

TRITIUM AND DEUTERIUM ARRHENIUS PARAMETER EFFECTS IN A BASE-PROMOTED ELIMINATION REACTION: EVIDENCE FOR TUNNELLING

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THEORETICAL APPROACH

The theory of isotope effects, based on absolute reaction rate theory, provides what is probably the single most powerful tool for the study of transition state structure. Thus, isotope rate effects are most frequently observed for the purpose of elucidating mechanism. However, sufficiently detailed observations of kinetic isotope effects on well-characterized reactions provide a valuable test not only of kinetic isotope effect theory but also of absolute reaction rate theory upon which it is based.

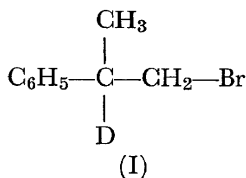
A relatively small number of isotope effects have been studied as a function of temperature; an even smaller number are known for two isotopes in the same reaction; in only the reaction of chlorine atoms with hydrogen molecules is there available information on *temperature-dependence of two isotope effects* in the same reaction. This system has recently been treated theoretically in some detail¹. The results "constitute a positive test of the transition state formulation of the effect of isotopic substitution on the rates of chemical reactions". It was not possible to conclude whether or not tunnelling is a significant feature of the process. Tunnel corrections, however, have been calculated to be generally large in a theoretical treatment of hydrogen atom transfer reactions and the results confirmed by reference to measured hydrogen-deuterium isotope effects as a function of temperature in the reactions of methyl radicals with organic compounds².

In a recent survey of isotope effects in proton transfer reactions in solution, Bell³ found only one study, of the bromination of carbethoxycyclopentanone, in which hydrogen-deuterium isotope effects had been measured as a function of temperature in a reaction simple enough to be amenable to quantitative treatment. A detailed theoretical analysis, based on a one-dimensional transition state model, indicated substantial tunnelling by hydrogen with a smaller but significant amount by deuterium. It was pointed out that while tunnelling might lead to recognizable abnormalities in isotope rate ratios or in activation energy differences, usually knowledge of transition state structure is insufficient to allow definitive conclusions in interpreting these parameters. On the other hand, the suggested most likely abnormality diagnostic of tunnelling was that the deuterium Arrhenius "A factor" was larger than that of hydrogen. In the theoretical

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calculation estimating the extent of tunnelling, it was assumed that in its absence the A-factor ratio would be unity. Largest tunnelling was found for proton abstraction from carbethoxycyclopentanone by fluoride ion, less in abstractions by chloroacetate ion and deuterium oxide.

Shiner and Smith⁴ subsequently published a study of temperature effects in the elimination of the elements of hydrogen bromide by ethoxide ion from 1-bromo-2-phenylpropane and the 2-deutero-analogue (I).

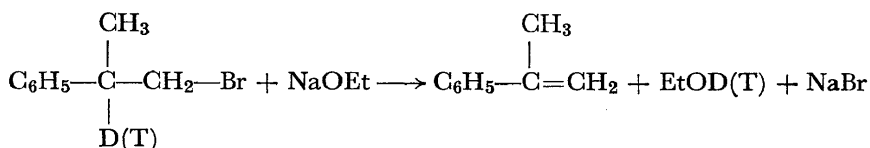


The clear-cut nature of the reaction, the single isotopic substitution and an accurate analytical method based on generated bromide ion made this process a particularly good one to study. In this example an abnormal activation energy effect ($E^*_{\text{D}} - E^*_{\text{H}} = 1766$ cal/mole) and A-factor ratio ($A^*_{\text{D}}/A^*_{\text{H}} = 2.53$) also indicated substantial proton tunnelling; the size of these "tunnelling indices" being similar to those for proton abstraction from carbethoxycyclopentanone by chloroacetate ion in the study by Bell, Fendley and Hulett⁵.

While tunnelling seemed to be definitely established in these studies, they were unsatisfactory from the point of view that tunnelling was indicated as a last resort when the theory neglecting it proved inadequate; there was no final check to prove the consistency of the arguments.

It occurred to us that it would be worthwhile to provide this for the elimination reaction studied by Shiner and Smith by determining the Arrhenius parameters for a second isotope effect involving, in this case, tritium. Because of the large molar radioactivity of tritium, rate effects with this isotope are most conveniently measured using the competitive reaction technique rather than by direct measurement of the reaction rate of the isotopically pure material, as was done for the hydrogen and deuterium compounds in this example. Moreover, since the accuracy of the competitive technique is best in the measurement of small isotope effects, it appeared most desirable to determine the tritium-deuterium rate effect by the competition method with tritium as a tracer in the deuterium compound (I). The isotopic labelling was accomplished *via* the synthesis described earlier⁴, except that the ester precursor, after having its active hydrogen completely exchanged for deuterium, was exchanged one last time with ethanol-d labelled with tritium in the hydroxyl group.

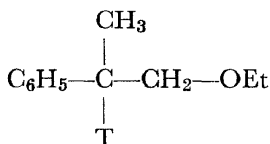
The reaction studied was elimination by sodium ethoxide in dry ethanol.



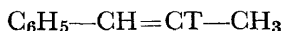
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The isotope effect causes tritium to be concentrated in the unreacted starting material during the course of the reaction. Its magnitude was determined by isolation of the organic portion, washed free of ethanol-d(t), and measuring its radioactivity with a scintillation counter. In several runs done at 45° the isotope effect was examined at various intervals through the entire reaction to determine that the results were not being adversely affected by isotopic impurities. After it was shown that the measured isotope effect was essentially constant through the entire reaction, subsequent measurements were made on samples which had undergone about 70–80 per cent reaction because the results at this stage would be expected to be most accurate.

In the earlier study it was shown that both the hydrogen and deuterium compounds gave 99 ± 1 per cent yield of olefin as determined by reaction with bromine. Thus, it was concluded that side reactions were unimportant. It was, therefore, surprising to find that after complete reaction of the tritium compound, 13 per cent of the initial reactivity remained in the ethanol-free organic fraction. Chromatographic separation and n.m.r. analysis showed the active compounds to be the substitution product, (II)



(II)



(III)

and β -methylstyrene- β -t, (III) in about equal proportions. Since tritium is eliminated about one-third as fast as deuterium, the occurrence of 6 per cent of (II) in the product of the reaction of the tritium compound is not inconsistent with the earlier results; the β -methylstyrene was entirely unexpected and must result from solvolysis and rearrangement. Assuming that the rates of formation of (II) and (III) are not affected by the isotopic substitution and knowing from the present measurements the isotope effect in elimination, the earlier results on the hydrogen–deuterium isotope effects could be corrected for these small side reactions. All of the hydrogen–deuterium rate ratios quoted earlier are after correction, as shown in Table 1, about 4 per cent higher.

The Arrhenius parameter effects were slightly smaller but within the limits of error, the same as given in the earlier publication. The Arrhenius parameters and their standard deviations are as follows:

$$\begin{aligned} E^*_{\text{H}} &= 20,655 \pm 74 \text{ cal/mole} \\ E^*_{\text{D}} - E^*_{\text{H}} &= 1766 \pm 115 \text{ cal/mole} \\ E^*_{\text{T}} - E^*_{\text{D}} &= 679.4 \pm 25 \text{ cal/mole} \\ \log A^*_{\text{H}} &= 11.033 \pm 0.008 \\ A^*_{\text{D}}/A^*_{\text{H}} &= 2.53 \\ A^*_{\text{T}}/A^*_{\text{D}} &= 1.19 \end{aligned}$$

Using the observed C–H and C–D stretching frequencies and calculating the one for the C–T bond from the harmonicity assumption, the zero point

energies in this mode in the initial state are, respectively 4150, 3079 and 2602 cal/mole. Thus the activation energy for the deuterium compound exceeds that of the hydrogen compound by an amount (1766 cal/mole) considerably greater than the difference in zero-point energies in the initial

Table 1. Isotope effects for the reaction of 1-bromo-2-phenylpropane and the 2-d-analogue with sodium ethoxide

<i>T</i>	$k_{\text{H}}/k_{\text{D}}$ (uncorrected) ^a	$k_{\text{H}}/k_{\text{D}}$ (corrected) ^b
5	9.387	9.742
15	8.303	8.626
25	7.510	7.815
35	6.542	6.807
45	6.165	6.434
55	5.868	6.133
	<i>Uncorrected</i> ^a	<i>Corrected</i> ^b
$E^*_{\text{D}} - E^*_{\text{H}}$ (cal)	1790 ± 110	1766 ± 115
$\log A^*_{\text{D}}/A^*_{\text{H}}$	0.437 ± 0.05	0.4035 ± 0.05

^a Reported in reference 4.

^b Corrected for a small fraction of substitution and rearrangement reaction observed with the tritium compound.

state stretching modes (1071 cal/mole). The discrepancy in the deuterium-tritium comparison is not nearly so large: 679.4 cal/mole difference in activation energy and 477 cal/mole difference in zero point energy. Perhaps even more striking is that the value of $A^*_{\text{T}}/A^*_{\text{D}}$ is very nearly unity. Both of these results, at face value, are consistent with the tunnelling explanation advanced earlier to explain the hydrogen-deuterium discrepancy. For the tritium-deuterium case, where the atoms are heavier and tunnelling should be much less, the abnormalities, although still present, are relatively small. Furthermore, Bell's earlier assumption that $A^*_{\text{D}}/A^*_{\text{H}}$ should be unity in the absence of tunnelling now finds its first experimental justification in the observed value for $A^*_{\text{T}}/A^*_{\text{D}}$ being very nearly unity. In our view this lends important support to the conclusions which were based on these calculations.

Although the experimental numbers themselves, without quantitative interpretation, provide strong confirmatory evidence for tunnelling, a quantitative treatment based on a simple transition state model is necessary to reveal the extent of tunnelling for each of the isotopes and to provide a check of the internal consistency of the data. For this purpose the method of Bell³, based on a three-centre transition state with a parabolic barrier seems quite satisfactory. Two separate calculations are possible; one for the H-D and another for the D-T effect.

These calculations will then provide two independent estimates of the true barrier heights for deuterium (E_{D}) and two estimates of the barrier width at half height (2*a*); the agreement between the independent estimates of these indices provides a quantitative measure of the internal consistency of the data. The results, given in Table 2, show remarkably good agreement; the calculated deuterium barriers are the same within the combined errors of estimate of the experimental isotope effects on the activation energy.

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Tunnelling is largest for hydrogen, intermediate for deuterium, least for tritium, as expected; further, the tunnelling difference between H and D is much larger than that between D and T. The barrier width is larger and the tunnelling in this reaction is appreciably less than in proton abstraction from carbethoxycyclopentanone. This is consistent with a higher activation energy and more highly broken C-H bond in the elimination reaction.

Table 2. Calculated barrier dimensions†

	From H-D effect	From D-T effect
E_H	22,099	
E_D	23,003	22,961
E_T		23,447
$2a$	1.589	1.592
$(1 - E^*_H/E_H)100\%$	5.4	
$(1 - E^*_D/E_D)100\%$	2.5	2.4
$(1 - E^*_T/E_T)100\%$		1.5

† Based on a three-centre transition state with a parabolic barrier. E_H , E_D , E_T are the true barrier heights for hydrogen, deuterium, and tritium, respectively, in cal/mole; $2a$ is the barrier width at half height in angstroms; E^*_H , E^*_D , and E^*_T are the Arrhenius activation energies.

§ This represents the percentage of the barrier height "tunnelled under".

The difference between the barrier heights should give the differential loss of zero point energy. $E_D - E_H$ gives 904 and 862 cal and the two estimates of $E_T - E_D$ are 486 and 444 cal. Thus, the differential loss in zero point energy is 84, 81, 101 and 93 per cent of the difference in zero point energy in the initial state stretching modes. This is consistent with the bond being about four-fifths broken in the transition state but with the bending modes not much influenced.

In conclusion it can be pointed out that for this proton transfer, tunnelling is appreciable but not large in comparison to the over-all activation energy. It shows up in the H/D activation energy difference about equal in importance to the zero point energy effect. Furthermore, and apparently *most generally useful in diagnosing tunnelling*, it contributes to making the A_D/A_H ratio greater than unity. It seems purely fortuitous that these two effects combine to give a k_H/k_D rate ratio at ordinary temperatures, very near "normal", *i.e.* corresponding superficially to complete loss of stretching zero point energy.

EXPERIMENTAL

Preparation of tritium oxide

One curie of tritium gas (1 ml at 327 mm) was released into a vacuum system, followed by an excess of dry air. The two components were caused to react by a glowing platinum wire. The product was condensed into a tube by cooling it with a carbon dioxide/acetone mixture; theoretical yield 0.4 milligrams.

Preparation of a mixture of ethyl 2-d-2-phenylpropionate and ethyl 2-t-2-phenylpropionate

Ethyl 2-d-2-phenylpropionate was prepared as before⁴ by the sodium-ethoxide-catalysed deuterium exchange between ethyl 2-phenyl-propionate and ethanol-d. As the final exchange was in progress, the tube containing the tritium oxide was detached from the combustion apparatus, dried on its exterior surface and dropped into the reacting solution.

After refluxing for 36 hours the ethanol was taken off under reduced pressure and the product was recovered by ether extraction and washing with water. The ether solutions were dried with anhydrous magnesium sulphate.

The ether was distilled off and the product was fractionated with a 18 × 400 mm Nestor spinning band column. Seventy-six grams of the deuterated and tritiated ester mixture were collected at 58° (0.7 mm). The deuterium analysis of the product by combustion and gradient density technique⁶ was 0.986 atoms of deuterium per molecule.

Preparation of a mixture of 1-bromo-2-phenylpropane-2-d and 1-bromo-2-phenylpropane-2-t

The mixed bromides were prepared from the mixed esters by the same sequence of reactions described previously⁴. The yield was 50.5 g of material boiling at 85.5° (5.2 mm) which gave a deuterium analysis of 0.967 atoms of deuterium per molecule.

Kinetic procedure

The kinetic procedure was identical to that of Shiner and Smith^{4, 7}, except that the extraction of the partially reacted mixture from the sealed tubes was modified, as described below, so that the extent of reaction of both the deuterated and tritiated compounds could be determined.

The exteriors of the sealed tubes containing partially reacted solution were cleaned with solvent before they were opened and dropped into a flask containing 25 ml of de-ionized water and 25 ml of Fischer Purified Grade toluene. The contents were swirled around and decanted into a separating funnel. The aqueous layer was run off into a second separatory funnel and washed twice with 50 ml of carbon tetrachloride which had been purified by passing through alumina. The toluene layer was washed first with 100 ml of dilute hydrochloric acid and then with 100 ml of distilled water and dried with anhydrous magnesium sulphate.

The extent of reaction of the 1-bromo-2-phenylpropane-2-d was estimated from the accumulation of bromide ion in the aqueous solution. After a short time this solution became clear as the droplets of carbon tetrachloride in suspension separated to the bottom of the flask and adhered to the glass. Then 20 ml of the supernatant liquid were pipetted out and titrated potentiometrically with silver nitrate solution⁸.

The extent of reaction of the 1-bromo-2-phenylpropane-2-t was determined by the reduction of radioactivity in the toluene solution. One millilitre of the supernatant liquid was pipetted into a 20 ml glass counting vial, which was then filled up with a scintillation solution of 2,5-diphenyl-oxazole ("PPO") (4 g/l.) and 1,4-bis-2-(4-methyl-5-phenyloxazolyl)-benzene

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("POPOP") (50 mg/l.) in Fischer Purified Grade toluene. Samples were counted on a Packard Tri-Carb liquid photoscintillation counter within a channel from 20 to 40 volts at a photomultiplier voltage of 1115 volts. Samples were counted ten times for five minutes each time, and the average taken.

Identification of the reaction products

The radioactivity of the toluene extracts did not fall to zero at the end of a run as expected, but to about 13 per cent of their original value. Chromatography of the reaction product by elution on an activity one alumina column with 1 per cent dichloromethane in pentane yielded two fractions; the first was non-radioactive 2-phenylpropene and the second was identified by n.m.r. as 1-phenyl-1-propene-2-d containing about 6 per cent of the original tritium. Further elution with 5 per cent ether in pentane gave a third fraction identified by n.m.r. as 1-ethoxy-2-phenylpropane-2-d containing 7 per cent of the tritium. Consequently, two side reactions compete with the second order elimination.

Expression for the rate ratio

The following expression for the rate ratio in the elimination reaction can be readily derived from the theory of competitive reactions⁹ to take into account the two side reactions, if it is assumed these reactions have no isotope effect. A correction is included for the deuterium content of the substrate.

$$\frac{k_D}{k_T} = \frac{\log \frac{T_\infty - T}{0.967 T_\infty} - \frac{C_\infty}{C_0} \log \frac{C - C_\infty}{C_0 - C_\infty}}{\log \frac{C - C_\infty}{C_0 - C_\infty} - \frac{C_\infty}{C_0} \log \frac{C - C_\infty}{C_0 - C_\infty}}$$

Where T is the titre and C the radioactivity count at time t and the subscripts $_0$ and $_\infty$ refer to measurements made at the start and end of the reactions.

Tabulation of results

At 45°									
Time (sec)	960	2100	3240	4620	6300	8340	11040	14820	21300
%, Reaction of D compound	12.3	24.2	34.1	43.2	53.0	62.4	71.6	81.7	91.7
Max. k_D/k_T value	5.55	3.48	3.22	3.15	2.72	2.61	2.51	2.62	2.53
Calculated k_D/k_T	2.85	2.78	2.81	2.84	2.53	2.45	2.40	2.51	2.43
Min. k_D/k_T value	1.36	2.30	2.47	2.58	2.35	2.33	2.29	2.41	2.34

Because of the decrease through the reaction in the effect of experimental error on the rate ratio, readings for the precise determinations of the rate ratio were only taken after 70–80 per cent reaction of the deuterium compound. The average of a number of such determinations at each temperature gave the following results:

Temperature (°C)	25	45	65
k_D/k_T	2.645 ± 0.05	2.47 ± 0.05	2.32 ± 0.04

A least squares treatment of the 37 individual values obtained at the three temperatures gives the following Arrhenius parameters:

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$\Delta E^* = 679.4$ cal/mole; standard deviation 24.5 cal/mole

$\text{Log } A^*_T/A^*_D = 0.0744$; standard deviation 0.0143

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References

- ¹ J. Bigeleisen, F. S. Klein, R. E. Weston Jr., and M. Wolfsberg. *J. Chem. Phys.* **30**, 1340 (1959).
- ² H. S. Johnston and D. Rapp. *J. Am. Chem. Soc.* **83**, 1 (1961).
- ³ R. P. Bell. *The Proton in Chemistry*, p. 203, Cornell University Press, Ithaca, New York (1959).
- ⁴ V. J. Shiner, Jr. and M. L. Smith. *J. Am. Chem. Soc.* **83**, 593 (1961).
- ⁵ R. P. Bell, J. A. Fendley, and J. R. Hulett. *Proc. Royal Soc.* **235**, 453 (1956).
- ⁶ V. J. Shiner, Jr. *J. Am. Chem. Soc.* **74**, 5285 (1952).
- ⁷ M. L. Smith. *Ph.D. Thesis*, Indiana University (1959).
- ⁸ V. J. Shiner, Jr. and M. L. Smith. *Anal. Chem.* **28**, 1043 (1956).
- ⁹ T. S. Lee. In *Techniques of Organic Chemistry* (Ed. A. Weissburger), 1st ed., vol. 8, p. 108.