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π-Participation in Solvolysis and Secondary Deuterium Isotope Effects. Octahydrodimethanonaphthalene System

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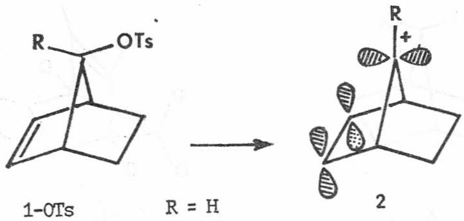
Specifically deuterated brosylates of unsaturated carbinols with *endo-*, *exo-*fused norbornanes structure 4-OH were prepared and their acetolysis rates measured at 25.0 °C. A secondary α-deuterium isotope effect of $k_H/k_D = 1.20$ was obtained which is close to the characteristic maximum for solvolysis of sulfonate esters. This result is rationalized in terms of an exponential correlation between the magnitude of the α-*d* effect and the bond order to incoming and leaving groups. The conclusion is reached that even large rate accelerations may indicate extensive charge delocalization occurring at large internuclear distances between the neighboring group and the reaction center in the transition state. Acetolysis of the compound with deuterated double bond (4-OBs-d_6) proceeds with an inverse isotope effect ($k_H/k_D = 0.93$) which is analogous to other cases of π-participation.

INTRODUCTION

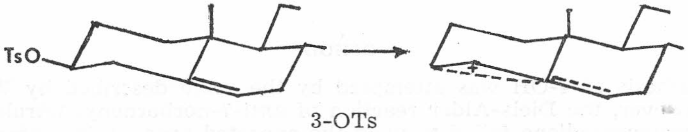
In previous publications we have reported on secondary deuterium isotope effects in solvolysis of *anti*-7-norbornenyl[1,2] and cholesteryl[2,3] *p*-toluenesulfonates, 1-OTs and 3-OTs, respectively, compounds which are known to react via π-participation[4,5].



1-OTs R = H

2

1-OTs-d_1 R = D



3-OTs

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* Taken in part from Ph. D. Thesis of R. M., University of Zagreb, 1976.

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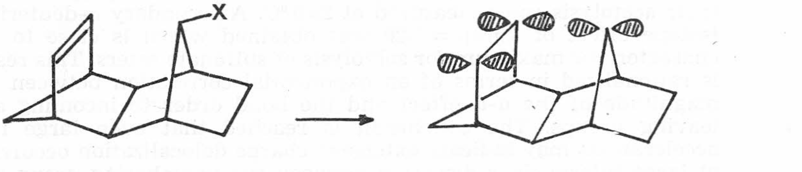
For both compounds the same α-deuterium isotope effect was found, $k_H/k_D = 1.13$. This identical isotope effect conceals however an enormous difference in rate accelerations brought about by the double bond as a participating neighboring group in solvolysis of the two compounds. Thus 1-OTs reacts some 10^{11} times[6] faster than the saturated analogue while the corresponding rate acceleration with 3-OTs is only about 10^2.[3] In general there seems to be no straightforward correlation between the magnitude of the α-d effect and the rate acceleration caused by neighboring groups in solvolysis[2]. It seemed therefore appropriate to obtain more data relating to this problem.

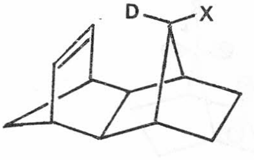
An interesting case of π-participation (participation by π-electrons of a double bond) was described by Winstein and Hansen[7]. Acetolysis of *endo,exo*-1,2,3,4,4a,5,8,8a,-octahydro-1,4:5,8-dimethanonaphthalene *anti*-10-p-bromobenzenesulfonate 4-OBs is only about 4 times slower than that of 1-OTs or 10^{10} to 10^{11} times faster than that of 7-norbornyl derivative. The geometry of 4-OBs seems eminently suited for participation since the empty p-orbital produced at the reaction center during ionization lies in the same plane with the π-electron cloud of the double bond, which is shown in 5. In order to investigate if and how such a large rate acceleration would affect secondary deuterium isotope effects, deuterated analogues 4-OBs-d_1 and 4-OBs-d_6 were prepared and their acetolysis rates measured. Herewith we report the results of this work.



5

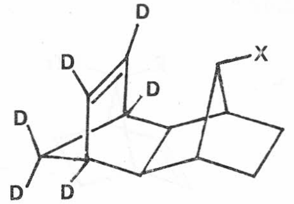
4-OH X = OH

4-OBs X = OBs



4-OBs-d_1 X = OBs

4-OH-d_1 X = OH



4-OBs-d_6 X = OBs

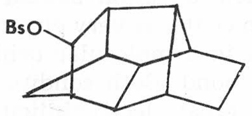
4-OH-d_6 X = OH

METHODS

The synthesis of 4-OH was attempted by the route described by Winstein and Hansen[7]. However, the Diels-Alder reaction of *anti*-7-norbornenyl tetrahydropyranyl ether with cyclopentadiene failed to yield the expected product. Therefore 4-OH was prepared by the older method[8] via addition of hexachloropentadiene to *anti*-7-norbornenol. Sodium[9] was found to be superior to lithium[10] in affecting dechlorination, as reported.[11] Deuterated alcohols 4-OH-d_1 and 4-OH-d_6 were obtained by substitution of $LiAlH_4$ for $LiAlD_4$ and of t-BuOH for t-BuOD respectively. The deuterium content was determined by mass spectroscopy (Varian MAT CH-7) on 4-OH-d_1 (98% d_1) and 4-OD-d_6 (79% d_6 and 18% d_5). Brosylates were prepared in the usual way. Reaction rates in acetic acid at 25.0 °C were followed by continuous automatic potentiometric titration of the liberated sulfonic acid by means of a pH-stat (Radiometer, Copenhagen). In each measurement 8 mg (0.02 mmol) of the brosylate was dissolved in 30 ml of acetic acid containing 1% acetic anhydride and the liberated acid titrated with a solution of 100 mg sodium carbonate in anh. acetic acid. In order to avoid complications due to a competitive rearrangement of the brosylate (see Results), reactions were followed only up to about 60% completion. The »infinity« titer and the first order rate constants were calculated by means of a non-linear least squares program.

RESULTS

During acetolysis 4-OBs yields, in a competitive reaction, 12% of the rearranged brosylate 6-OBs[7]. Although 6-OBs is much less reactive ($k = 8.9 \times \times 10^{-5}$ at 75.0 °C)[7] than 4-OBs, care was taken to avoid any errors in the rate constants due to liberation of acid from 6-OBs. Titrimetric rate constants obtained as described in Methods represent the sum of the rate constants for acetolysis and rearrangement of 4-OBs. The results are given in Table I.



6-OBs

TABLE I

First Order Rate Constants for Disappearance of 4-OBs and Deuterated Analogues in Acetic Acid at 25.0 °C

	k, 10^{-4}s^{-1}		
Compound	4-OBs-d_1	4-OBs	4-OBs-d_6
	2.02 (1)[a]	2.29 (1)	2.52 (2)
	1.90 (1)	2.26 (1)	2.48 (1)
	1.84 (1)	2.34 (1)	2.43 (1)
	1.99 (1)	2.31 (1)	2.39 (1)
	1.86 (2)	2.30 (1)	2.48 (1)
Mean values	1.92 (3)	2.30 (1)[b]	2.46 (2)
Isotope effects k_H/k_D	1.20 (3)		0.93 (2)

[a] Values in parentheses are standard deviations, i. e. 2.02 (1) = 2.02 ± 0.01
[b] Reported[7] value 2.38 ± 0.02

DISCUSSION

It has been shown that largest secondary α-deuterium isotope effects occur in solvolyses in which the rate determining step is the transformation of one type of ion pair into another[12,13,15]. In such reactions there is no covalent bonding to the leaving group in the reaction transition state. The characteristic maximum α-d effect for solvolyses of sulfonate esters is about $k_H/k_D = 1.23$ at 25 °C. The isotope effect measured in acetolysis of 4-OBs-d_1 approaches this value. Such a conclusion is not invalidated by the fact that the rate constants reported in Table I represent composite values rather than acetolysis rate constants. The rearrangement observed is probably internal in nature, i. e., it occurs through return from the intimate ion pair. Since a reaction in which the formation of the intimate ion pair is rate determining (rearrangement of 4-OBs to 6-OBs) proceeds with a smaller[12,14] α-d effect than a reaction in which the transformation of the intimate ion pair to a solvent separated ion pair is rate determining[12,13] (acetolysis of 4-OBs), the isotope effect on acetolysis proper can only be larger than on the rate of disappearance of 4-OBs. It appears therefore that the α-d effect in acetolysis of 4-OBs (4-OBs-d_1) is of a magnitude typical for reactions in which the formation of an external ion pair is rate determining. The enormous rate enhancement due to the participation of the double bond has no apparent influence on the α-d isotope effect. This is dramatically illustrated by the numerically identical α-effect (k_H/k_D 1.13) observed in the solvolysis of 7-norbornyl-7d_1-triflate in 80% trifluoroethanol at 65 °C.*

It has been pointed out that in anchimerically assisted reactions bridging (formation of covalent bond to internal nucleophile) might lag behind ionization and charge delocalization. This phenomenon has recently been analyzed by Shiner[18] for solvolysis of neophyl esters in terms of modified energy contour diagrams of O'Ferrall[19] and Jencks[20] in order to rationalize the observed α-d effects. From accumulated evidence it seems reasonable to assume that lagging of bridging behind charge delocalization should be especially pronounced if (*a*) the incipient carbonium ion center is very electrophilic and (*b*) if the electrons of the neighboring group are in a molecular orbital extending far into space, as in a π-orbital of a double bond. Both conditions are met in solvolysis of a substrate such as 4-OBs. The great electrophilicity of the carbonium ion at C_7 in reactions of norbornyl derivatives is apparent in the large solvolysis rate acceleration brought about C_7-methyl substitution and in large CH_3-/CD_3-β-deuterium isotope effects[21,22].

α-Deuterium isotope effects are due to a change in the out-of-plane bending frequencies of the CH(D) bond between initial and transition states[2,12]. In direct displacement reactions the approach of the nucleophile tends to compensate the decrease in the relevant bending force constants due to the departure of the leaving group, resulting in k_H/k_D values of about unity. Where this compensation is not operative, as in limiting solvolysis, α-d effects significantly larger than unity are observed. An exponential correlation between the magnitude of the α-d k_H/k_D value and distances in the transition state, from the reaction center to incoming and departing groups has been previously proposed[2,23] and is shown schematically in Figure 1.

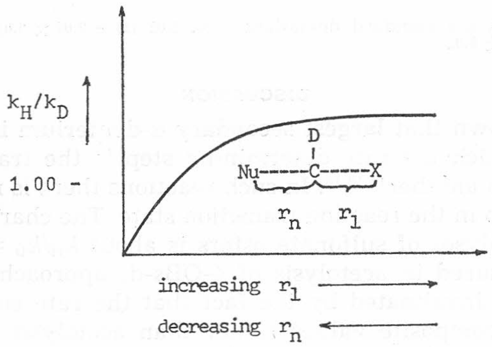


Figure 1. Correlation between the magnitude of α-d isotope effects and distances to incoming and departing groups in the transition state

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* V. Deljac, unpublished result from these laboratories

The correlation in Figure 1 explains the observation that reactions in which a relatively small elongation of r_l represents the rate determining step display a rather large *a*-d isotope effect. Thus solvolyses in which the formation of the intimate ion pair from a covalent bond is rate determining often proceed with an α-*d* effect of about three quarters of the maximum characteristic of the particular leaving group[12]. It should be noted that according to Hammond postulate[24], there should be little covalent bonding to the leaving group in the transition state of such reactions. Conversely, in anchimerically assisted solvolyses where the interaction with the (internal) nucleophile is part of the rate determining step, α-*d* effects are expected to be significantly reduced in magnitude only if r_n is short[2]. Therefore, if participation lowers α-*d* effects, this can be taken as an indication of close approach of the neighboring group with some covalent bonding to the reaction center in the transition state. Moreover, in such cases the magnitude of the α-*d* effect will be sensitive to minor changes in the substrate structure affecting r_l and r_n, which is observed[18].

In acetolysis of 4-OBs (4-OBs-d_1) the rigid structure hinders a close approach of the neighboring group to the reaction center and the α-*d* effect is not lowered. However, the nature of interacting orbitals and the geometry of this interaction allows effective charge delocalization at a relatively large distance. In this respect it is instructive to compare the structures of carbonium ions **2** and **5** produced in solvolysis of 1-OTs and 4-OBs respectively. In both reactions the rate acceleration relative to the same standard, 7-*anti*-norbornenyl derivative, is very large and of about the same order of magnitude. In the transition state leading to **2** the interaction between the incipient empty p-orbital at C-7 and the orbitals of the double bond occurs at an angle and is of the mixed σ-π type. In **5** the axes of all three *p*-orbitals lie in the same plane allowing a pure σ-interaction. Since σ-interaction is more effective than π-interaction for given interatomic distances and since 1-OTs and 4-OBs solvolyze nevertheless at about the same rate, it follows that the neighboring group must come closer to the reaction center in the transition state of the reaction with 1-OTs than with 4-OBs.

This conclusion is consistent with the observed *a*-*d* effects. With 1-OTs-d_1 a reduced k_H/k_D value of 1.13 was measured[1] as compared with 1.20 for 4-OBs-d_1.

It can be concluded that even dramatic rate increases in anchimerically assisted solvolyses do not necessarily imply important covalent bonding but may be indicative for extensive charge delocalization occuring at large internuclear distances between the neighboring group and the reaction center in the transition state. In the opinion of one referee »acceleration could in part be due to this and in part due to the relief of the considerable strain that must exist in the reactant state because the α-H is pushed quite close into the double bond. It seems likely also that this crowding could elevate the initial state frequencies sufficient to cause the α-*d* rate effect to be larger than 1.13. While this cannot be considered as the preferred explanation, it certainly cannot be excluded and should be considered as a reasonable possibility.«

Small inverse isotope effects were observed with substrates deuterated at the double bond and solvolyzing by way of π-participation (analogues of 1-OTs[1] and 3-OTs[3]) which has been rationalized in terms of rehybridization of CH(D) bonding orbitals in the rate determining step. The small rate increase due to deuteration as in the acetolysis of 4-OBs-d_6 relative to 4-OBs can be explained in the same manner. However, some contribution to the inverse isotope effect of deuteriums attached to saturated carbons[25] cannot be excluded.

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SAŽETAK

π-Participacija u solvolizi i sekundarni deuterijski izotopni efekt. Oktahidrodimetanonaftalenski sustav

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Priređeni su brosilati specifično deuteriranih nezasićenih karbinola sa strukturom endo, egzo-spojenih norbornanskih prstenova, 4-OH. Izmjerene su konstante brzine acetolize kod 25 °C te su izračunani izotopni efekti. Dobiven je α-deuterijski sekundarni izotopni efekt $k_H/k_D = 1.20$, što je blizu karakteristične maksimalne vrijednosti za solvolizu sulfonskih estera. Takav rezultat dade se objasniti eksponencijalnom ovisnošću veličine α-d efekta o udaljenosti reakcijskog centra i ulazne odnosno izlazne skupine u prijelaznom stanju. Zaključuje se da čak ni velika ubrzanja ne moraju obvezatno značiti da je kovalentno vezanje susjedne skupine na reakcijski centar znatnije napredovalo u prijelaznom stanju.

Kod acetolize spoja sa deuteriranom dvostrukom vezom (4-OBs-d_6) zapažen je obrnuti izotopni efekt ($k_H/k_D = 0.93$) analogno drugim slučajevima π-participacije.

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