# DEUTERIUM KINETIC ISOTOPE EFFECTS

## V. TEMPERATURE DEPENDENCE OF $\beta$ -DEUTERIUM EFFECTS IN WATER SOLVOLYSIS OF ISOPROPYL COMPOUNDS<sup>1</sup>

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#### ABSTRACT

The secondary  $\beta$ -deuterium isotope effect  $(k_{\rm H}/k_{\rm D})$  has been measured over a range of temperature for the water solvolysis reactions of isopropyl methanesulphonate, *p*-toluene-sulphonate, and bromide. In these cases the isotope effect is due to a difference in entropies of activation of the isotopic analogues rather than a difference in the enthalpies of activation. It is suggested that the observed isotope effect is due to internal rotational effects of the methyl groups in the isopropyl radical, and the lack of an isotope effect on the enthalpy of activation is accounted for by a cancellation of an effect from this source and one from zero-point energy.

Secondary  $\beta$ -deuterium isotope effects in solvolytic reactions have been studied by several groups of workers (1–12). In all cases, replacement of hydrogen on  $\beta$ -carbon atoms of the alkyl radical by deuterium led to a reduction in the rate of solvolysis. The rate ratio ( $k_{\rm H}/k_{\rm D}$ ) was found to vary from close to unity, for primary compounds (11, 12), to about 2.5, for tertiary compounds (1, 11). The source of this reduction in rate with deuterium substitution has usually been discussed in terms of the effect of changes in hyperconjugation associated with the activation process. The resulting weakening of C—H and C—D bonds implies a corresponding change in the difference in the zeropoint energies. If this is the main source of the observed isotope effect, then an analysis of the temperature dependence of this effect should show a difference in the corresponding enthalpies of activation and any difference in the entropies and heat capacities of activation should be small. This explanation is in accord with the results reported by Shiner and Verbanic (2, 13) and by Lewis and Coppinger (5), who found in three solvolytic reactions that deuteration led to a change in both enthalpy and entropy of activation, the former being the major factor.

As a continuation of our general survey of  $\beta$ -deuterium isotope effects in the water solvolysis of alkyl halides and sulphonates (11), we have examined to what extent the above assumption is valid for the isopropyl system.

### RESULTS AND DISCUSSION

Rate data over a range of temperature are given in Table I for the hydrolysis of isopropyl methanesulphonate, p-toluenesulphonate, and bromide, and their fully  $\beta$ -deuterated analogues. The rate data for the normal compounds were calculated from the three constant rate – temperature relationships previously determined in this laboratory (14). These relationships have been shown to reproduce the rate constants to better than the experimental error, and agreement between the rates so derived and experimentally determined for the protium compound was demonstrated for each of the above compounds, immediately prior to rate determinations on the deuterated

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1989

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Can. J. Chem. Vol. 39 (1961)

TABLE I	
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Temperature dependence of the  $\beta$ -deuterium isotope effect for the solvolysis of isopropyl compounds in water

Compound	$10^4 k_{\rm H} \; ({\rm sec}^{-1})$	$10^4 k_{\rm D} \; ({\rm sec}^{-1})$	Temp. (°C)	$k_{\rm H}/k_{\rm D}$ (±0.006)
Isopropyl methanesulphonate	3.691 1.965 1.019 0.3619 0.3612 0.1197	$\begin{array}{c} 2.386\\ 1.267\\ 0.6570\\ 0.2340\\ 0.2345\\ 0.07698\end{array}$	$\begin{array}{c} 30.001\\ 25.000\\ 20.002\\ 12.514\\ 12.501\\ 5.000 \end{array}$	$\begin{array}{c} 1.54_{7}\\ 1.55_{1}\\ 1.55_{1}\\ 1.54_{7}\\ 1.54_{0}\\ 1.55_{5}\end{array}$
Isopropyl p-toluenesulphonate	$\begin{array}{c} 7.664 \\ 7.650 \\ 4.085 \\ 4.082 \\ 2.122 \\ 1.071 \\ 0.5248 \\ 0.2900 \end{array}$	$\begin{array}{c} 4.960 \\ 4.942 \\ 2.655 \\ 2.648 \\ 1.375 \\ 0.6933 \\ 0.3415 \\ 0.1881 \end{array}$	$\begin{array}{c} 30.017\\ 30.001\\ 25.005\\ 24.999\\ 20.005\\ 15.003\\ 10.003\\ 6.008 \end{array}$	$1.54_{5}\\1.54_{8}\\1.53_{9}\\1.54_{2}\\1.54_{3}\\1.54_{3}\\1.54_{5}\\1.53_{7}\\1.54_{2}$
Isopropyl bromide	$\begin{array}{c} 10.11\\ 10.10\\ 6.004\\ 3.486\\ 3.461\\ 1.981\\ 0.3123\\ 0.3123\\ 0.3123\end{array}$	$\begin{array}{c} 7.638 \\ 7.670 \\ 4.542 \\ 2.645 \\ 2.631 \\ 1.509 \\ 0.2381 \\ 0.2371 \end{array}$	$\begin{array}{c} 69.994\\ 69.993\\ 65.002\\ 60.000\\ 59.933\\ 55.005\\ 40.005\\ 40.005\\ 40.005\\ \end{array}$	$1.32_4 \\ 1.31_7 \\ 1.32_2 \\ 1.31_8 \\ 1.31_5 \\ 1.31_3 \\ 1.31_2 \\ 1.31_7$

compound. The rate ratios  $(k_{\rm H}/k_{\rm D})$ , given in the final column, are seen to be almost independent of temperature. The results were fitted to the transition-state relationship

[1] 
$$\log_{10} (k_{\rm H}/k_{\rm D}) = \frac{(\Delta H_{\rm D}^{\pm} - \Delta H_{\rm H}^{\pm})}{2.303RT} - \frac{(\Delta S_{\rm D}^{\pm} - \Delta S_{\rm H}^{\pm})}{2.303R}$$

by the method of least squares, and the resulting enthalpy and entropy differences are given in Table II. Thus the rate decrease resulting from  $\beta$ -deuteration in this system is

## TABLE II

Changes in enthalpy and entropy of activation produced by  $\beta$ -deuteration in the solvolysis of isopropyl compounds in water

Compound	$(\Delta H_{\rm D}^{\pm} - \Delta H_{\rm H}^{\pm}) \pm \text{std. error}$ (cal mole <sup>-1</sup> )	$(\Delta S_{\rm D}^{\pm} - \Delta S_{\rm H}^{\pm}) \pm \text{std. error}$ (cal mole <sup>-1</sup> deg <sup>-1</sup> )
Isopropyl methanesulphonate Isopropyl <i>p</i> -toluenesulphonate Isopropyl bromide	$7\pm 28 \\ -21\pm 14 \\ -35\pm 15$	$-0.84 \pm 0.1 -0.93 \pm 0.05 -0.65 \pm 0.05$

due almost entirely to a difference between the entropies of activation of the isotopic analogues. This is in marked contrast to the earlier work and cannot be explained in terms of zero-point energy effects alone.

When equation [1] is used, it is assumed that the heat capacities of activation  $(\Delta C_p^{\pm})$  for the protium and deuterium compounds are the same. Since it has been observed that  $\Delta C_p^{\pm}$  is much more sensitive to changes in the anionic group than to changes in the alkyl radical (15), this assumption probably would not introduce a significant error in the general case. If such an error were detectable it would appear as a curvature in

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# LEFFEK ET AL.: ISOTOPE EFFECTS

a plot of  $\log_{10} (k_{\rm H}/k_{\rm D})$  versus  $T^{-1}$ . For the present case of the isopropyl compounds,  $(\Delta H_{\rm D}^{\pm} - \Delta H_{\rm H}^{\pm})$  is approximately zero and, therefore,  $(\Delta C_{p, \rm D}^{\pm} - \Delta C_{p, \rm H}^{\pm})$  must also be very close to zero (less than -0.5 cal mole<sup>-1</sup> deg<sup>-1</sup>).

Any explanation of the results in Table II must be capable of producing the entropy of activation difference and at the same time account for the lack of an enthalpy of activation difference. The probable sources of secondary deuterium isotope effects will be examined in the light of these requirements.

## Zero-Point Energy Effects

It has been generally claimed that the formation of a positive charge in the transition state of a solvolytic reaction proceeding via a carbonium ion brings about an increase in hyperconjugation in the activation process. The vibrational frequencies of the  $\beta$ -C—H (or  $\beta$ -C—D) bonds are, therefore, reduced in the transition state relative to the initial state. As a result, the difference between the zero-point energies of the  $\beta$ -C—D bonds and the  $\beta$ -C—H bonds is less in the transition state than in the initial state, leading to a higher enthalpy of activation for the deuterated compound. This argument is well established (1–12) and was applied in an earlier paper (11) to isopropyl compounds solvolyzing in water. Our present results show that if such an effect is present in the isopropyl case, it must be cancelled by another enthalpy effect of the opposite sign. The earlier work of Shiner *et al.* (2, 13) and Lewis *et al.* (5) on the temperature dependence of the secondary deuterium isotope effect seems to indicate that, in general, enthalpy of activation differences do occur. It is concluded, therefore, that the lack of an enthalpy difference in our system is probably due to a fortuitous cancellation of two (or more) effects.

# Solvation Effects

Specific solvation effects as a source of secondary  $\beta$ -deuterium isotope effects in solvolytic reactions were considered by Shiner (1, 2), although Lewis and Coppinger (5) and later Streitwieser *et al.* (7) produced evidence against such an explanation.

Indirect evidence against solvation effects as a major contributor to the isotope effect is also available from the derived kinetic parameters for hydrolysis reactions. Briefly, a consideration of the changes in the entropy of activation ( $\delta_{\mathbf{R}}\Delta S^{\pm}$ ) accompanying the structural change ethyl to isopropyl for a series of halides and sulphonates leads to the conclusion that no appreciable solvent reorganization has taken place about the alkyl group at the transition state (14). Even stronger evidence is the lack of significant differences in the solvent isotope effect (15). The lack of correlation between  $\delta_{\mathbf{R}}\Delta S^{\pm}$  and  $\delta_{\mathbf{R}}\Delta C_{p}^{\pm}$  is also consistent with this conclusion.

Finally, there is the evidence from the work of Maccoll *et al.* (17) that an isotopic effect very similar to those reported here has been observed in the absence of solvent. In the gas-phase pyrolysis of normal and  $\beta$ -deuterated isopropyl bromide, a reaction which is postulated to have a quasi-carbonium-ion transition state, an isotope effect  $(k_{\rm H}/k_{\rm D}) = 2.5$  was obtained. This rate ratio was also not greatly dependent on temperature. The result, by its marked similarity to those results given in Table I, supports the conclusion that solvation effects are not an important source of the isotope effect in this system, although the evidence is not strong enough to rule them out entirely.

## Internal Effects

Isotope effects from this source arise as a result of differences between the partition functions of the normal and deuterated molecules in the initial and transition states CANADIAN JOURNAL OF CHEMISTRY, VOL. 39, 1961

(equation [2]). The partition function Q may be factorized into  $Q_{\text{trans}} \times Q_{\text{rot}} \times Q_{\text{vib}} \times Q_{\text{int rot}}$ .

[2] 
$$(k_{\rm H}/k_{\rm D})_{\rm int} = \frac{Q_{\rm H}^{\pm}}{Q_{\rm H}} \cdot \frac{Q_{\rm D}}{Q_{\rm D}^{\mp}} .$$

The maximum rate ratios which could arise from the translational and rotational partition function differences would occur if the initial state were unsolvated and the transition state highly solvated (11). For this extreme case the rate ratios are given by the equations

$$\left(k_{
m H}/k_{
m D}
ight)_{
m trans}=\left(rac{M_{
m D}}{M_{
m H}}
ight)^3$$

$$(k_{\mathrm{H}}/k_{\mathrm{D}})_{\mathrm{rot}} = \left(\frac{\Pi I_{\mathrm{D}}}{\Pi I_{\mathrm{H}}}\right)^{1/2}$$

In practice neither of these contributions to the isotope effect can be expected to exceed a few per cent. The contribution from the vibrational partition function is also small at the ordinary temperatures used in this study (18, 19).

The theory regarding internal rotation in molecules has remained less than adequate despite the considerable amount of research into the subject (20). Nevertheless, it has been recognized that changes in barriers to internal rotation during chemical reactions must be important in determining the thermodynamic reaction parameters (20). The isotope effects observed during this study can be accounted for semiquantitatively on the basis of the following two postulates concerning the barriers to internal rotation of the methyl groups in isopropyl compounds for the water solvolysis reaction. It is postulated: (a) that there is a considerable decrease in the barrier to rotation of the CH<sub>3</sub> (or CD<sub>3</sub>) groups on going from the initial to the transition state and (b) that the barrier to rotation of the methyl groups is higher in the protium compound than in the deuterium compound in the initial state.

The justification of the first postulate is the empirical rule that sixfold barriers to rotation are considerably smaller than threefold barriers (20, 21). Examples can be found in methyl derivatives of benzene where the barriers to rotation of the methyl groups are about 0.5 kcal per mole (21). If it is accepted that the transition state in the water solvolysis of isopropyl sulphonates and halides approximates a planar carbonium ion, then the barrier will become sixfold during the activation process and hence will be greatly reduced in the transition state. The entropy of activation for the water solvolysis reaction becomes increasingly more positive along the series ethyl halide, isopropyl halide, tertiary butyl halide (16), a variation which is also in qualitative agreement with postulate (a).

Postulate (b) is based on a limited number of microwave spectroscopic measurements. Swalen and Costain (22) found that the barrier to internal rotation for the CH<sub>3</sub> group in acetone is approximately 6% higher than that for the CD<sub>3</sub> groups in acetone- $d_6$ . In nitromethane, the barrier to internal rotation of the methyl group is 16% greater in the normal compound that in the deuterated compound (23). On the other hand, recent work on the barrier in deuterated ethanes, using infrared data, gives no clear indication that CH<sub>3</sub> groups have a higher barrier than CD<sub>3</sub> groups (24). Theoretical support for postulate (b) is not easily found since barriers to internal rotation are not well understood. Bartell (25) has recently drawn attention to the size effects among isotopic molecules as a possible explanation for secondary deuterium isotope effects. Since

1992

[3]

[4]

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### LEFFEK ET AL.: ISOTOPE EFFECTS

hydrogen–carbon bonds are slightly longer and have slightly larger amplitudes of vibration than deuterium-carbon bonds, it might be expected that normal methyl groups will have higher barriers to rotation than deuteromethyl groups, in consideration of the calculations made by Kreevoy and Mason (26) on steric effects and barriers to rotation. Libby suggests (27) "that a further investigation of the dependence of barrier height on isotopic substitution might settle the question as to whether repulsion between hydrogen atoms is the cause of the barrier in ethane". While it is admitted that steric considerations alone certainly grossly oversimplify the problem of barriers to internal rotation, further experimental measurements may well prove postulate (b) correct.

On the basis of the two postulates, approximate calculations have been made for a molecule  $(CH_3)_2CHX$ , where X is a heavy group. For several assumed barrier heights, the contributions to the enthalpy and entropy of activation from the restricted rotation of methyl groups were determined using Pitzer's Tables (28). The use of these tables introduces the additional assumption that the two methyl groups in the isopropyl radical are non-interacting, an assumption which is probably incorrect. However, since the values of the moments of inertia and barrier heights used in the calculation are only approximate, the results contain inherent uncertainties large enough to justify the neglect of any methyl-methyl interaction.

Some results of these calculations are shown in Table III. The top half of this table

water from internal rotation effects						
Barrier to methyl rotation (cal mole <sup>-1</sup> )						
Initial	state	Transition state	$(\Delta H_{\rm D}^{\pm} - \Delta H_{\rm H}^{\pm})_{\rm int  rot}$	$(\Delta S_{\rm D}^{\pm} - \Delta S_{\rm H}^{\pm})_{\rm int rot}$		
H cpd.	D cpd.	Both cpds.	(cal mole <sup>-1</sup> )	(cal mole <sup>-1</sup> deg <sup>-1</sup> )		
3000	3000	0	-65	0.06		
3000	3000	1200	$-29 \\ -15$	$0.05 \\ 0.04$		
3000	2400	0	-93	-0.26		
3000	2400	600	-31	-0.26		
3000	2400	1200	44	-0.26		

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Contributions to the secondary  $\beta$ -deuterium isotope effects for the solvolysis of isopropyl compounds in

TABLE III

shows results obtained by the application of postulate (a) alone. The entropy of activation difference here is due to the difference in mass between hydrogen and deuterium and is seen to be small and in the direction opposite to that observed in Table II. The bottom half of Table III shows the results obtained by application of both postulates, assuming a 20% difference between the barriers to internal rotation of the normal methyl and deuteromethyl groups. When the figures in the right-hand column, for the entropy of activation difference per methyl group, are multiplied by 2, quite a large part of the observed entropy difference can be explained. At the same time an enthalpy of activation difference is obtained opposite in sign to that springing from a zero-point energy effect.

It is therefore suggested that the major part of the observed isotope effect for the water solvolysis of isopropyl compounds is due to internal rotational effects, and that the most probable cause of the lack of an isotope effect on the enthalpy of activation is a fortuitous cancellation between enthalpy effects arising from zero-point energy sources and internal rotational effects.

#### CANADIAN IOURNAL OF CHEMISTRY, VOL. 39, 1961

### EXPERIMENTAL

Isopropyl- $\beta$ - $d_6$  alcohol was obtained by the reduction of acetone- $d_6$  with lithium aluminum hydride using the procedure described by Shiner (29). The crude product was redistilled, boiling point range 83.5-84.5° C. Yields up to 99% were obtained using this procedure. The N.M.R. spectrum of this compound showed that the  $\beta$ -carbon atom was fully deuterated. Treatment of the alcohol with "constant boiling" hydrobromic acid yielded the bromide, boiling point range  $60-61^{\circ}$  C, in 55% yield after purification.

Isopropyl- $\beta$ - $d_6$  methanesulphonate and p-toluenesulphonate were prepared by reaction of the bromide with the appropriate silver sulphonate as previously described for ethyl compounds (30). The sulphonates were purified by distillation under a vacuum.

The protium analogues of the above compounds were prepared by parallel reactions and were used to check the rate constants which had been previously determined in this laboratory (14).

The rate measurements were made conductometrically as described in detail in Part III of this series (31).

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1994