Intra- and Inter-molecular Hydron Abstraction from Allylic Carbocation Intermediates in Aqueous Solvent. Observation of a Substantial Deuterium Isotope Effect for 1,4-Elimination of Acetic Acid from One of the Ion-pair Intermediates

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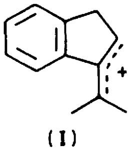
The allylic carbocation intermediate formed from 3-(2-chloropropan-2-yl)indene (**1**-Cl) and from (1,1-$^2H_2$)-(**1**-Cl) in 75 vol % water–acetonitrile at 35 °C reacts rapidly with solvent water to give the allylic alcohols but is also subject to hydron abstraction by general bases to produce 1-isopropylideneindene (**3**) and 3-isopropenylindene (**4**). The Brønsted parameters measured with substituted acetate anions were found to be small, β 0.16 for formation of (**3**) and 0.14 for production of (**4**). The kinetic deuterium isotope effect on hydron abstraction from the intermediate with acetate anion to form the olefin (**3**) (k^H/k^D) is 3.0 ± 0.4. The corresponding intramolecular elimination of acetic acid from the contact ion pair formed from 3-(2-acetoxypropan-2-yl)indene (**1**-OAc) to yield (**3**) shows a substantial isotope effect, $k^H/k^D = 5.2 \pm 1.0$. The allylic isomer 2-acetoxy-1-isopropylideneindan (**2**-OAc) yields a contact ion pair that reacts to give (**3**) with a considerably smaller isotope effect, $k^H/k^D = 2.9 \pm 0.3$. The free carbocation generated from protonated 3-(2-hydroxypropan-2-yl)indene (**1**-OH) and its (1,1-$^2H_2$)-analogue undergo hydron abstraction to give the olefin (**3**) with an isotope effect $k^H/k^D = 4.1 \pm 0.3$. These isotope effects do not include the isotope effect on the rate-limiting ionization step, which were found to be $k^H/k^D = 1.07$ and 1.22 in the reactions of (**1**-OAc) and (**2**-OAc), respectively. The elimination isotope effects for the ion pairs are evaluated by assuming that the formation of alcohols from the intermediates has an isotope effect of unity.

Elimination reactions proceeding *via* carbocation intermediates generally show a higher preference for the more stable olefin than do concerted one-step elimination reactions. Thus both the proportion of the Saytzev-rule product and the ratio of *trans*- to *cis*-olefin are usually greater in *E*1 than in *E*2 reactions.[1] Accordingly, the product-determining transition state may be close to olefin in structure, *i.e.* the proton transfer is more than half complete. On the other hand, this conclusion is not consistent with the Hammond postulate, which predicts a transition state for the second step that resembles the high-energy intermediate. However, there is evidence that the carbocation intermediate as well as the transition state for its formation is stabilized by hyperconjugation. This partial breaking of carbon hydrogen bond(s) in the position β to the leaving group implies some product-like characteristics. Apparently hyperconjugation is of importance in determining the elimination product composition. It has also been found that if the carbocation has several β hydrogen atoms, one is loosened more than the others.[2]

In elimination reactions that proceed *via* carbanions there is also hyperconjugative stabilization of the transition state for formation of the intermediate, but by loosening of the bond to the leaving group.[3] Obviously there are considerable resemblances amongst *E*1, *E*2, and *E*1cB$_I$ reactions. All involve more or less partial breaking of the bonds to the β hydrogen atom and the leaving group in the rate-limiting transition state.

The preceding paper describes the high reactivity of the allylic carbocation (I) towards nucleophilic reagents. It was found that some elimination accompanies the solvolysis. Proton abstraction both of an indene proton and of a methyl proton was observed, *i.e.* two elimination products are provided. The present paper describes an investigation of these elimination reactions; it is concluded that they proceed *via* discrete contact ion pairs with the leaving group associated with C-1 or C-3 of the allylic carbocation. It is suggested that the large kinetic deuterium isotope effect exhibited by one of the 1,4-elimination reactions is caused by reaction branching,[4] *i.e.* the observed isotope effect is approximately the product of two kinetic deuterium isotope effects.


(I)

The free allylic carbocation provides both elimination products, despite the expected large difference in thermodynamic stability of the olefins.

Results

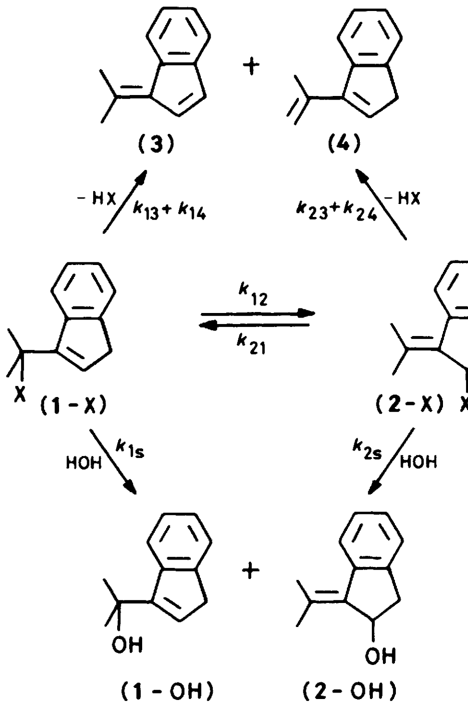
Reactions of (**1**-Cl) *and* (**1**-OH_2^+).—The solvolysis of 3-(2-chloropropan-2-yl)indene (**1**-Cl) at 35 °C in 10.3 mol % (25 vol %) acetonitrile in water at a constant ionic strength of 0.75M ($NaClO_4$) rapidly provides 3-(2-hydroxypropan-2-yl)indene (**1**-OH) and 2-hydroxy-1-isopropylideneindan (**2**-OH) as the main products, accompanied by 1-isopropylideneindene (**3**) and 3-isopropenylindene (**4**) (Scheme 1). In the presence of acetate anion, small amounts of the isomeric acetates 3-(2-acetoxypropan-2-yl)indene (**1**-OAc) and 2-acetoxy-1-isopropylideneindan (**2**-OAc) are also formed. The ratio between the acetate products, [(**1**-OAc)]:[(**2**-OAc)], is 1.3:1. The product mixture was analysed by high-performance liquid chromatography (h.p.l.c.).

The formation of the olefins is catalysed by general bases, *i.e.* the amounts of (**3**) and (**4**) are increased relative to the solvolysis products (**1**-OH) and (**2**-OH). This is shown quantitatively in Figure 1 for acetate anion. Substituted acetate anions, which are less basic, show the same behaviour but with smaller slopes. Assuming that the rate constant for the reaction of the carbocation intermediate with water to produce (**1**-OH) and (**2**-

Table 1. Base-promoted formation of the olefins (**3**) and (**4**) from the carbocation intermediate in 75 vol % H_2O–CH_3CN[a]

Base	pK_a[b]	Substrate	$\frac{10^{-6}\,k_3{}^c}{dm^3\,mol^{-1}\,s^{-1}}$	$\frac{10^{-6}\,k_4{}^c}{dm^3\,mol^{-1}\,s^{-1}}$	$k_3{}^H/k_3{}^D$
$CF_3CH_2O^-$	12.37	(**1**-Cl)	781		
AcO^-	4.76	(**1**-Cl)	49	51	3.0 ± 0.4[d]
		(1,1-$^2H_2$)-(**1**-Cl)	16	51	
$MeOCH_2CO_2^-$	3.53	(**1**-Cl)	35	38	
$NCCH_2CO_2^-$	2.43	(**1**-Cl)	21	23	
$CF_3CO_2^-$	0.23	(**1**-Cl)	9.2	12	
H_2O	−1.74	(**1**-Cl)	<0.4	<0.8	
H_2O	−1.74	(**1**-OH_2^+)	0.210		4.1 ± 0.3[d]
		(1,1-$^2H_2$)-(**1**-OH_2^+)	0.051		

[a] At 35.00 ± 0.03 °C; μ = 0.75M, maintained with $NaClO_4$. [b] In water (ref. 5). [c] Based on the rate constant $k'(H_2O) = 1.0 \times 10^8 \times 41.67\ s^{-1}$ for the reaction of carbocation with water (ref. 6). [d] The errors given are maximum errors.



Scheme 1.

OH) [with $k(H_2O) = 1.0 \times 10^8\ dm^3\ mol^{-1}\ s^{-1}$][6] is not affected by the base makes it possible to calculate the rate constants for abstraction by the catalyst of an indene proton (k_3) and of a methyl proton (k_4) from the slopes (Table 1). The intercepts of these plots ordinarily correspond to proton abstraction by the solvent. However, owing to the experimental difficulty in accurately determining trace amounts of (**3**) and (**4**) in the reactive substrate (**1**-Cl), only upper limits for the proton abstraction by water are reported in Table 1. The stronger base 2,2,2-trifluoroethoxide anion yields very little of (**4**). The reason is that (**4**) is not as stable in a strongly basic solution as it is in the bufferred acetate anion solutions.

The alcohol (**1**-OH) is thermodynamically more stable than (**2**-OH). Trace amounts of acid rapidly convert all (**2**-OH) into (**1**-OH). Thus the reaction of (**1**-OH_2^+), which has also been studied, exclusively gives (**3**) and (**4**) as products, and no trace of (**2**-OH) is detected by h.p.l.c.* However, it is possible to estimate the rate constant for the acid-catalysed hydrolysis of (**1**-OH) [a degenerate reaction that gives back (**1**-OH)] by having a small amount of methanol in the reaction solution. The rate constant for the hydrolysis can be calculated from the rate constant measured for the reaction with methanol and knowing the selectivity between methanol and water [$k(MeOH)/k(H_2O)$ = 2.3;[6] ratio of second-order rate constants]. The rate constant for the solvolysis of (**1**-OH) in water containing 15mM-$HClO_4$ evaluated by this method is 119 × $10^{-6}\ s^{-1}$. The second-order rate constant for the acid-catalysed reaction is then 7.9 × $10^{-3}\ dm^3\ mol^{-1}s^{-1}$. The corresponding rate constant with (1,1-$^2H_2$)-(**1**-OH) was found to be somewhat smaller (7.7 × $10^{-3}\ dm^3\ mol^{-1}\ s^{-1}$).

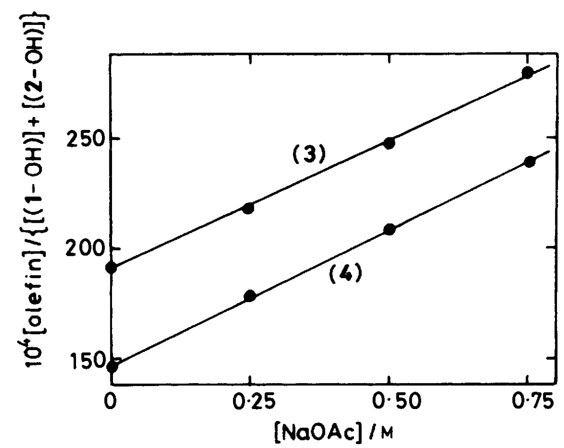


Figure 1. The fraction of olefin products as a function of the sodium acetate concentration for the solvolysis of (**1**-Cl) in 75 vol % H_2O–CH_3CN; μ = 0.75M, maintained with $NaClO_4$

The production of the olefin (**3**) from (**1**-OH) in 15mM-$HClO_4$ was studied in initial-rate experiments. Since the rate constants for the acid-catalysed hydrolysis were known (see before), the rate ratio for proton abstraction from the free carbocation and trapping with water could be calculated. By multiplication by the rate constant for reaction of the carbocation with solvent [$k(H_2O) = 1.0 \times 10^8\ dm^3\ mol^{-1}\ s^{-1}$],[6] the second-order rate constants for proton abstraction from the carbocation with water were obtained (Tables 1 and 2).

Brønsted plots, based upon the data in Table 1, are shown in Figure 2. The β values are low: 0.16 and 0.14 for abstraction of an indene and a methyl proton, respectively. The deuterio-compounds (1,1-$^2H_2$)-(**1**-Cl) and -(**1**-OH_2^+) produce less olefin

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* This indicates that departure of H_2O occurs much more easily from (**2**-OH_2^+) than from (**1**-OH_2^+), or that the pK_a of (**2**-OH_2^+) is higher than that of (**1**-OH_2^+).

Table 2. Product compositions, rate constants, and kinetic deuterium isotope effects for the formation of (**3**) and (**4**) from ($1^+\,{}^-OAc$), ($2^+\,{}^-OAc$), and free carbocation in 75 vol % H_2O–CH_3CN[a]

Substrate	$\frac{[(3)]}{[(1\text{-OH})] + [(2\text{-OH})]}$	$\frac{[(4)]}{[(1\text{-OH})] + [(2\text{-OH})]}$	$\frac{10^{-6}\,k_3{}^b}{s^{-1}}$	$k_3{}^H/k_3{}^D$	$\frac{10^{-6}\,k_4{}^b}{s^{-1}}$
(**1**-OAc)	13.9×10^{-3}	38.7×10^{-3}	57.9	5.2 ± 1.0^c	161
(1,1-$^2H_2$)-(**1**-OAc)	2.7×10^{-3}	38.8×10^{-3}	11.2		162
(**2**-OAc)	28.1×10^{-3}	8.3×10^{-3}	117	2.9 ± 0.3^c	35
(3,3-$^2H_2$)-(**2**-OAc)	9.6×10^{-3}	7.9×10^{-3}	44.6		37
(**1**-$OH_2{}^+$)	2.1×10^{-3}		8.4	4.1 ± 0.3^c	
(1,1-$^2H_2$)-(**1**-$OH_2{}^+$)	0.51×10^{-3}		2.1		

[a] At 35.00 ± 0.03 °C; $\mu = 0.75$M, maintained with $NaClO_4$. [b] Based on the rate constant $k'(H_2O) = 1.0 \times 10^8 \times 41.67\ s^{-1}$ for the reaction of carbocation with water (ref. 6). [c] The errors given are maximum errors.

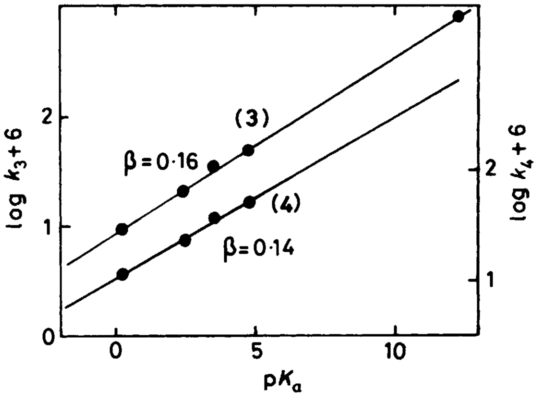


Figure 2. Brønsted plot for the deprotonation of the carbocation intermediate(s) by carboxylate anions in 75 vol % H_2O–CH_3CN

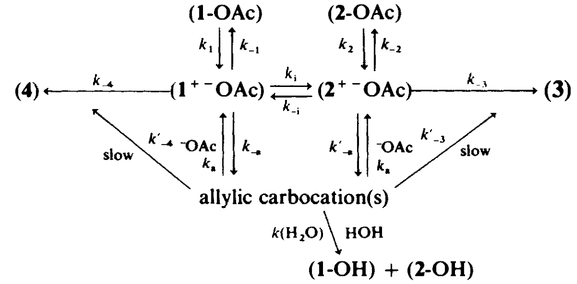
(**3**) than the protio-substrates (Table 1). An error in $k(H_2O)$ does not propagate as an error into isotope effects or Brønsted parameters.

The acetates (**1**-OAc) and (**2**-OAc) are solvolysed much more slowly. The reactions are not accompanied by any significant acyl–oxygen cleavage. The rate constant for the protio-substrates (**1**-OAc) and (**2**-OAc) has been measured.[6] Allylic isomerization competes with the solvolyses (Scheme 1). The deuterio-analogues (1,1-$^2H_2$)-(**1**-OAc) and (3,3-$^2H_2$)-(**2**-OAc) react more slowly. The isotope effects on the disappearance of these substrates (k^H/k^D) are 1.07 and 1.22, respectively. The product compositions of alcohols and the olefin (**4**) are the same as in the reactions of the protio-substrates, but much less (**3**) is produced. The rate constants for the formation of the olefins from the carbocation intermediate (ion pair) were evaluated from the product compositions (Table 2). There is a considerably larger isotope effect on k_3 in reaction from (**1**-OAc) than in reaction from (**2**-OAc). A small correction for olefin production from the rearranged acetate has been made in the evaluation of these data (see Experimental section).

The solvolysis of 1-(2-chloropropan-2-yl)indene is much slower. The rate constant for the disappearance of this substrate in water–acetonitrile in the presence of 0.75M-NaOAc is *ca.* $5 \times 10^{-4}\ s^{-1}$. The alcohol is the dominant product.

Discussion

It was concluded in the preceding paper that two discrete contact ion pairs are involved in the solvolysis of (**1**-OAc) and (**2**-OAc), and that the allylic interconversion of these acetates does not proceed *via* a concerted thermal pericyclic reaction but by these ion-pair intermediates. Quite different elimination product compositions are produced from these two ion pairs (Table 2). The 1,2-elimination products dominate the products that derive from 1,4-elimination. Thus the olefin mixture obtained from (**1**-OAc) contains 26% of the 1,4-elimination product (**3**), whereas (**2**-OAc) gives 23% of the 1,4-elimination product (**4**). Since the free carbocation, generated from solvolysis of (**1**-$OH_2{}^+$), is much less prone to undergo elimination (Table 2), it is concluded that the leaving acetate anion in the ion pairs catalyses the formation of the olefins (**3**) and (**4**). Catalysis from the leaving group has been reported for other systems.[2b,7,8] The mechanistic scheme shown as Scheme 2 is consistent with the experimental data. Direct nucleophilic attack of water on the intimate ion pairs probably occurs to a small extent but is not included in the scheme.[6]



Scheme 2.

The allylic carbocation can also be formed from the chloride (**1**-Cl).[6] Furthermore, this substrate reacts to produce mainly the alcohols (**1**-OH) and (**2**-OH), accompanied by some elimination products (**3**) and (**4**). The reaction is very rapid and it has not been possible to measure the ionization rate constant or to detect any isomerized material (**2**-Cl).

The amount of elimination products obtained from (**1**-Cl) is increased in the presence of buffer bases. The data in Table 1 show that a benzylic proton is approximately three times as easy as a methyl proton to abstract. The Brønsted coefficient (Figure 2) is larger for abstraction of the former type of proton (β 0.16) than for the latter (β 0.14). This small difference is not significant but it is in the same direction as would be expected from the Hammond postulate. The deprotonation of the 1-(4-methylphenyl)ethyl carbocation in 50% water–trifluoroethanol with substituted acetate anions exhibits a β value of 0.14.[8]

As indicated in Scheme 2, the substituted acetate anions also act as nucleophiles and attack the allylic carbocation to form small amounts of the two isomeric esters. The reported Brønsted coefficient of near zero (β_{nuc} *ca.* 0.03)[6] implies a β_{lg} value close to −1. Accordingly, the solvolytic reactivity of these esters is strongly dependent on the pK_a of the corresponding substituted acetic acid. Thus when in solvolysis of (**1**-Cl) in the presence of $CF_3CO_2^-$ no trace of the esters (**1**-O_2CCF_3) and (**2**-O_2CCF_3) (which are the most reactive of the esters and expected to be formed in the smallest amounts) was detected. All esters produce some olefins on solvolysis. However, owing to the small amounts of esters that are formed, no significant amount of (**3**) or (**4**) is obtained *via* the esters when (**1**-Cl) is solvolysed in the presence of 0.75M-buffer base.

Evaluation of Microscopic Rate Constants.—The increase in the amounts of olefins that are produced in the presence of acetate anion may come not only from the ion pairs (**1**$^{+}$ $^{-}$OAc) and (**2**$^{+}$ $^{-}$OAc) (Scheme 2) but also from direct base-promoted deprotonation of the chloride ion pairs (**1**$^{+}$ $^{-}$Cl) and (**2**$^{+}$ $^{-}$Cl). The following crude calculation suggests that the main portion of the elimination products comes from rate-limiting acetate-promoted elimination of HCl from the ion pairs (**1**$^{+}$ $^{-}$Cl) and (**2**$^{+}$ $^{-}$Cl).

Let us first calculate some of the microscopic rate constants of Scheme 2 on the basis of the observed rate constants[6] for the acetates (**1**-OAc) and (**2**-OAc) and the data in Table 2. Thus the ratios between collapse and elimination from the two ion pairs are $k_{-2}/k_{-3} \approx k_{12}/k_{13} = (1.0 \times 10^{-6})/(5.5 \times 10^{-6} \times 0.0139/1.0526) = 13.8$ and $k_{-1}/k_{-4} \approx k_{21}/k_{24} = (2.8 \times 10^{-6})/(10.9 \times 10^{-6} \times 0.0083/1.0364) = 32.1$. These calculated rate constant ratios are too low, since k_{13} and k_{24} are not corrected for the small amount of olefin that comes from free carbocation. The elimination rate constants k_{-3} and k_{-4} can be approximated by the values 117×10^{6} s^{-1} and 161×10^{6} s^{-1}, respectively, given in Table 2. The collapse rate constants are then $k_{-1} = 5.2 \times 10^{9}$ s^{-1} and $k_{-2} = 1.6 \times 10^{9}$ s^{-1}; *i.e.* they are of the same magnitude as the rate constant for trapping the carbocation with solvent. Since k_i and k_{-i} are relatively small, these large collapse rate constants indicate some internal return in the solvolysis of the acetates.

If we assume that all acetate-promoted elimination in the solvolysis of (**1**-Cl) derives from the ion pairs (**1**$^{+}$ $^{-}$OAc) and (**2**$^{+}$ $^{-}$OAc), the ratio between collapse and elimination from (**2**$^{+}$ $^{-}$OAc) is $k_{-2}/k_{-3} = \{[(\mathbf{2}\text{-OAc})]/([(\mathbf{1}\text{-OH})] + [(\mathbf{2}\text{-OH})])\}/(k_3[^{-}\text{OAc}]/k(\text{H}_2\text{O})[\text{H}_2\text{O}]) = 0.038/\{49 \times 10^{6} \times 0.75/(1.0 \times 10^{8} \times 41.67\} = 4.3$, and from (**1**$^{+}$ $^{-}$OAc), $k_{-1}/k_{-4} = \{[(\mathbf{1}\text{-OAc})]/([(\mathbf{1}\text{-OH})] + [(\mathbf{2}\text{-OH})])\}/(k_4[^{-}\text{OAc}]/k(\text{H}_2\text{O})[\text{H}_2\text{O}]) = 0.049/\{51 \times 10^{6} \times 0.75/(1.0 \times 10^{8} \times 41.67)\} = 5.3$. Multiplication by k_{-3} and k_{-4} as before yields $k_{-1} = 8.5 \times 10^{8}$ s^{-1} and $k_{-2} = 5.0 \times 10^{8}$ s^{-1}. These values are several times lower than those previously calculated. The calculations are of course very approximate, but the discrepancies between the two calculations are large. The reason may be that the main part of the acetate-promoted elimination of HCl from (**1**-Cl) occurs *via* proton abstraction from the chloride ion pairs. Apparently, the input values of $k_3 = 49 \times 10^{6}$ and $k_4 = 51 \times 10^{6}$ dm^{3} mol^{-1} s^{-1} used in the calculation are far too large.

The equilibrium constant for the reaction of (**1**-OAc) to give (**2**-OAc) has been measured as $K_{eq} = 0.35$.[6] If we assume that the solvolysis rate constants can be employed as approximations of the ionization rate constants, *i.e.* $k_1 \approx 6.4 \times 10^{-6}$ s^{-1} and $k_2 \approx 13.7 \times 10^{-6}$ s^{-1},[6] it is possible to calculate an equilibrium constant for the interconversion of the ion pairs. Combined with the collapse rate constants already calculated this gives an equilibrium constant between the ion pairs (**1**$^{+}$ $^{-}$OAc) and (**2**$^{+}$ $^{-}$OAc) (k_i/k_{-i}) of $K_{eq}(k_2/k_1)(k_{-1}/k_{-2}) \approx 2$. The interconversion is relatively slow and equilibrium concentrations of the ion pairs are not obtained during solvolysis. It is interesting that (**2**$^{+}$ $^{-}$OAc) may be more stable than (**1**$^{+}$ $^{-}$OAc). The situation is the opposite for the corresponding covalent materials, and probably originates from strong hyperconjugative stabilization by the two indene protons in (**2**$^{+}$ $^{-}$OAc). This assumption is supported by the large secondary kinetic deuterium isotope effect (k^{H}/k^{D}) of 1.22 for the overall reaction of (**2**-OAc) and the three times higher reactivity of an indene proton than of a methyl proton towards a proton-abstracting base.

Isotope Effects.—The relatively small β values (Figure 2) for the chloride indicate that the proton is transferred less than half to the proton-abstracting base in the transition states. Since a β value of 0.38 is expected to correspond to 50% proton transfer from carbon to oxygen,[9] the extent of proton transfer should be about 20% in the transition states for elimination of HCl from the chloride ion pairs [to give (**3**) and (**4**)]. A crude estimate of the isotope effect k_3^{H}/k_3^{D} can be made by assuming that $\beta = 0.38$ corresponds to a maximum isotope effect of 7. Linear extrapolation yields an approximate value of 2.9 for k_3^{H}/k_3^{D}. The experimentally measured value with $^{-}$OAc as base is 3.0 ± 0.4 (Table 1). Hydron abstraction directly from the substrate is expected to exhibit a substantially larger isotope effect and a considerably larger β value. For example the elimination of acetic acid from (**1**-OAc) with hydroxide anion in 65 wt.% water–dimethyl sulphoxide, which is an irreversible *E*1cB reaction, exhibits an isotope effect (k^{H}/k^{D}) of 9.7.[4a]

The elimination reactions presented in this report cannot be reasonably regarded as of *E*1cB or *E*2 type since the related substrate 1-(2-chloropropan-2-yl)indene is solvolysed much more slowly in 0.75M-NaOAc ($t_{\frac{1}{2}}$ *ca.* 26 min) than is (**1**-Cl), and produces very little of (**3**) but much of the alcohol. An *E*1cB or *E*2 reaction of this substrate is expected to be faster than that of (**1**-Cl).*

Studies on rate-limiting attack of base on ion pairs have been reported, but only small isotope effects have been measured.[2b,10] However, Bunton *et al.* have studied the abstraction of a hydron from carbocations stabilized by one or two ferrocenyl groups[11] (which makes these ions so stable that they can be isolated as salts). An isotope effect (k^{H}/k^{D}) as large as 6.7 and $\beta = 0.32$ have been measured with tertiary amines in 50% water–acetonitrile. This seems to be the first investigation that demonstrates substantial kinetic isotope effects for dehydronation of a carbocation.

The observed isotope effects in the reactions of the acetates reflect the isotope effect on one or several steps in Scheme 2. The observed isotope effects on the overall rates of solvolysis of (**1**-OAc) and (**2**-OAc) ($k_{obs}^{H}/k_{obs}^{D} = 1.07$ and 1.22, respectively) are probably good approximations of the ionization isotope effects k_1^{H}/k_1^{D} and k_2^{H}/k_2^{D}. The reactions of the ion pairs (*via* the free carbocation) to form the allylic alcohols, as well as the collapse to esters, are expected to exhibit small inverse secondary isotope effects. These inverse effects are included in the measured isotope effects on k_3 (and k_4) in Table 2. Correction for these effects lowers the isotope effects on k_3.

The isotope effect $k_3^{H}/k_3^{D} = 2.9 \pm 0.3$ measured for (**2**$^{+}$ $^{-}$OAc) is approximately equal to k_{-3}^{H}/k_{-3}^{D}. The considerably larger isotope effect for the elimination from (**1**$^{+}$ $^{-}$OAc) to form (**3**) (5.2 ± 1.0) may be the result of the branched reaction mechanism of Scheme 2. Enlarged primary kinetic isotope effects caused by reaction branching have been reported previously.[4]

According to the mechanistic scheme, the isotope effect is composed of the isotope effects of several individual steps. If $k'_{-a} \gg k_{-2}, k_{-i}$ the equations (1) and (2) may be derived.

$$k_3 = k_i k_{-3}/k'_{-a} \qquad (1)$$

$$k_3^{H}/k_3^{D} = (k_i^{H}/k_i^{D})(k_{-3}^{H}/k_{-3}^{D})(k'^{D}_{-a}/k'^{H}_{-a}) \qquad (2)$$

According to equation (2), the measured isotope effect is

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* Owing to the hyperconjugative effect of the chloro substituent (ref. 3).

composed of three isotope effects. The ratio $k_{-3}{}^{H}/k_{-3}{}^{D}$ has been concluded to be *ca.* 2.9. The two other factors of equation (2) are also expected to be larger than unity. As already discussed $k'_{-a}{}^{D}/k'_{-a}{}^{H}$ is presumably small. Most of the amplification of the isotope effect $k_{-3}{}^{H}/k_{-3}{}^{D}$ therefore comes from the first factor. This isotope effect on the isomerization of (**1**$^{+}$ $^{-}$OAc) to (**2**$^{+}$ $^{-}$OAc) originates from the stabilization effect that the partial breaking of bonds to the two indene hydrons has on (**2**$^{+}$ $^{-}$OAc). Equation (2) yields an isotope effect on this interconversion ($k_i{}^{H}/k_i{}^{D}$) of *ca.* 5.2/2.9 ≈ 1.8. This value is unusually large for a secondary isotope effect and is greater than might be expected since the isotope effect for the solvolysis of (**2**-OAc) is considerably smaller (1.22). However, the error in this estimate of $k_i{}^{H}/k_i{}^{D}$ may be large since it contains the errors from two isotope effects. Furthermore, it is based upon several approximations as already discussed.

The free cation formed from solvolysis of the protonated alcohol (**1**-OH$_2$$^{+}$) also undergoes some elimination to give (**3**) and (**4**). The isotope effect for formation of (**3**), $k_3{}^{H}/k_3{}^{D}$ = 4.1 ± 0.3, by hydron transfer to water is higher than the isotope effects measured with the chloride or the acetate with acetate anion as proton acceptor. The reason might be that the indene hydrons are not loosened so much in the free carbocation as they are in the ion pair (**2**$^{+}$ $^{-}$X). An alternative explanation is a more symmetrical transition state for hydron abstraction by a water molecule than by an acetate anion, *i.e.* a Melander-Westheimer effect.[12]

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 1084B liquid chromatograph equipped with a variable-wavelength detector on a C8 reversed-phase column (4.6 × 230 mm). 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), (**3**), and 1-(2-chloropropan-2-yl)indene have been reported previously.[3b,13] The deuterium contents of the substrates (1,1-^{2}H$_2$)-(**1**-OH), -(**1**-OAc), and -(**1**-Cl) were 98.2 ± 1.0, 98.2 ± 1.0, and 98.3 ± 1.0 atom % (in the 1 position), respectively. The preparations of compounds (**2**-OAc), (**1**-OMe), (**2**-OMe), and (**4**) are described in the preceding paper. Acetonitrile (Fluka, for u.v. spectroscopy) was used as a solvent without further purification. Stock solutions of the bases were made by diluting the respective acid (p.a. or spectroscopic quality) with 0.97 equivalents of sodium hydroxide solution. All other chemicals were of reagent grade and used without further purification. A stock solution of sodium perchlorate was prepared from perchloric acid and sodium hydroxide solution. The relative extinction coefficients have been reported previously.[6]

*2-Acetoxy-*1*-isopropylidene*(3,3-^{2}H$_2$)*indan* (3,3-^{2}H$_2$)-(**2**-OAc). This was synthesized from (1,1-^{2}H$_2$)-(**1**-OH) and isolated according to the method described for (**2**-OAc).[6] ^{1}H N.m.r. and h.p.l.c. showed that the product was pure apart from a trace of the other isomer (1,1-^{2}H$_2$)-(**1**-OAc) (<0.4 mol %). The deuterium content in the 3-position was 98.3 ± 1.0 atom % measured by ^{1}H n.m.r.

Solvolysis Reaction Procedure.—The reactions were run at constant ionic strength in solutions prepared by mixing three volumes of aqueous solution of the salt(s) (at constant ionic strength 1.00M, maintained with NaClO$_4$) with one volume of the organic solvent at room temperature, *ca.* 22 °C. The reaction temperature was 35.00 ± 0.03 °C. The sodium perchlorate 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 with (**1**-Cl).—The fast reactions of (**1**-Cl) 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 the mixture was analysed by h.p.l.c. and the mol % of each product was determined. The solvent for the concentrated substrate solution of (**1**-Cl) was either chloroform or acetonitrile. However, the latter solvent caused some difficulties due to the instability of the substrate in this solvent. More scattered data were therefore obtained when acetonitrile was used. The amount of substrate solution added to 1.3 ml of solvent was 0.4 μl (CHCl$_3$) or 1—25 μl (CH$_3$CN, with a spring-loaded syringe).

Kinetics.—The reactions of (**1**-OAc), (**2**-OAc), (**1**-OH), and 1-(2-chloropropan-2-yl)indene were started in thermostatted 5 ml pear-shaped flasks filled with solvent mixture. After mixing, the solution was rapidly transferred to pre-thermostatted h.p.l.c. flasks as before (one separate flask for each analysis). The analyses gave the mol % of the reactant and each of the products. The evaluation of the phenomenological rate constants has been described.[6]

The solvolysis experiments with (**1**-OH) to give the methyl ethers (**1**-OMe) and (**2**-OMe) were carried out in the following way. Methanol (200 μl) mixed with acetonitrile (800 μl) and 20mM-perchloric acid solution (μ = 1.00M, NaClO$_4$) (3 ml) was used as reaction medium. The formation of the methyl ethers was measured at the beginning of the solvolysis, before the formation of the olefins had become significant. By assuming a second-order rate constant ratio [k(MeOH)/k(H$_2$O)] of 2.3 (ref. 6) for trapping of the carbocation with methanol and water, the degenerate rate constant for the acid-catalysed hydrolysis of (**1**-OH) was obtained.

The rate constants for proton abstraction from the carbocation with solvent water were obtained in experiments in 15mM-HClO$_4$ in water–acetonitrile without addition of methanol. The degenerate reaction rate constant for reaction of (**1**-OH) was assumed to be the same as that in the medium with small methanol addition. The olefin (**3**) was found to be stable in 15mM-HClO$_4$ for several days.

The solvolysis and elimination reactions of (**1**-OAc) and (**2**-OAc) are accompanied by allylic isomerization. The observed ratios of elimination products and solvolysis thus change slightly during a kinetic run. A small correction has therefore been made by approximating the observed ratio as the sum of the ratio which reflects the reaction from (**1**-OAc) and the ratio which reflects reaction from (**2**-OAc) weighted by the average concentration and overall rate constant for each of the isomeric acetates.

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