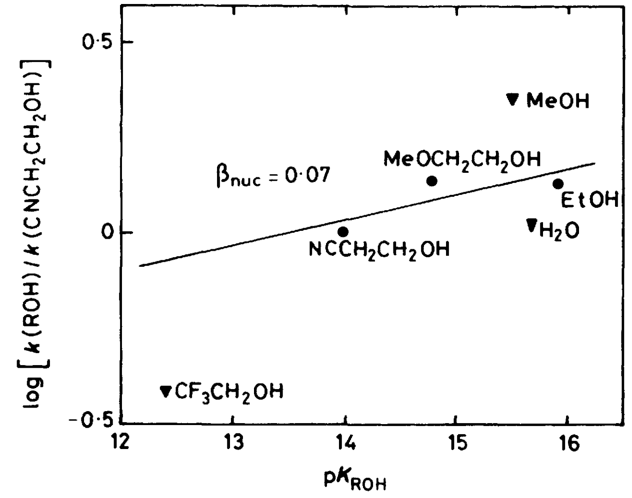


Figure 1. Relative rate constants for the reactions of alcohols with the allylic carbocation plotted against the pK_a of the alcohol

The carbocation exhibits a very low discrimination between acetate anion and chloroacetate anion: β_{nuc} *ca.* 0.03. This was found in the water–acetonitrile medium using equimolar amounts of sodium acetate and sodium chloroacetate. It was important not to wait too long before analysing the products since the chloroacetate adducts are rapidly solvolysed. Acetate ion is about four times better a nucleophile than water (Table 3).

The high reactivity of the allylic carbocation implied by the low discrimination between different nucleophiles also includes azide anion. Thus azide is only about 50 times better a nucleophile than water as measured in experiments with (1-Cl) and the acetates (1-OAc) and (2-OAc). The reasonable assumption that the reaction with N_3^- is diffusion-controlled makes it possible to calculate approximate rate constants for the reaction of the carbocation with different nucleophilic reagents, by combining the azide–solvent selectivity values with an estimated value of the diffusion-controlled reaction rate constant. A rate constant for the diffusion process of 5×10^9 dm^3 mol^{-1} s^{-1} has been employed for the calculation. The same value of the diffusion-controlled rate constant with azide was used by Richard and Jencks for reactions in water mixed with alcohols or acetonitrile at room temperature.[2] The results of the calculations are summarized in Table 4.

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* 2,2-Dichloroethanol has also been employed. Owing to the instability of this alcohol no useful result was obtained.

Table 2. Rate constants for the reactions of (**1**-OAc) and (**2**-OAc) in 10.3 mol % CH_3CN–H_2O at 35 °C[a,b]

Salt	$10^6(k_{12} + k_{1p})$/s^{-1}	10^6k_{12}/s^{-1}	10^6k_{1p}/s^{-1}	$10^6(k_{21} + k_{2p})$/s^{-1}	10^6k_{21}/s^{-1}	10^6k_{2p}/s^{-1}
None	4.8[d]					
0.75M-$NaClO_4$	6.4 ± 0.2	1.0 ± 0.1	5.5 ± 0.2	13.7 ± 0.3	2.8 ± 0.2	10.9 ± 0.2
0.75M-NaCl	4.9[d]					
0.75M-NaBr	6.0[d]					
0.75M-NaN_3	6.0 ± 0.2	0.8 ± 0.1	5.2 ± 0.2	13.7 ± 0.3	2.3 ± 0.2	11.4 ± 0.2
0.50M-NaN_3[c]	6.1[d]					
0.25M-NaN_3[c]	6.4[d]					
0.75M-NaOAc	3.0 ± 0.1	0.6 ± 0.1	2.4 ± 0.1	6.2 ± 0.2	1.7 ± 0.1	4.5 ± 0.2
0.50M-NaOAc[c]	4.0[d]					
0.25M-NaOAc[c]	5.2[d]					

[a] Substrate concn. 0.1mM. [b] The errors given are maximum errors. [c] Ionic strength 0.75M maintained with $NaClO_4$. [d] The observed rate constant (not data-simulated).

Table 3. Selectivities towards solvent components and towards carboxylate anions and azide anion for reactions of (**1**-X) and (**2**-OAc) at 35 °C

		Substrate			
Nucleophile (Nuc)	pK_a	(**1**-Cl)	(**1**-OH_2^+)	(**1**-OAc)	(**2**-OAc)
		k(Nuc)/k(H_2O)[e]			
0.75M-N_3^- [a]	4.8	~63		~56	~57
0.50M-N_3^- [a,b]				~47	
0.37M-N_3^- [a,b]		~55			
0.25M-N_3^- [a,b]				~44	
0.75M-AcO^- [a]	4.8	4.3			
0.37M-AcO^- [a]					
0.37M-$ClCH_2CO_2^-$ [a]	2.9	$k(AcO^-)/k(ClCH_2CO_2^-) = 1.2$			
		k(ROH)/k(NC[CH_2]$_2$OH)[e]			
EtOH[c]	15.9[g]	1.4[c,f]	1.3[f]	1.4[f]	1.3[f]
MeOH[d]	15.5[g]	2.3			
$MeOCH_2CH_2OH$[c]	14.8[g]	1.4			
$NCCH_2CH_2OH$[c]	14.0[g]	1		1	1
CF_3CH_2OH[c]	12.4[g]	0.4			
H_2O[c]	15.7	1.0[c,f]		1.0[f]	

[a] In 10.3 mol % CH_3CN–H_2O. [b] Ionic strength maintained at 0.75M with $NaClO_4$. [c] Medium 6.25 vol % of each of ethanol, methoxyethanol, cyanoethanol, and trifluoroethanol in water, if not otherwise stated; ionic strength 0.71M ($NaClO_4$). [d] Medium as *c* but methanol instead of methoxyethanol. [e] Ratio of second-order rate constants. [f] Medium 12.5 vol % ethanol and 12.5 vol % cyanoethanol in water; ionic strength 0.75M ($NaClO_4$). [g] P. Ballinger and F. A. Long, *J. Am. Chem. Soc.*, 1960, **82**, 795.

Table 4. Rate constants[a] for the reactions of the allylic carbocation with solvent and other nucleophiles at 35 °C[b]

Nucleophile	k/dm^3 mol^{-1} s^{-1}
H_2O	1.0×10^8
AcO^-	4.3×10^8
$ClCH_2CO_2^-$	3.6×10^8
EtOH	1.3×10^8
MeOH	2.1×10^8
$MeOCH_2CH_2OH$	1.3×10^8
$NCCH_2CH_2OH$	9.1×10^7
CF_3CH_2OH	3.6×10^7

[a] Obtained by combining an azide–water selectivity value of 50 and the water–nucleophile selectivity values with the diffusion-controlled rate constant of 5×10^9 dm^3 mol^{-1} s^{-1} for reaction with azide ion. [b] In water–acetonitrile or water–alcohol mixture at constant ionic strength 0.75M ($NaClO_4$).

Discussion

Carbocation reactions are frequently discussed in terms of an intermediate in which the carbocation is associated with the leaving group in a contact ion pair (R^+X^-) or in a solvent-separated ion pair ($R^+\|X^-$) in which a solvent molecule has been inserted between the ions[5] (Scheme 2). The present experimental results do not necessitate the introduction of a solvent-separated ion pair as a discrete intermediate. Such an intermediate is therefore not included in the mechanistic schemes in the following discussion.[*]

Reactions of the 'Free' Allylic Carbocation.—The ready formation of the allylic carbocation (I) in aqueous solvents makes it possible to study its formation from the acetates (**1**-OAc) and (**2**-OAc) without interference from acyl–oxygen cleavage. The assumption that the solvolysis of (**1**-OAc), (**1**-Cl), and (**1**-OH_2^+) proceeds *via* a 'free' solvent-equilibrated carbocation is strongly supported by the fact that similar solvolysis product ratios are obtained with different leaving groups (Table 3) and with the isomeric acetate (**2**-OAc). Consistently, zero-order reaction with azide ion is indicated by the observation that the azide concentration has no effect on the observed reaction rate under conditions where 50% of the product is the azide product. Furthermore, there is a substantial common ion effect on the solvolysis of (**1**-OAc) and (**2**-OAc) (Table 2).[†] The species subject to nucleophilic attack by the solvent may either be a delocalized free ion or two rapidly equilibrating free ions. It is not possible to distinguish between these two possibilities.

Despite the rapid formation of the allylic carbocation, which indicates a high thermodynamic stability, its reactivity with solvent molecules is high. Thus the selectivity of the cation towards alcohols is small (Figure 1), β_{nuc} *ca.* 0.07. This indicates that bond formation in the transition state of nucleophilic attack is minor, which is consistent with, according to the reactivity-selectivity principle, a short-lived cation. The nucleophile water exhibits a negative deviation from the Brønsted plot.

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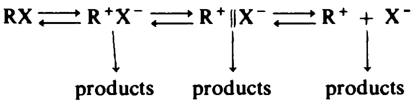
[*] The involvement of a solvent-separated allylic ion pair has been suggested in the solvolysis of *N*-sulphonyloxyacetanilides in aqueous solution.[6] However, a free carbocation may also be consistent with the results of that investigation.

[†] The association of free carbocation with 0.75M-$^-$OAc has a rate constant (k_a) of $5 \times 10^9 \times 0.75 \simeq 3.8 \times 10^9\ s^{-1}$, of similar magnitude to its rate constant with solvent, $k_{H_2O}' \simeq 4.2 \times 10^9\ s^{-1}$. Therefore, the rate constants for the disappearance of (**1**-OAc) and (**2**-OAc) are expected to be decreased to about 50% at 0.75M-$^-$OAc, in accord with the experimental data.



Scheme 2.

This may be attributed to the low polarizability of the water molecule. The alcohols are easier to polarize, as indicated by the much higher basicity of alcohols than of water in the gas phase where solvation effects are absent.[7] Methanol is expected to react with the cation faster than the other alcohols, for steric reasons.

The negative deviation for trifluoroethanol has been found previously and has been explained in terms of an anomaly in the pK_a value of the alcohol.[2b] Furthermore, the trifluoroethyl group is more electronegative than the OH group, and is presumably oriented toward the cation to a significant extent, *i.e.* in an unfavorable position for reaction with the carbocation. General base catalysis, if it occurs, should be most important for addition of weakly basic alcohols. However, reaction of (**1**-Cl) in the presence of 0.75M-acetate ion was not found to increase the amount of trifluoroethyl ether products, which suggests that the reaction is not susceptible to general base catalysis.

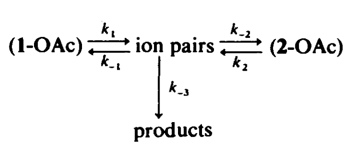
The discrimination between cation reactions with chloroacetate anion and acetate anion is even smaller than with the alcohols. The Brønsted value, based upon these two acetates (β_{nuc}), is *ca.* 0.03. Acetate is about four times better in attacking the cation than a water molecule. Smaller β_{nuc} values for substituted acetates than for alcohols have been found previously.[2b]

Azide anion is more efficient in trapping the cation than is water (about 50 times per molecule; Table 3). Presumably the reaction with azide is diffusion-controlled. This assumption is supported by the low selectivity in the reaction of the cation with nucleophiles, which indicates a very high reactivity of the cation. The reactivity is probably higher than the reactivity of 1-(4-methylphenyl)ethyl carbocation in 50% trifluoroethanol–water, which has been found to react with alcohols with a β_{nuc} value of 0.16;[2b] the selectivity k(azide)/k(H_2O) is about the same as with the allylic cation. This ion as well as other less reactive 1-arylethyl carbocations has been assumed to exhibit a diffusion-controlled reaction with azide, an assumption supported by experimental evidence.[2]

Assuming a diffusion-controlled reaction with azide ($k = 5 \times 10^9$ dm^3 mol^{-1} s^{-1}) makes it possible to calculate approximate rate-constant values for nucleophilic attack on the cation (Table 4). These values are all lower than the crude estimates of limiting rate constants * that could be obtained from the data of Jencks and Richard.[2b]

The rate constant of 4.3×10^8 dm^3 mol^{-1} s^{-1} (Table 4) for reaction of the cation with acetate anion is close to the limiting rate constant of 4.5×10^8 dm^3 mol^{-1} s^{-1} estimated for the corresponding reaction with 1-arylethyl carbocations in 50% trifluoroethanol–water.[2] The reason for the relatively low rate constant is presumably strong solvation of the acetate anion, which has to be broken before the anion is able to attack the cation. Reaction with azide ion does not show such a kinetic barrier.[2b,8]

Reaction via *Contact Ion-pair Intermediates*.—This is indicated by several experimental observations. For example, there is a mass-law effect on the disappearance of (**1**-OAc) at constant ionic strength, but a simple S_N1 mechanism is not consistent with the data; $1/k_{obs}$ is not a linear function of [$^-$OAc]. Moreover, the rate of isomerization of (**1**-OAc) and (**2**-OAc) diminishes only slightly when acetate anion is present, whereas the rates of solvolysis decrease considerably (Table 2). Accordingly, the presence of sodium acetate increases the steady-state concentration of the ion pairs and lowers that of the free ion.



Scheme 3.

Estimation of the amount of ion-pair return may be based upon the mechanistic Scheme 3 (which is kinetically equivalent to a one-intermediate mechanism). When the steady-state approximation is applied to this reaction scheme the relationship between the phenomenological and microscopic rate constants can be expressed by equations (4)—(7). The ratio between

$$k_{12} = k_1\frac{k_{-2}}{k_{-1} + k_{-2} + k_{-3}} \qquad (4)$$

$$k_{21} = k_2\frac{k_{-1}}{k_{-1} + k_{-2} + k_{-3}} \qquad (5)$$

$$k_{1p} = k_1\frac{k_{-3}}{k_{-1} + k_{-2} + k_{-3}} \qquad (6)$$

$$k_{2p} = k_2\frac{k_{-3}}{k_{-1} + k_{-2} + k_{-3}} \qquad (7)$$

the collapse rate constants can be calculated by employing the data of Table 2 as $k_{-2}/k_{-1} = (k_{12}/k_{1p})/(k_{21}/k_{2p}) = 0.7$ when the salt concentration is 0.75M ($NaClO_4$ or NaOAc). A similar value was obtained from the product composition experiment when reacting (**1**-Cl) with acetate ion. The amount of return can be calculated from $k_{-1}/(k_{-2} + k_{-3}) = (k_{21}/k_{2p})/(k_{12}/k_{1p} + 1) = 0.22$ as being 18 ± 2% in the experiments starting from (**1**-OAc) ($NaClO_4$). This value seems reasonable. An analogous calculation employing the data at 0.75M-NaOAc yields 23 ± 3% return, which is an unreasonably low value since k_{obs} decreases considerably in the presence of NaOAc (Table 2). The fact that the Scheme 3 mechanism is not consistent with the kinetic data of Table 2 suggests that two discrete ion-pair intermediates are involved in the reactions and that these are not in fast equilibrium with each other.

Scheme 4 seems to be the simplest mechanistic scheme that takes into account all experimental data with the acetates. The substrate (**1**-OAc) is reversibly ionized to the ion pair (**1**$^+$ $^-$OAc) as indicated by the common ion effect on solvolysis. The acetate anion can abstract a proton within the ion pair to give the 1,2-elimination product (**4**), or can rearrange to the isomeric ion pair (**2**$^+$ $^-$OAc), or the acetate anion can diffuse away to give a 'free' carbocation. Two discrete ion-pair intermediates are required since (**1**-OAc) and (**2**-OAc) yield quite different compositions of the elimination products [26 and 77% of (**3**), respectively]. The free solvent-equilibrated carbocation produces very small amounts of the olefins. This was found in separate experiments starting from (**1**-OH_2^+); proton abstraction from the free carbocation is much slower than trapping by a nucleophilic solvent molecule.[9] Thus the fate of the free carbocation is mainly a nucleophilic attack to give the solvolysis products (**1**-OH) and (**2**-OH), accompanied by adducts with other nucleophiles present.

The presence of azide anion does not increase the rate of

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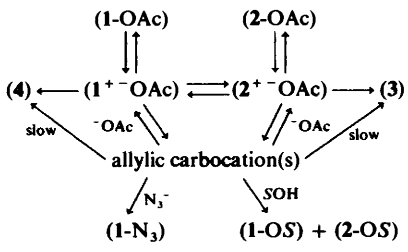
* The limiting rate constant is the rate constant which cannot be increased by making the intermediate thermodynamically more unstable.



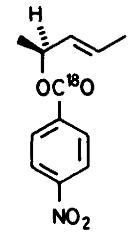
Scheme 4.

reaction of (1-OAc) (Table 2). Consequently the return of the ion pair is not affected by the presence of azide ion. Since the amount of return should be significant, it is concluded that the azide ion does not attack the ion pairs to any considerable extent but reacts with the free ion (Scheme 4). However, a small but probably significant decrease in k_{12} and k_{21} indicates that the ion pairs may be attacked by N_3^-. Similar results have been reported for the reaction of allylic *p*-nitrobenzoates in methanol or 60 vol % dioxane in water with sodium azide.[10] Ta-Shma and Rappoport have assorted and critically examined literature data on azide–water competition in solvolysis reactions.[11]

Only one azide adduct is formed [presumably (1-N$_3$)] from (1-Cl), (1-OAc), and (2-OAc) according to the analytical data. The same has been found for other allylic systems.[10] Winstein and his co-workers have reported that some allylic azides undergo a ready intramolecular rearrangement.[12] Accordingly, a likely explanation to the observation is that the azide composition reflects thermodynamic control; (2-N$_3$) rapidly isomerizes to (1-N$_3$).

A separate reaction route not involving the ion pairs (1^{+} $^{-}$OAc) and (2^{+} $^{-}$OAc) is possible for the isomerization. However, it is more likely that the isomerization utilizes the ion pairs than proceeds by a concerted pericyclic process since (i) the isomerization does not occur in a less polar solvent such as methanol, even after prolonged reaction at 35 °C [only elimination product (3) is produced]; however, at elevated temperature (100 °C) some isomerization occurs but is then accompanied by solvolysis and elimination [to (3) and (4)]; (ii) the closely related 3-(1-acetoxyethyl)indene does not undergo such an isomerization when pyrolysed (neat) at 182 °C.[13]

Allylic isomerization of acetates has to our knowledge not been studied previously. Acetates are usually too unreactive and the experiments are complicated by acyl–oxygen fission. However, allylic systems with more efficient leaving groups like tosylate and *p*-nitrobenzoate have been employed in several studies. For example, Goering and his co-workers have found that the enantiomer (5) is converted into (6) (the other enantiomer with unlabelled oxygen in the carbonyl group) in 90% acetone–water faster than the oxygens are equilibrated within an enantiomer.[14] The conversion (5) ⟶ (6) was thus concluded to proceed *via* a symmetrical species (7). This could be either an intermediate or a transition state, the one for the interconversion of (8) into (9). Our experiments with the acetates do not provide information about whether oxygen equilibration occurs.



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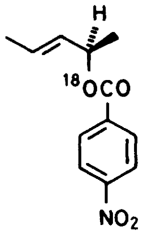
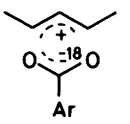


(6)



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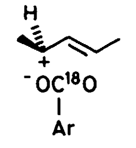

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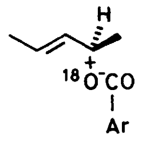

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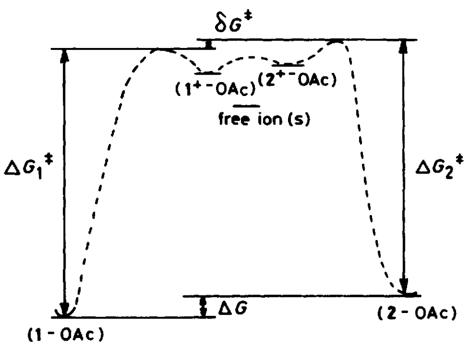

Figure 2. Free-energy diagram for the rearrangement of (1-OAc) to (2-OAc) in water–acetonitrile

The allylic cation can also be formed from the chloride (1-Cl). The contact ion pair (1^{+} $^{-}$Cl) should be much less prone to exhibit return to starting material or to isomerize than (1^{+} $^{-}$OAc). No indication for return from (1^{+} $^{-}$Cl) has been found. Moreover, the ion pair with Cl^{-} may be less favoured owing to a smaller stabilizing effect of the anion [*cf.* structure (7)]. Thus dissociation to free ions and proton abstraction from the ion pair should be much faster than the other processes. The free cation, for example formed from the chloride, can be attacked by acetate anion to give (1^{+} $^{-}$OAc) and (2^{+} $^{-}$OAc). The experimentally measured product ratio of (1-OAc) to (2-OAc) (1.3:1) corresponds to a difference in free energy of the ionization transition states for the acetates ($\delta G^{\ddagger}$) of 0.16 kcal mol^{-1} (0.7 kJ mol^{-1}). It is also possible to estimate $\delta G^{\ddagger}$ from the kinetic experiments with the acetates. According to Figure 2 $\delta G^{\ddagger} = \Delta G + (\Delta G_1^{\ddagger} - \Delta G_2^{\ddagger})$. Employing the experimental values for the equilibrium constant ($K_{eq} = 0.35$) and the rate ratio $(k_{21} + k_{2p})/(k_{12} + k_{1p}) = 13.6/6.4$ yields $\delta G^{\ddagger} =$ 0.18 kcal mol^{-1} (0.8 kJ mol^{-1}), in good agreement with the value obtained from the product ratio measurement.

It is likely that the ion pairs to some extent are trapped by the solvent, *i.e.* a fraction of the ion pairs undergoes direct nucleophilic attack by water. It has been estimated that roughly 27% of the alcohol product obtained from 1-(4-methylphenyl)-ethyl chloride is formed by such a mechanism.[2b]

Experimental

General Procedures.—The ^{1}H n.m.r. analyses were made with a JEOL FX 100 spectrometer equipped with a 5 mm dual probe (^{1}H, ^{13}C) or a 5 mm ^{1}H probe. The high-performance liquid chromatography (h.p.l.c.) analyses were carried out with a Hewlett-Packard 1084 B liquid chromatograph equipped with a variable-wavelength detector on a C8 reversed-phase column (4.6 × 230 nm). The mobile phase was a solution of methanol in water. The studied reactions were performed at constant temperature in a HETO 01 PT 623 thermostat.

Materials.—The syntheses and purification of the substrates (**1**-OH), (**1**-OAc), (**1**-Cl), and (**3**) have been reported previously.[15] The chloride (**1**-Cl) was not distilled but stored as a concentrated solution in chloroform. A high purity was confirmed by ^1H n.m.r. Acetonitrile (Fluka for u.v. spectroscopy) was used as a solvent without further purification. Cyanoethanol (Merck; 99%) contained 1.8% glucol (determined by standard addition; ^1H n.m.r.) but was free from other impurities. 2,2,2-Trifluoroethanol and 2-methoxyethanol were Aldrich Gold Label Grade. Methanol and ethanol (0.5% water) were of spectroscopic quality. The purity of the alcohols was checked by ^1H n.m.r. and h.p.l.c. All other chemicals, except chloroacetic acid (Merck; 99%), were of reagent grade and used without further purification. A stock solution of sodium perchlorate was prepared from perchloric acid and sodium hydroxide solution.

3-(2-*Methoxypropan*-2-*yl*)*indene* (**1**-OMe). This was prepared in a small amount for calibration purposes. 3-(2-Acetoxypropan-2-yl)indene (**1**-OAc) (0.41 g) was dissolved in dry methanol (40 ml) and M-H_2SO_4 (in methanol) (800 μl) was added. After 22 h at room temperature the solution was poured into a mixture of ether (50 ml) and water (50 ml) containing $NaHCO_3$ (0.2 g). After two further extractions with ether the combined ether fractions were washed once with water and twice with saturated sodium chloride solution. Evaporation, and flush distillation of the residue, gave a slightly yellowish liquid which had a purity of 97% (h.p.l.c.); δ_H (100 MHz; $CDCl_3$) 1.55 (6 H, s), 3.07 (3 H, s), 3.32 (2 H, d), 6.28 (1 H, t), and 7.13—7.86 (4 H, complex).

2-*Acetoxy*-1-*isopropylideneindan* (**2**-OAc). The alcohol (**1**-OH) (0.66 g) was dissolved in acetic anhydride (20 ml), and a pinch of anhydrous zinc dichloride was added. The mixture was shaken vigorously for 1 min and then poured into ice-water–pentane. The water phase was extracted twice with pentane. The combined pentane fractions were washed three times with water. Evaporation of the pentane yielded a mixture of (**2**-OAc) (29 mol %) and (**1**-OAc) (71 mol %), with a trace of impurities (h.p.l.c.). The desired isomer was isolated by semipreparative h.p.l.c. (4.3 × 30 + 8 × 250 mm RP 8 column). Extraction of the eluate with pentane gave pure material as shown by h.p.l.c. and ^1H n.m.r. analysis; δ_H (100 MHz; $CDCl_3$) 1.96 (3 H, s), 2.01 (3 H, s), 2.14 (3 H, s), 2.83 (1 H, d, *J* 17 Hz), 3.35 (1 H, dd, *J* 17 and 6 Hz), 6.03 (1 H, d, *J* 6 Hz), and 7.07—7.67 (4 H, complex).

2-*Methoxy*-1-*isopropylideneindan* (**2**-OMe). This was isolated from the product mixture obtained from methanolysis of (**1**-Cl) by semipreparative h.p.l.c.; δ_H (100 MHz; $CDCl_3$) 2.04 (3 H, s), 2.12 (3 H, s), 3.01 (2 H, ds), 3.31 (3 H, s), 4.66 (1 H, t), and 7.07—7.65 (4 H, complex).

3-*Isopropenylindene* (**4**). This was obtained similarly; δ_H (100 MHz; $CDCl_3$) 2.05 (3 H, s), 3.33 (2 H, d), 5.16 (1 H, t, *J* small), 5.40 (1 H, s), 6.40 (1 H, t), and 7.09—7.67 (4 H, complex).

Determination of Relative Extinction Coefficients.—Standard mixtures of (**1**-OH), (**1**-OAc), (**1**-OMe), and (**3**), prepared by weighing, were used for the determination of the relative extinction coefficients at 254 nm (reference 430 nm). The extinction coefficient ratio for (**2**-OAc) and (**2**-OH) was measured in the following way. A concentrated solution of pure (**2**-OAc) in acetonitrile was diluted with a large amount of methanol. The same amount (70 μl) was injected into the h.p.l.c. apparatus five times to obtain an accurate area determination. Exactly 200 μl of 0.12M-NaOMe was added to 1 000 μl of the methanol solution. After 16 h at room temperature the ester cleavage was complete and only an insignificant trace of (**3**) accompanied the product (**2**-OH). Addition of acetic acid (0.7 μl) to the reaction solution followed by an accurate area determination on the h.p.l.c. apparatus gave the extinction coefficient ratio. Another portion of the methanolic solution of (**2**-OAc) was solvolysed by addition of M-H_2SO_4 in methanol, which produced (**1**-OMe). Thus the relative response factors of (**1**-OMe) and (**2**-OAc) could be measured.

Solvolysis of (**1**-Cl) in a 50 vol % mixture of methanol and acetonitrile saturated with sodium acetate gave a product mixture which was worked up by extraction with ether and evaporation, and analysed by ^1H n.m.r. The areas of the enlarged peaks of the exocyclic methylene protons of (**4**) and the methyl protons of (**3**) were measured by employing a desk computer equipped with a digitizer. The molar ratio obtained in this way was compared with the area ratio obtained by h.p.l.c., yielding an estimation of the relative extinction coefficients for these two compounds.

To obtain the relative reponse factor of (**2**-OMe) the following method was used. The alcohol (**2**-OH) was prepared from the acetate by cleavage with NaOMe as already described. Solvolysis with sulphuric acid yielded a mixture of (**1**-OMe) and (**2**-OMe) along with a trace of alcohol and olefin (**3**). Analysing the solution of (**2**-OH) and the reaction mixture obtained after the addition of acid, and combining the data with the relative response factors determined previously, gave the relative response factor of (**2**-OMe).

The foregoing measurements gave the following extinction coefficient ratios: 1:2.26 (**1**-OAc), 1:1.18 (**2**-OAc), 1:2.21 (**1**-OH), 1:1.20 (**2**-OH), 1:2.25 (**1**-OMe), 1:1.05 (**2**-OMe), 1:1 (**3**), and 1:2.67 (**4**).

Solvolysis of a fixed amount of (**1**-Cl) in water–acetonitrile, methanol, ethanol, or methoxyethanol, respectively, followed by h.p.l.c. analyses on the basis of the foregoing extinction coefficient ratios, gave similar 'corrected' total peak areas. This shows that the ethers formed from ethanol and substituted ethanols have the same extinction coefficients within experimental error as the methyl ethers. Furthermore, the azide adduct has approximately the same extinction coefficient as (**1**-OH) since the presence of azide anion in a reaction solution did not significantly change the total corrected peak area.

Solvolysis Reaction Procedure.—The reactions were run at constant ionic strength in solutions prepared by mixing three volumes of water solution of the salt(s) (at constant ionic strength 1.00M, maintained with $NaClO_4$) with one volume of the organic solvent(s) at room temperature, *ca.* 22 °C. The reaction temperature was 35.00 ± 0.03 °C. When the organic solvent was acetonitrile the salt concentration at this temperature was found to be 0.747M. The reactions were initiated by rapid addition of the substrate dissolved in acetonitrile or in chloroform [in some experiments with (**1**-Cl)] with a syringe or, in some runs, with a spring-loaded syringe to the thermostatted solvent mixture. The concentration of the substrate in the reaction solution was usually about 0.1mM.

Product Composition Studies.—The fast reactions of (**1**-Cl) and (**1**-OH_2^+) were run in 1.5 ml h.p.l.c. flasks sealed with tight polytetrafluoroethylene septa and placed in an aluminium block in the water thermostat. After 10 min [in some experiments with (**1**-OH_2^+) after longer times] the reaction mixture was analysed on the h.p.l.c. apparatus and the mol % of each of the products was determined. The chloroacetic adducts were assumed to have extinction coefficients equal to those of the corresponding acetates (**1**-OAc) and (**2**-OAc), respectively. It was not possible to study the nucleophilic attack of methanol and methoxyethanol in the same experiment since the retention times for the adducts are very close. The chromatographic peak of (**4**) and the one of the azide adduct are not separated. However, the peak of (**4**) without the presence of azide anion is small; it is not likely that the azide ion enhances the amount of (**4**). A small correction is made when calculating the mol % of azide adduct by assuming the ratio of (**4**) and (**3**) is the same with and without the presence of sodium azide.

Kinetics.—The reactions of (**1**-OAc) and (**2**-OAc) were run in 4 ml pear-shaped flasks equipped with a polytetrafluoroethylene stop cock (high-vacuum type). Samples of the reaction solution were transferred with a syringe to an h.p.l.c. flask and analysed. Since the solvolyses of the acetates are slow, no significant reaction takes place on the column. The mol % of the starting material and of each of the products were measured. Approximate rate constants for the disappearance of the starting material were obtained from plots of ln(mol % starting material) *versus* time. Computer simulation using the approximate values as initial values for the calculation yielded more accurate rate constants.[16]

For example when starting from pure (**1**-OAc) the concentrations of (**1**-OAc) and (**2**-OAc) are described by equations (i) and (ii). All estimated errors are considered as maximum errors

$$\text{mol \% } (\mathbf{1}\text{-OAc}) = a\,e^{-m_1 t} + (100 - a)e^{-m_2 t} \qquad \text{(i)}$$

$$\text{mol \% } (\mathbf{2}\text{-OAc}) = b\,e^{-m_1 t} - b\,e^{-m_2 t} \qquad \text{(ii)}$$

where

$$a = 100\,(k_{12} + k_{1p} - m_2)/(m_1 - m_2)$$
$$b = 100\,k_{12}/(m_2 - m_1)$$

$$m_1 = [\tfrac{1}{4}(k_{12} + k_{1p} + k_{21} + k_{2p})^2 - k_{12}k_{2p} - (k_{21} + k_{2p})k_{1p}]^{\frac{1}{2}} + \tfrac{1}{2}(k_{12} + k_{1p} + k_{21} + k_{2p})$$

$$m_2 = [\tfrac{1}{4}(k_{12} + k_{1p} + k_{21} + k_{2p})^2 - k_{12}k_{2p} - (k_{21} + k_{2p})k_{1p}]^{\frac{1}{2}} + \tfrac{1}{2}(k_{12} + k_{1p} + k_{21} + k_{2p})$$

derived from maximum systematic errors and random errors.

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