Kinetic Isotope Effects and Aliphatic Diazo-compounds. Part III.† Solvent Isotope Effects for 3-Diazobutan-2-one and Ethyl Diazopropionate

By **W. J. Albery** * and **A. N. Campbell-Crawford**, Physical Chemistry Laboratory, Oxford

Data are reported for the isotopic analysis of the products of the acid-catalysed decomposition of 3-diazobutan-2-one and ethyl diazopropionate and for the rate of reaction for both compounds in mixtures of H_2O and D_2O. The kinetic data are analysed to obtain the fractionation factors for the proton transferred to carbon and for the two secondary solvent protons. The fractionation factors from the product analysis agree with the factors for the proton transferred to carbon. A simple analytical correction for the breakdown of the rule of the geometric mean which will hold for most A–S_E2 transition states is presented and applied to the data.

The data for 3-diazobutan-2-one were obtained by the differential method and their higher precision allows the investigation of models other than the simple one for the A–S_E2 transition state and in particular the inclusion of transition-state solvation terms. The results are not completely conclusive but suggest that the simple model is the most probable one. The values of α deduced from the secondary solvent isotope effect do not agree with those from the Brønsted catalysis law.

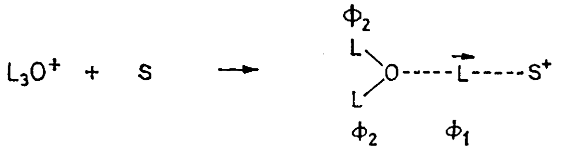
THE study of the variation of reaction rate with x, the atom fraction of deuterium, in mixtures of H_2O and D_2O can give detailed information about the nature of the transition state. The variation is best described by fractionation factor theory.[1,2] For an A–S_E2 reaction the simplest formulation, which we shall call the simple model, of the reaction is shown in Scheme 1, which leads to equation (1). The value of l has been measured

$$\frac{k_x}{k_0} = \frac{(1 - x + \phi_1 x)(1 - x + \phi_2 x)^2}{(1 - x + lx)^3} \qquad (1)$$

to be 0·69.[3-5] Analysis of the variation of (k_x/k_0) with x then allows in theory the determination of ϕ_1 and ϕ_2. In practice one requires very accurate kinetic data to obtain an unambiguous determination of ϕ_1 and ϕ_2 from the kinetics alone. In many reactions the L–S bond once formed in the transition state does not further exchange and so ϕ_1 can often be measured from the isotopic content[2] of the product measured as ϕ_P [equation (2)]. A recent paper[6] reviews values

$$\phi_P = \frac{[DS]}{[HS]}\left(\frac{1 - x}{x}\right) \qquad (2)$$

of ϕ_1 and ϕ_2 measured by these methods. For the acid-catalysed decomposition of $N_2{\cdot}CMe{\cdot}COMe$ and $N_2{\cdot}CMe{\cdot}CO_2Et$ we have succeeded in measuring the kinetic ratios accurately enough to determine ϕ_1 and ϕ_2 from equation (1); we have also measured ϕ_P from equation (2). The differential method[7,8] was used for the diazo-ketone but not for the diazo-ester where the reaction rates were too fast.



SCHEME 1

EXPERIMENTAL

Materials and Solutions.—Most chemicals have been described.[9] D_2O was supplied by Norsk Hydro Electrisk and was stated to contain 99·7 g of D_2O per 100 g of liquid. The H content of the D_2O was measured by examining the ^1H n.m.r. spectrum of a sample of the D_2O with a small quantity of MeOH (*ca.* 0·03 g in 5 g of D_2O) as an internal standard. Typical values of 99·65 g and 99·66 g of D_2O per 100 g were obtained which agreed well with the manufacturers' figure. Acid solutions for kinetic experiments were made up by weight from a stock solution of 0·10M-$HClO_4$ and H_2O or D_2O. For ethyl diazopropionate $[L_3O^+]$ was throughout 1·00 mM. For 3-diazobutan-2-one, to obtain the full benefit of the differential method two stock acid solutions were made up in H_2O and D_2O with $[H_3O^+] = 2$ mM and with $[D_3O^+] \simeq 5$ mM $\simeq 2{\cdot}5[H_3O^+]$; reaction solutions were mixtures of these H_3O^+ and D_3O^+ solutions. The factor of 2·5 offset the isotope effect so that the actual rate of reaction in the H_2O–D_2O mixture was always close to the rate in the pure H_2O with which it was being compared.

Kinetic Measurements.—The apparatus and technique, both single[9] and differential,[8] were as described. In the differential runs twice as much of the diazo-ketone was added to the pure H_2O solution.

Isotopic Analysis of Products.—The isotopic analysis was carried out by ^1H n.m.r. on the major product, $LO{\cdot}CL{\cdot}Me{\cdot}COR$ where R is Me or OEt. 10 ml of H_2O–D_2O mixture containing *ca.* 5 mM-L_3O^+ were made up by weight.

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† Part II, W. J. Albery, J. S. Curran, and A. N. Campbell-Crawford, preceding paper.

[1] V. Gold, *Trans. Faraday Soc.*, 1960, **56**, 255.

[2] A. J. Kresge, *Pure Appl. Chem.*, 1964, **8**, 243.

[3] V. Gold, *Proc. Chem. Soc.*, 1963, 141.

[4] A. L. Allred and A. J. Kresge, *J. Amer. Chem. Soc.*, 1963, **85**, 1541.

[5] K. Heinzinger and R. E. Weston, *J. Phys. Chem.*, 1964, **68**, 744.

[6] R. A. More O'Ferrall, G. W. Koeppl, and A. J. Kresge, *J. Amer. Chem. Soc.*, 1971, **93**, 9.

[7] W. J. Albery and B. H. Robinson, *Trans. Faraday Soc.*, 1969, **65**, 980.

[8] W. J. Albery and M. H. Davies, *Trans. Faraday Soc.*, 1969, **65**, 1066.

[9] W. J. Albery, A. N. Campbell-Crawford, and K. S. Hobbs, *J.C.S. Perkin II*, 1972, 2180.

Diazo-compound (1·5 ml) was added gradually dropwise during 2—3 h; the slow addition kept the concentration of diazo-compound low throughout the decomposition. Evolution of N_2 ceased after 4—6 h. In the case of 3-diazobutan-2-one, the acetoin was extracted into ether by continuous liquid extraction. After being dried (Na_2SO_4) and the ether having being distilled off on a water-bath, the acetoin [HOCLMeCOMe] was distilled over in a micro-distillation apparatus at 30 °C under a pressure of 14 mmHg. The ^1H n.m.r. spectra were obtained on a Varian A60A instrument at 10 °C. It was necessary to use the lower temperature to separate the CH quartet from the OH resonance. The unsplit CH_3 of the CH_3CO was used as the internal standard. It was necessary to check that enolisation did not exchange either the CL proton or the CH_3 of the internal standard. Over a period of weeks no exchange could be detected in protioacetoin dissolved in 10^{-2}M-D_3O^+ in D_2O. In 10^{-1}M-D_3O^+ a slight drop was found in the CH_3 signal. This agrees with a half-time[10] of 1·5 days for the CH_3 and 5 days for the CL site in 2M-D_2SO_4. These rates are far too slow to affect our experiments. Concerning ethyl diazopropionate, in the ^1H n.m.r. spectrum of ethyl lactate, LO·CLMe·CO_2Et, the CH_2 signal is inextricably entwined with that from the CL. The product was therefore acetylated by use of the same procedure as previously[8] except that acetyl chloride was used as the acetylating agent. The CL and the CH_2 signals are then well separated. The ^1H n.m.r. spectra were measured on a Perkin-Elmer R12 instrument. To check that no exchange took place, first all-protioethyl lactate was stirred for several hours in 10^{-3}M-D_3O^+ and then acetylated; the ratio of the integrated CH_2 and CL peaks was 2 : 1. Secondly ethyl diazopropionate was decomposed in D_2O; the resulting ethyl acetyl-lactate had less than $\frac{1}{2}$% of CH present. In measuring the ^1H n.m.r. spectra care was taken to avoid integrating spinning side bands and ^{13}C satellites. Multiple (at least 14) upfield and downfield sweeps were carried out.

Solubility Measurements.—The solubility of the diazo-compounds in H_2O–D_2O mixtures was measured by partition between 25 ml of a 1 mM solution of the diazo-compound in CCl_4 and 5 ml of L_2O at pH 10 (to prevent decomposition). After equilibration at 25 °C the optical density of the aqueous phase was measured. Since less than 2% of the diazo-compound dissolved in the aqueous phase and since there was very little change in the solubility the chemical potential of the diazo-compound in the organic phase is the same in each experiment. Hence the ratio of the solubilities is given by the ratio of optical densities.

RESULTS

Differential Runs for 3-*Diazobutan*-2-*one.*—In order to test the differential method and in particular that there was no systematic temperature difference between the two cell compartments, runs were carried out in the same H_3O^+ solution; the only difference between the resulting solutions was that one cell had twice as much diazo-ketone (two drops of 3-diazobutan-2-one solution rather than one). This meant that the acid concentration was *ca* $\frac{1}{2}$% more dilute in the cell with more ketone. Typical results are plotted in Figure (1), according to equation[8] (3), where $k' = k(1 + \delta)$, and $D''_t = D'_t - D_t$, and D'_t and D_t are

$$y = \log\left[\frac{D''_t - D''_\infty}{D_{t+\Delta t} - D_\infty} + \exp(k\Delta t)\right] = \text{constant} - \frac{\delta kt}{2{\cdot}303} \qquad (3)$$

the optical densities at time t measured against a cell containing solvent and $D'_t > D_t$; k' and k are the respective first-order rate constants and Δt is a small constant time interval between the measurement of D''_t in the differential mode and $D_{t+\Delta t}$ in the normal single mode. D_t Was the L_2O solvent and D'_t the pure H_2O. During the run readings are taken alternately of D''_t and $D_{t+\Delta t}$, and these are then paired together. The value of k required to calculate y and δ from δk is found from a normal first-order plot of $\log(D_t - D_\infty)$ against time. The reason D'_0 is made twice D_0 is so that throughout the run $D'' \sim D$; this leads to cancellation in slide-wire errors. The gradient of equation (3) is a direct measure of δk and hence of the small difference between the rate constants. In a blank run $\delta = ca.$ 0·005. Figure 1 also shows another typical run where $\delta = 0{\cdot}132$ in an H_2O–D_2O mixture of $x = 0{\cdot}191$. To calculate k_x/k_0 we write equation (4). The results are in Table 1.

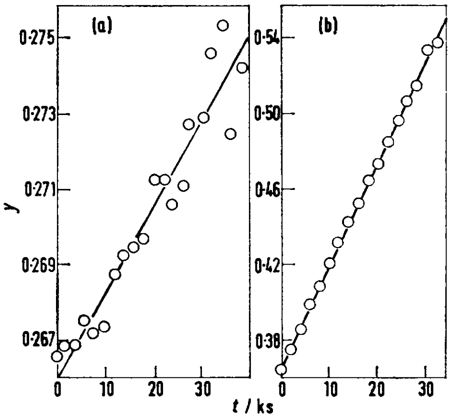

FIGURE 1 Typical results by differential method for 3-diazobutan-2-one plotted by equation (3); (a) blank run with difference *ca.* 0·5%; (b), $x = 0{\cdot}196$ with difference *ca.* 13%

$$\frac{k_x}{k_0} = \frac{[H_3O^+]}{[L_3O^+](1 + \delta)} \qquad (4)$$

Kinetic Results for Ethyl Diazopropionate.—The results for k_x/k_0 are given in Table 2. Each result was the mean of three determinations. The value of k_0 is calculated from all the kinetic data as discussed below.

Isotopic Analysis of the Products.—Results for ϕ_P for both compounds are given in Table 3. The values of $\phi_P{}^*$ have been corrected through equation (5) for the breakdown of the rule of the geometric mean[11] in the solvent and ϕ_P refers to a standard state of $x = 0{\cdot}50$. Since

$$\phi_P = \phi_P{}^*[1{\cdot}00 - 0{\cdot}06(\tfrac{1}{2} - x)] \qquad (5)$$

$\phi_P = ca.$ 0·20 the experiments were carried out for $x > 0{\cdot}50$ so that the D : H ratio in the product was not too small.

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[10] J. W. Marsinon, J. Lubach, and W. Drenth, *Rec. Trav. chim.*, 1969, **88**, 193.

TABLE 1

Differential runs for 3-diazobutan-2-one

x	$[H_3O^+]/[L_3O^+]$	$10^2\delta$	k_x/k_0	Mean	k_x/k_0(Calc.)
0·000	0·993	−0·7 ± 0·2	1·000		0·000
Blank	0·992	−0·8 ± 0·1	1·000		
runs	0·995	−0·1 ± 0·1	0·996	0·999	1·00
	0·995	−0·9 ± 0·2	1·004	±0·001	
	0·994	−0·3 ± 0·2	0·997		
	0·995	−0·7 ± 0·1	1·002		
0·191	0·810	−13·2 ± 0·1	0·933		
	0·810	−13·5 ± 0·2	0·937	0·935	0·934
	0·810	−13·4 ± 0·2	0·935	±0·001	
0·394	0·677	−19·2 ± 0·2	0·839		
	0·677	−19·3 ± 0·1	0·840	0·839	0·846
0·607	0·577	−21·8 ± 0·2	0·738		
	0·577	−21·0 ± 0·3	0·730	0·735	0·725
	0·577	−21·9 ± 0·2	0·738	±0·002	
0·798	0·510	−13·9 ± 0·3	0·592		
	0·510	−13·8 ± 0·2	0·592	0·592	0·584
0·992	0·456	+15·7 ± 0·2	0·394		
	0·456	+15·8 ± 0·1	0·394	0·394	0·394
	0·456	+15·8 ± 0·2	0·394		

TABLE 2

Solvent isotope effect for ethyl diazopropionate

$k_0 = 19{\cdot}0 \pm 0{\cdot}1$ l mol^{-1} s^{-1}

x	k_x/k_0(obs)	k_x/k_0(calc.
0·000	0·999 ± 0·006	1·000
0·156	0·949 ± 0·009	0·949
0·172	0·948 ± 0·015	0·943
0·304	0·895 ± 0·003	0·890
0·515	0·792 ± 0·010	0·785
0·694	0·660 ± 0·002	0·670
0·897	0·508 ± 0·007	0·498
0·988	0·406 ± 0·003	0·401

TABLE 3

Product fractionation factors

x	CD/CH	ϕ_P
	3-Diazobutan-2-one	
0·525	0·241	0·220
0·527	0·255	0·230
0·629	0·310	0·180
0·754	0·606	0·205
0·817	0·814	0·205
	Mean	0·208 ± 0·008
	Ethyl diazopropionate	
0·513	0·200	0·190
0·705	0·479	0·222
0·800	0·785	0·200
	Mean	0·204 ± 0·009

TABLE 4

Solubility ratios

x	Solubility in L_2O / Solubility in H_2O
3-Diazobutan-2-one	
0·45	$1{\cdot}00_0$
	$0{\cdot}99_3$
0·90	$0{\cdot}98_3$
	$0{\cdot}97_3$
Ethyl diazopropionate	
0·99	$0{\cdot}97_7$
0·99	$0{\cdot}98_3$
	$0{\cdot}98_6$

Solubility Measurements.—The ratios of the solubility of 3-diazobutan-2-one and ethyl diazopropionate in L_2O compared to H_2O are given in Table 4.

DISCUSSION

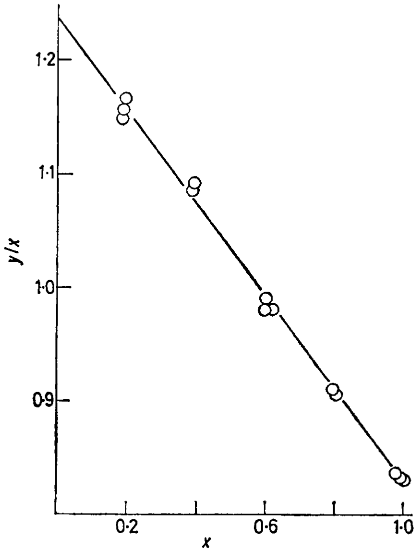

FIGURE 2 Plot of y/x against x from equation (6) for 3-diazobutan-2-one

We first analyse the data in Tables 1 and 2 according to equation (1). The solubility experiments suggest that we can ignore any reactant fractionation factors describing the solvation of the diazo-compound; to a first approximation they may cancel with those in the transition state. Equation (1) is rearranged to give (6) where $\theta_n = 1 - \phi_n$. On the left-hand side the

$$y = 1 - k_x/k_0(1 - x + lx)^3 - \theta_1\theta_2{}^2x^3 = (\theta_1 + 2\theta_2)x - \theta_2(2\theta_1 + \theta_2)x^2 \qquad (6)$$

$\theta_1\theta_2{}^2x^3$ term is small since even at $x = 1$, $\theta_1\theta_2{}^2$/R.H.S. = *ca.* 0·04 for $\theta_1 = 0{\cdot}80$ and $\theta_2 = 0{\cdot}20$. Thus this term is allowed for by successive iteration in the values of y until the values of θ_1 and θ_2 converge to within ½%. If one divides equation (6) by x one can obtain a linear plot[11] of y/x against x. Figure 2 shows the data for 3-diazobutan-2-one plotted in this way. However, we now think that this procedure gives too much weight to the rather uncertain points when both the left-hand side of equation (6) and x tend to zero. We have therefore found values of a and b which minimise the square of the deviations in equation (7). We

$$y = ax + bx^2 \qquad (7)$$

then solve the quadratic equations for θ_1 and θ_2 taking

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[11] W. J. Albery, *Progr. Reaction Kinetics*, 1967, **4**, 353.

the roots for which $\theta_1 \geqslant \theta_2$ as in equation (8) and (9).

$$\theta_1 = \tfrac{1}{3}[a + 2(a^2 + 3b)^{\frac{1}{2}}] \qquad (8)$$

$$\theta_2 = \tfrac{1}{3}[a - (a^2 + 3b)^{\frac{1}{2}}] \qquad (9)$$

We have also worked out the standard errors on the values of θ according to equation (10), where d_i is the

$$E_{\theta_m} = \sqrt{\left(\frac{\sum_1^n d_i^2}{(n-2)}\right)}\sqrt{\left[\sum_1^n\left(\frac{\partial\theta_m}{\partial y_i}\right)^2\right]} \qquad (10)$$

difference for the ith run between y_{obs} and y_{calc}. The algebraic equations are given in Appendix 1.

For ethyl diazopropionate we have used a similar treatment; it is more complicated, since the raw data do not consist of rate ratios from the differential method, but they are single rate constants as a function of x. Most previous treatments of solvent isotope data take as knowns the values of k at $x = 0$ and in many cases the value of k at $x = 1$ as well. Gold has discussed the validity of this procedure [12] and we prefer to give equal weight to all our runs. Hence from equation (6) we write (11), and y is fitted to equation (12) by iterating

$$y = k_x(1 - x + lx)^3 + k_0\theta_1\theta_2^2x^3 = k_0[1 - (\theta_1 + 2\theta_2)x + \theta_2(2\theta_1 + \theta_2)x^2] \qquad (11)$$

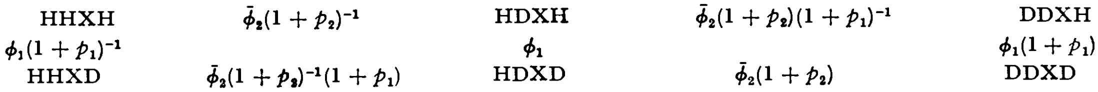
$$y = a' + b'x + c'x^2 \qquad (12)$$

for the small term in y till k_0, θ_1, and θ_2 converge to within $\frac{1}{2}\%$. The equations are given in Appendix 2.* Values for the fractionation factors and their standard errors calculated from equation (6) and (11) are given in Table 6. These are the simple equations which are usually adequate to describe A–S_E2 reactions, but owing to the precision of our data we must discuss two further corrections. The first of these is the breakdown of the rule of the geometric mean. We have suggested a simple analytical correction [equation (13)] [12] which is accurate to within two parts in a thousand. $g(x)$ Is given by equation (14), and p_1 and p_2 describe the

$$\frac{k_x}{k_0} = \frac{(1 - x + \phi_1x)(1 - x + \phi_2x)^2}{(1 - x + lx)^3}[1 + g(x)] \qquad (13)$$

$$g(x) = x(1 - x)\left[3p_3 - 2p_2 - p_1\left\{\frac{\phi_1\phi_2^{-1}(1 - x) + \phi_2x}{(1 - x + \phi_2x)}\right\}\right]; \qquad (14)$$

breakdown for the transition state and p_3 the breakdown in the reactant L_3O^+. The factors for the transition state are shown in Scheme 2. L_3O^+ is a special case of this Scheme with $p_1 = p_2$ and $\phi_1 = \phi_2 = l$.



SCHEME 2

In our treatment we did not know the values of p_1, p_2, or p_3 although we suggested that p_1 would be small for symmetrical and product-like transition states and that p_2 would lie between p_3 and 0·03. More O'Ferrall, Koeppl, and Kresge[6] have recently attempted to calculate these quantities. Their scheme of fractionation factors is identical with ours but they express it in the different notation of equations (15) and (16).

$$p_3 - p_1 = \tfrac{1}{2}(1 - R_1) \qquad (15)$$

$$p_3 - p_2 = \tfrac{1}{4}(1 - R_1) - \tfrac{1}{2}(1 - R_2) \qquad (16)$$

From their calculated values of R_1 and R_2 and of $p_3 = 0{\cdot}03$ we can obtain values of our parameters and thus combine their calculations with our simple analytical expression.

In fact in equation (14), since p_1 is small for symmetrical and product-like transition states ($\alpha > 0{\cdot}3$) we can write equation (17) with a maximum error of less than one part in a thousand:

$$1 + g(x) = 1 + Px(1 - x) \qquad (17)$$

where $P = (1 - R_1) - (1 - R_2) = 3p_3 - 2p_2 - p_1 \simeq p_3 = 0{\cdot}03$. Table 5 shows values of $[(1 - R_1) - (1 - R_2)]$ and for these transition states ($\alpha > 0{\cdot}3$), $P \simeq 0{\cdot}03$. We can reach the same conclusion more directly by following our original arguments; we put $p_3 = 0{\cdot}03$, p_2 between 0·03 and p_3, and $p_1 = 0{\cdot}0$. Therefore to allow for a correction for the breakdown of the rule of the geometric mean we multiply the observed k_x/k_0 or k_x by $[1 - 0{\cdot}03x(1 - x)]$. This correction should hold for most A–S_E2 transition states.

TABLE 5

Correction function for breakdown of rule of geometric mean from data in ref. 6

Bond order	0	0·125	0·25	0·375	0·5	0·625	0·75	0·875	1·0
10^2P	0	0·2	1·7	3·6	3·3	3·2	3·3	3·1	3·0

The second correction that we have to allow for in the particular case of the diazo-compounds is the interference from the second transition state.[13] The full expression for the rate constant [13] is (18) or (19) where ϕ_S describes the possible fractionation [14] in the second

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* Copies of computer programmes written in Fortran which perform these calculations may be obtained from the authors.

[12] V. Gold, *Adv. Phys. Org. Chem.*, 1969, **7**, 259.

[13] W. J. Albery, J. S. Curran, and A. N. Campbell-Crawford, preceding paper.

[14] W. J. Albery and M. H. Davies, *Trans. Faraday Soc.*, 1967, 1059.

transition state. In fact it makes very little difference to the final results whether we put $\phi_S = 1{\cdot}0$ or $0{\cdot}88$. Again the correction is applied by multiplying k_x/k_0 or k_x by the square bracket of equation (19).

$$k_{\text{obs}} = \frac{k_{\text{L}^+}}{1 + k'_{\text{L}_2\text{O}}/k_{2,\text{L}}} \qquad (18)$$

$$k_{\text{L}^+} = k_{\text{obs},x}\left[1 + \frac{k'_{\text{H}_2\text{O}}}{k_{2,\text{H}}}\,\frac{(1 - x + \phi_1 x)(1 - x + \phi_2 x)^2}{(1 - x + \phi_S x)^2}\right]$$

$$\simeq k_{\text{obs},x}\left[1 + \frac{k'_{\text{H}_2\text{O}}}{k_{2,\text{H}}}\,\frac{k_{\text{obs},x}}{k_{\text{obs},0}}\,\frac{(1 - x + lx)^3}{(1 - x + \phi_S x)^2}\right] \qquad (19)$$

The effects of these corrections and of performing the calculation with a different value of $l = 0{\cdot}70$ are shown in Table 6. Tables 1 and 2 compare observed and calculated data for the asterisked row in Table 6.

TABLE 6

Fractionation factors

P	l	$k'_{\text{H}_2\text{O}}/k_{\text{H}}$	$10^3\phi_1$	$10^3\phi_2$	α_{L^+}	$10^3\sigma$
			3-Diazobutan-2-one			
0·00	0·69	0·000	210 ± 3	778 ± 4	$0{\cdot}32 \pm 0{\cdot}01_4$	1·7
	0·69	0·009	211 ± 3	774 ± 4	$0{\cdot}31 \pm 0{\cdot}01_4$	1·7
	0·70	0·009	213 ± 3	789 ± 4	$0{\cdot}33 \pm 0{\cdot}01_5$	1·7
0·03	0·69	0·000	219 ± 4	765 ± 5	$0{\cdot}28 \pm 0{\cdot}01_8$	2·0
	0·69	0·009	219 ± 4	762 ± 5	$0{\cdot}27 \pm 0{\cdot}01_6$	2·0 *
	0·70	0·009	220 ± 4	777 ± 5	$0{\cdot}29 \pm 0{\cdot}01_7$	2·0
Product analysis 208 ± 8						
			Ethyl diazopropionate			
0·00	0·69	0·000	208 ± 9	785 ± 12	0·35 ± 0·04	2·6
	0·69	0·010	209 ± 9	780 ± 12	0·33 ± 0·04	2·6
	0·70	0·010	211 ± 9	795 ± 13	0·36 ± 0·04	2·6
0·03	0·69	0·000	216 ± 9	772 ± 12	0·30 ± 0·04	2·6
	0·69	0·010	217 ± 9	768 ± 12	0·29 ± 0·04	2·6 *
	0·70	0·010	218 ± 9	782 ± 12	0·32 ± 0·04	2·6
Product analysis 204 ± 9						

* Used to calculate results in Tables 1 and 2.

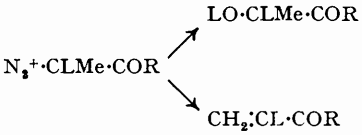
The values of α_{L^+} in Table 6 are calculated from the relationship (20) suggested by Gold.[1] In order to allow a comparison to be made with the other results in the compilation of More O'Ferrall *et al.*[6] we have also calculated their parameter as given in equation (21).

$$\phi_2 = l^{1-\alpha_{\text{L}^+}} \qquad (20)$$

$$\sigma = \left\{\sum_{1}^{n}\,[(k_x/k_0)_{\text{obs}} - (k_x/k_0)_{\text{calc}}]^2/n(n-1)\right\}^{\frac{1}{2}} \qquad (21)$$

The value of σ for ethyl diazopropionate is similar to the better values in the compilation while that for 3-diazobutan-2-one is significantly lower. The standard errors, arising from the experimental scatter of the data, on the fractionation factors and values of α from 13 differential experiments for diazo-ketone are also lower than those from 26 single experiments for the diazo-ester. Kresge[2] and Gold[12,15] have rightly emphasised the difficulty of determining fractionation factors from kinetic data. We believe that this work demonstrates the advantage of using the differential method to increase the precision of the kinetic data. For ethyl diazopropionate the difference in the fractionation factors caused by including the correction for the breakdown of the rule of the geometric mean or by changing the value of l are comparable with the uncertainty from the scatter of the experimental data. However for 3-diazobutan-2-one the uncertainty is caused first by the correction for the rule of the geometric mean, secondly by the uncertainty in l, and only thirdly by the experimental scatter. The correction for the second transition state is rather unimportant and is less than the experimental scatter. The inclusion of the correction for the geometric mean gives a less good fit and a value of ϕ_1 which is further from that found by product analysis; these differences however are not very significant. The rather reactant-like transition state may mean that the correction has been overestimated and there must still be some doubt as to the exact value of ϕ_3.

We now turn to the values for ϕ_1. A complication in the determination of ϕ_1 from the products is that in these reactions two products are formed,[9,16] as shown in Scheme 3. Our analysis has been confined to the major product, the hydroxy-compound. If there should be a large secondary isotope effect on the product-determining step then the D : H ratio in the intermediate would not be the same as that in either product. The correct expression is (22) where ρ_{L} is given by (23).



SCHEME 3

$$\frac{[\text{N}_2{}^+\text{CD}]}{[\text{N}_2{}^+\text{CH}]} = \frac{[\text{LOCD}]}{[\text{LOCH}]} \times \frac{(1 + \rho_{\text{D}})}{(1 + \rho_{\text{H}})} \qquad (22)$$

$$\rho_{\text{L}} = \frac{[\text{CH}_2\text{:CL}]}{[\text{LOCL}]} \qquad (23)$$

We have measured ρ_{L} to be $0{\cdot}33 \pm 0{\cdot}05$ for both H and D; hence the correcting ratio is likely to be negligible and can at worse only be a few percent.

In Table 6 the values of ϕ_1 for both compounds obtained from the independent sets of kinetic and product experiments are in good agreement. This

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[15] V. Gold and D. C. A. Waterman, *J. Chem. Soc.* (*B*), 1968, 839.

[16] H. Dahn and M. Ballenegger, *Helv. Chim. Acta*, 1969, **52**, 2417.

agreement as in previous work [15,17,18] is consistent with the simple model of the A–S_E2 transition state, but it is possible that it is fortuitous; other models with or without extra fractionation factors could fit the data just as well. In view of the greater precision of our data for 3-diazobutan-2-one it is worth exploring this point in more detail.

Instead of fitting the data to the simple model we write equation (24) where $n_3 > n_2$. The left-hand side

$$\begin{aligned} y_x &= (1 - x + \phi_P x)(1 - x + lx)^3[1 - Px(1 - x)]k_x/k_0 \\ &= (1 - x + \phi_2 x)^{n_2}(1 - x + \phi_3)^{n_3} \qquad (24) \end{aligned}$$

contains the L_3O^+ fractionation, the term for the proton transferred to carbon, and the geometric mean correction; k_x has also been corrected for the second transition state. The remaining part of the isotope effect on the right-hand side is attributed to two as yet unspecified groups of factors. Following the procedure suggested in a recent paper [19] we fit y to an equation of the form (25) and calculate the normalised curvature

$$y_x - 1 = a''x + b''x^2 \qquad (25)$$

parameter (26). For $P = 0$, $\gamma = 0{\cdot}51 \pm 0{\cdot}13$ and

$$\begin{aligned} \gamma &= 4y_{\frac{1}{2}}(1 + y_1 - 2y_{\frac{1}{2}})/(1 - y_1)^2 \\ &= b''(2 + a'' + \tfrac{1}{2}b'')/(a'' + b'')^2 \qquad (26) \end{aligned}$$

for $P = 0{\cdot}03$, $\gamma = 0{\cdot}75 \pm 0{\cdot}13$. The parameter γ describes how curved is the residual fractionation function containing ϕ_2 and ϕ_3. For a straight line $\gamma = 0$, for a perfect square $\gamma = 0{\cdot}5$, and for a ln curve $\gamma = 1{\cdot}0$. The results are shown in Figures 3 and 4 which show γ as a function of ξ_3 (or ξ_2) where we have equations (27)

$$\xi_2 + \xi_3 = 1 \qquad (27)$$

$$\begin{aligned} \xi_m &= n_m \frac{(\phi_m - 1)}{(\phi_m + 1)} \; \frac{(2 + a'' + \frac{1}{2}b'')}{(a'' + b'')} \\ &\simeq n_m(1 - \phi_m)/(1 - y_1) \qquad (28) \end{aligned}$$

and (28). Figure 3 is for $P = 0$, that is, no geometric mean correction, and Figure 4 for $P = 0{\cdot}03$.

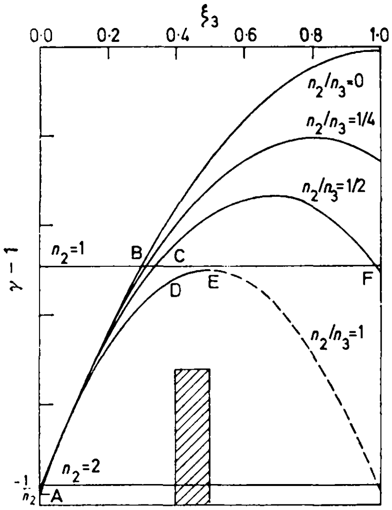

FIGURE 3 Plots of $\gamma - 1$ to find possible models for transition states with no correction for breakdown of the rate of the geometric mean. Horizontal solid lines represent $\gamma - 1$ from data and equation (26) for different values of n_2. Parabolas represent $\gamma - 1$ as a function of ξ_3 for different values of n_2/n_3; ξ_3 is defined by equation (28). Shaded rectangle is the area where possible transition states would have to lie if $\phi_2 = l^{1-\alpha_B}$

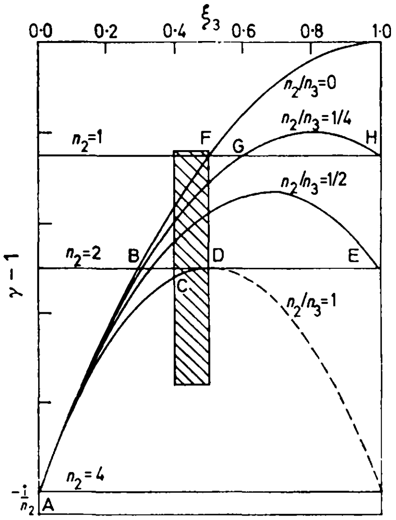

FIGURE 4 Plots of $\gamma - 1$ to find possible models for transition states with $P = 0{\cdot}03$ correction for breakdown of the rule of the geometric mean

Possible transition states are where the horizontal lines representing the values of γ from the data and equation (26) intersect the parabolas; each parabola corresponds to a particular ratio $n_2 : n_3$ (which is <1). In particular the parabola for which $n_3 \longrightarrow \infty$ ($n_2/n_3 = 0$) represents a contribution from a generalised medium effect on either the reactants or the transition state.[19] The scale on the y axis is in units of n_2^{-1} so there is a horizontal line for γ for each value of n_2; hence the intersection of each line and each parabola defines the values of n_2 and n_3. The fractionation factors are given from the value of ξ_3 by equations (27) and (28). It is likely that the factors are less than unity so the area of possible solutions is bounded by $\xi_3 = 0$ (or $\xi_2 = 1$) and $\xi_3 = 1$ (or $\xi_2 = 0$).

The error on γ is rather large, so our conclusions must be correspondingly tentative. For both values of P it appears that $n_1 \leqslant 4$; the point $\xi_3 = 1$, $\gamma - 1 = 0$, which would ascribe the whole of the effect to a generalised medium effort, is an improbable solution. The characteristics of different transition states are given

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[17] V. Gold and M. A. Kessick, *J. Chem. Soc.*, 1965, 6718.

[18] M. M. Kreevoy, P. J. Steinwand, and W. V. Kayser, *J. Amer. Chem. Soc.*, 1966, **88**, 124.

[19] W. J. Albery and M. H. Davies, *J.C.S. Faraday I*, 1972, 167.

in Table 7. C in Figure 3 is interesting since it is a possible alternative model to the simple one shown in structure (I). However, a value of ϕ_2 as large as 0·72

TABLE 7

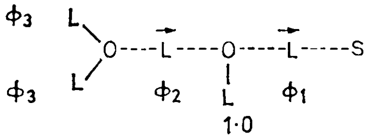
Possible transition states from Figures 3 and 4

Figure 3

	n_2	ϕ_2	n_3	ϕ_3	$\phi_3^{n_3}$	Comments
A	2	0·78	?		1·00	Simple transition state
B	1	0·69	4 to ∞		0·88	Single factor of 0·69 unlikely
C	1	0·72	2	0·92		Improbable, see text.
D	1	0·74	1	0·82		Two unequal single factors are improbable.
E	1	0·78	1	0·78		Simple transition state.
F	1	1·00	2	0·78		Simple transition state.

Figure 4

	n_2	ϕ_2	n_3	ϕ_3	$\phi_3^{n_3}$	Comments
A	4	0·88	?		1·00	4 such factors are improbable.
B	2	0·83	4 to ∞		0·88	Simple transition state + solvation.
C	2	0·86	2	0·90		Second pair unlikely.
D	2	0·88	2	0·88		See A
E	2	1·00	4	0·88		See A
F	1	0·76	∞		0·78	Single factor unlikely and too large a medium effect.
G	1	0·84	4	0·92		All factors somewhat improbable.
H	1	1·00	4	0·88		See A.



(I)

suggests that this proton is in fact bound to the second oxygen, in which case this model reverts to the simple one. The two non-transferring protons on the second oxygen could only have different factors if the energy redistribution was slow compared with the second proton transfer. Such effects are possible in low-pressure gas reactions but are unlikely in solution and in particular in this case if the ϕ_1 proton has time to receive energy from the ϕ_2 proton then so does the third proton.

The argument for the simple model for the A–S_E2 transition state has hitherto rested uncomfortably on Ockham's razor. This analysis does suggest that the most probable models are indeed A, E, or F, the simple transition state, in Figure 3 or B in Figure 4. The solvation factors for the transition state in B, $\Pi\phi_3 = 0{\cdot}88$, are about as large as one would expect remembering that the solubility of 3-diazobutan-2-one does not vary greatly between H_2O and D_2O and that the reaction only involves cations and neutral species.[12] These solvation factors are nearly unity if, instead of taking the most probable value of $\phi_P = 0{\cdot}208$, one takes a value one standard deviation away from the mean $\phi_P = 0{\cdot}216$.

In Table 8 we have collected values of α_{L^+} to compare them with α_B, the Brønsted α for carboxylic acids. We also include Kreevoy and Konasevich's similar data for diazoacetate anion.[20-22] The first thing to note is how the inclusion of $\Pi\phi_3 = 0{\cdot}88$ has a drastic effect on α_{L^+}. Depending on their temperaments previous workers have either despaired[20] or have assumed optimistically that $\Pi\phi_3 = 1{\cdot}00$.[15,17,18,21] We have tried in our analysis to show how one might obtain some information about $\Pi\phi_3$. We cannot yet claim to have been completely successful. To match the improved precision of the kinetic data we now need more precise values for ϕ_P, l, and, most important, direct experimental confirmation of the theoretical value of p_3.

TABLE 8

Values of α, from this work if no reference given

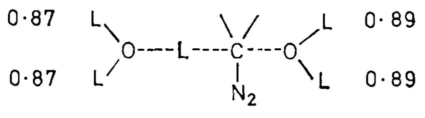
	P	$\Pi\phi_3$	α_{L^+} from equation (20)	Ref.	α_B for RCO_2H	Ref.
$N_2CHCO_2^-$		1·00	0·30 ± 0·10*	19	0·51 ± 0·03	22
3-Diazobutan-2-one	0·00	1·00	0·31 ± $0{\cdot}01_4$			
	0·03	1·00	0·27 ± $0{\cdot}01_6$		0·61 ± 0·03	9
	0·03	0·88	0·50 ± 0·02			
Ethyl diazopropionate	0·00	1·00	0·35 ± 0·04		0·59 ± 0·04	9
	0·03	1·00	0·30 ± 0·04			

* Standard error estimated from errors quoted, 4·2 ± 0·10 being taken for product analysis.

Table 8 shows that the values of α_{L^+} are less than the values for α_B. We have shown this for 3-diazobutan-2-one in another way by plotting in Figure 3, the shaded rectangles in which the transition states would have to lie if $n_2 = 2$ and equation (29) holds for a range

$$\phi_2 = l^{1-(0{\cdot}61 \pm 0{\cdot}03)} \qquad (29)$$

of γ within one standard deviation of the mean. No models can be found in Figure 3. In Figure 4 models with $n_3 > 4$ represent a solvation contribution of $\Pi\phi^{\ddagger}_{i} = 0{\cdot}77$; this seems to us implausibly large. We did consider transition state C and whether it might be structure (II), but this is unlikely in view of the analysis



(II)

in Part II,[13] in which the carbon–nitrogen bond is broken in a second separate transition state.

Thus we believe that we have shown that α_{L^+} is significantly less than α_B even when one allows a reasonable amount of solvation fractionation in the transition

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[20] E. A. Halevi, Solvent Isotope Effects, 22nd Farkas Memorial Symposium, 1970, to be published.

[21] M. M. Kreevoy and D. E. Konasewich, *J. Phys. Chem.*, 1970, **74**, 4464.

[22] M. M. Kreevoy and D. E. Konasewich, *Adv. Chem. Phys.*, 1971, **21**, 243.

state. This is experimental confirmation of an earlier warning [11] of the dangers of calculating ϕ_2 from equation (20) and α_B. This point is further discussed in Part V, and the reasons for the differences in α are discussed in Part VI.

APPENDIX 1

This contains the equations for working out the values and standard errors of θ_1 and θ_2 from a set of n values of y and x in equations (6) and (7). In equation (7), a and b are given by (30) and (31) where $X = (\Sigma x^3)^2 - \Sigma x^4 \Sigma x^2$;

$$a = X^{-1}(\Sigma x^3 \Sigma x^2 y - \Sigma x^4 \Sigma xy) \quad (30)$$

$$b = X^{-1}(\Sigma x^3 \Sigma xy - \Sigma x^2 \Sigma x^2 y) \quad (31)$$

θ_1 and θ_2 can then be worked out from equation (8).

To work out the errors we need the functions (32)—(36) from which we obtain equation (37), components of which are given by equations (38)—42).

$$\Sigma d_i^2 = a^2 \Sigma x^2 + 2ab\Sigma x^3 + b^2 \Sigma x^4 - 2a\Sigma xy - 2b\Sigma x^2 y + \Sigma y^2 \quad (32)$$

$$E_y^2 = \Sigma d^2/(n - 2) \quad (33)$$

$$E_a^2 = E_y^2(\Sigma x^4/X) \quad (34)$$

$$E_b^2 = E_y^2(\Sigma x^2/X) \quad (35)$$

$$E_{ab} = E_y^2(\Sigma x^3/X) \quad (36)$$

$$E_{\theta_n}^2 = Z_{a.n}^2 E_a^2 + 2Z_{a.n} Z_{b.n} E_{ab} + 2_{b.n}^2 E_b^2 \quad (37)$$

$$Z_{a.1} = \tfrac{1}{3}(1 + 2a/r) \quad (38)$$

$$Z_{a.2} = \tfrac{1}{3}(1 - a/r) \quad (39)$$

$$Z_{b.1} = 1/r \quad (40)$$

$$Z_{b.2} = -1/2r \quad (42)$$

$$r = \sqrt{(a^2 + 3b)} \quad (42)$$

APPENDIX 2

This contains the equations for working out the values and standard errors of k_0, θ_1, and θ_2 from a set of n values of y and x in equations (11) and (12). In equation (12) we have the relationships (43)—(46). In equation (8)

$$c' = X^{-1} \begin{vmatrix} \Sigma y & \Sigma xy & \Sigma x^2 y \\ \Sigma x & \Sigma x^2 & \Sigma x^3 \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^4 \end{vmatrix} \quad (43)$$

$$a' = X^{-1} \begin{vmatrix} \Sigma y & \Sigma xy & \Sigma x^2 y \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^4 \\ n & \Sigma x & \Sigma x^2 \end{vmatrix} \quad (44)$$

$$b' = X^{-1} \begin{vmatrix} \Sigma y & \Sigma xy & \Sigma x^2 y \\ n & \Sigma x & \Sigma x^2 \\ \Sigma x & \Sigma x^2 & \Sigma x^3 \end{vmatrix} \quad (45)$$

$$X = \begin{vmatrix} n & \Sigma x & \Sigma x^2 \\ \Sigma x & \Sigma x^2 & \Sigma x^3 \\ \Sigma x^2 & \Sigma x^3 & \Sigma x^4 \end{vmatrix} \quad (46)$$

$a = -b'/a'$ and $b = -c'/a'$; hence values of θ_1 and θ_2 can be found.

For the errors we need the functions (47) and (48)—(54), from which we obtain equation (55), where $Z_{a.n}$ and $Z_{b.n}$ have the same values as in Appendix 1, and relations (56) and (57) apply.

$$\Sigma d^2 = n(c')^2 + 2b'c'\Sigma x + [(a')^2 + 2b'c']\Sigma x^2 + 2a'b'\Sigma x^3 + (b')^2 \Sigma x^4 - 2c'\Sigma y - 2a'\Sigma xy - 2b'\Sigma x^2 y + \Sigma y^2 \quad (47)$$

$$E_y^2 = \Sigma d^2/(n - 3) \quad (48)$$

$$E_{c'}^2 = E_y^2 X^{-1}[\Sigma x^2 \Sigma x^4 - (\Sigma x^3)^2] \quad (49)$$

$$E_{a'}^2 = E_y^2 X^{-1}[n\Sigma x^4 - (\Sigma x^2)^2] \quad (50)$$

$$E_{b'}^2 = E_y^2 X^{-1}[n\Sigma x^2 - (\Sigma x)^2] \quad (51)$$

$$E_{c'a'} = E_y^2 X^{-1}[\Sigma x^3 \Sigma x^2 - \Sigma x \Sigma x^4] \quad (52)$$

$$E_{a'b'} = E_y^2 X^{-1}[\Sigma x^2 \Sigma x - n\Sigma x^3] \quad (53)$$

$$E_{c'b'} = E_y^2 X^{-1}[\Sigma x \Sigma x^3 - (\Sigma x^2)^2] \quad (54)$$

$$E_{\theta_n}^2 = c'^{-2}[Z_{a.n}^2 E_{a'}^2 + Z_{b.n}^2 E_{b'}^2 + Z_{c.n}^2 E_{c'}^2 + 2Z_{a.n} Z_{b.n} E_{a'b'} + 2Z_{a.n} Z_{c.n} E_{c'a'} + 2Z_{b.n} Z_{c.n} E_{c'b'}] \quad (55)$$

$$Z_{c.1} = \theta_1 - b/r \quad (56)$$

$$Z_{c.2} = \theta_2 + \tfrac{1}{2}b/r \quad (57)$$

[2/448 *Received, 28th February, 1972*]