Kinetics of Proton and Deuteron Transfer Reactions of 4-Nitrophenylnitromethane with Triethylamine and Tri-n-butylamine in Acetonitrile Solvent

BY E. F. CALDIN,* A. JARCZEWSKI † AND K. T. LEFFEK ‡

Received 8*th June*, 1970

The second-order rate constants for the proton and deuteron transfer reactions between 4-nitrophenylnitromethane and the organic bases triethylamine and tri-n-butylamine have been determined at eight different temperatures between 0 and 35°C, using the stopped-flow technique. The four reactions are characterized by low enthalpies of activation and large negative entropies of activation. The isotope effects give values for $(\Delta D_{\mathrm{D}}^{\ddagger}-\Delta H_{\mathrm{H}}^{\ddagger})$ of 1.02 and 0.74 kcal mol^{-1} and $(\Delta S_{\mathrm{D}}^{\ddagger}-\Delta S_{\mathrm{H}}^{\ddagger})$ of 1.2 and 0.9 cal mol^{-1} K^{-1} for triethylamine and tri-n-butylamine respectively. The rate ratios are small for primary deuterium effects; $k_{\mathrm{H}}/k_{\mathrm{D}}$ for Et_3N at 0°C is 3.56 and for n-Bu_3N at 0°C is 2.41. These reaction constants are used to elucidate the type of energy barrier involved in the reaction and the nature of the transition state.

The reaction of 4-nitrophenylnitromethane with the strong organic bases triethylamine and tri-n-butylamine in acetonitrile gives a reddish-brown solution. Proton magnetic resonance and visible-spectroscopic measurements indicate that this reaction is a reversible proton transfer whose product is a coloured ion-pair:

$$NO_2C_6H_4CH_2NO_2+R_3N\rightleftharpoons[NO_2C_6H_4CHNO_2]^-H\overset{+}{N}R_3. \qquad (1)$$

Since the anion absorbs strongly in the region of 490 nm, the kinetic measurements have been made spectrophotometrically, using the stopped-flow technique, over a temperature range 0-35°C.

This reaction was originally chosen for study in the hope that large primary deuterium isotope effects would be found, so that they might be used to investigate the phenomenon of quantum-mechanical tunnelling,[1] as for the reactions of 4-nitrobenzyl cyanide with ethoxide ion.[2] Tri-n-butylamine was chosen in accordance with the suggestion of Lewis [3] that in sterically-hindered proton transfers the steeply-rising repulsion energy contribution might produce an energy-barrier exceptionally favourable to tunnelling. In the event, however, the primary isotope effects have been found to lie within the conventional range, and although the values of $A_{\mathrm{D}}/A_{\mathrm{H}}$ are greater than unity they are not definitely indicative of tunnelling.

EXPERIMENTAL

MATERIALS

4-Nitrophenylmethane was prepared by the method of Cooke and Macbeth [4] (m.p. 88.5-89°C). The silver nitrite was prepared by the method described by Kornblum *et al.*[5]

* University Chemical Laboratory, University of Kent at Canterbury, Canterbury, Kent.

† Chemistry Dept., Dalhousie University, Halifax, Nova Scotia, Canada. Post-doctoral Fellow at Dalhousie 1969-70.

‡ Chemistry Dept., Dalhousie University, Halifax, Nova Scotia, Canada. Leverhulme Visiting Fellow at Kent 1967-68.

Deuteration of the 4-nitrophenylnitromethane was accomplished by dissolving 0.2 g in 20-25 ml of dry diethyl ether, to which was added 5 ml of methanol-d containing about 1×10^{-3} mol of sodium methoxide, followed by 2 ml of deuterium oxide. Neutralization of this mixture was effected, after about $\frac{1}{2}$ h, with a few drops of concentrated deuterium chloride in D_2O. This procedure was carried out in a closed system, the additions being made with syringes to a flask closed with a serum cap. The suspension was evaporated to dryness under vacuum, redissolved in about 3 ml of purified chloroform, filtered through a sintered-glass disc, and then poured into an excess of petroleum ether (b. range 60-80°C) which caused precipitation of the $NO_2C_6H_4CD_2NO_2$. Throughout these manipulations the reaction system remained closed. Four such exchanges yielded deuterated material containing more than 98 % D on the aliphatic carbon atom, as judged from the nuclear magnetic resonance spectrum.

Reagent-grade acetonitrile was purified by the method of O'Donnell *et al.*[6] with sodium carbonate and potassium permanganate. The solvent was always freshly prepared and used within 3 days of the fractional distillation.

Triethylamine was dried for 3 days over sodium hydroxide pellets, filtered and distilled. This material was then fractionally redistilled; b.p. 89.5°C at atmospheric pressure.[7] Tri-n-butylamine was dried overnight with sodium hydroxide pellets, filtered and distilled at atmospheric pressure. It was then dried with Drierite for 3 days and redistilled at reduced pressure; boiling range 91-92°C at 9 mmHg.[7, 8]

KINETIC PROCEDURE

Preliminary rate measurements were made at the University of Kent using a stopped-flow apparatus developed there.[9] All the final results were obtained at Dalhousie University with a Durrum-Gibson spectrophotometer manufactured by the Durrum Instrument Corporation. The flow system was made of Kel-F components and included an optical cell of 2 cm light-pathlength. The traces showing transmittance against time were displayed on a Tektronix 564 storage oscilloscope screen and subsequently photographed with a polaroid camera. The polaroid print was enlarged to about 50 × 40 cm on millimetre graph paper and the rate constant was calculated by the method of Guggenheim.[10] The reaction solutions were kept dilute enough so that the final transmittance at complete reaction was never less than 80 %. The approximation that the transmittance can be used in place of the optical density to calculate the concentration of ion-pair is valid under these conditions. In addition, the concentration of the base was kept always in large excess over that of the acid so that the kinetics were first order. The time-base of the oscilloscope was varied from 2 s to 100 ms to suit the conditions of reaction. Frequently, two different time-bases were used for the same run as a check. The temperature of the optical cell was maintained by means of a Townson and Mercer refrigeration unit which maintained a constant temperature in its bath to ±2°C. Liquid from this bath was pumped through the cooling coil of a second thermostatted bath which was maintained constant to ±0.03°C, and the liquid from this second bath was pumped through the circulating system of the spectrophotometer. A part of this circulating system is a small reservoir in which the drive-syringes of the apparatus are immersed. It is the temperature of this reservoir which is quoted as the reaction temperature.

RESULTS

SPECTROSCOPIC AND EQUILIBRIUM MEASUREMENTS

The n.m.r. spectra of 4-nitrobenzyl cyanide, 4-nitrobenzyl iodide, and 4-nitrophenylnitromethane in acetonitrile were recorded. All three substances showed a singlet, at $\delta = 4.00$, 4.68 and 5.73 p.p.m. respectively; this was assigned to the methylene protons, by comparison with the measurements of Caldin *et al.*[11] and Crampton.[12] In the presence of excess triethylamine (3 : 2 mol ratio), the methylene resonance decreased and a new broad peak appeared at $\delta = 7.0$. Integration of the spectrum gave the number of methylene protons remaining as about 1.2, and the number of protons in the new broad peak as about 0.7. It is concluded that under these conditions an extensive proton-transfer has taken place from the substrate to the amine.

The u.-v.-visible spectrum of a mixture of 4-nitrophenylnitromethane and either triethylamine or tri-n-butylamine in acetonitrile gave a single broad peak with λ_{max} = 490 nm. This wavelength was therefore used for the kinetic absorption measurements.

The nature of the reaction product and the equilibrium constant may be determined by carrying out a series of optical density measurements at constant acid concentration and varying base concentration, as follows. For the equilibrium,

$$\text{acid (A)} + \text{base (B)} \rightleftharpoons \text{ion-pair (I.P.)}, \qquad (2)$$

the equilibrium constant when $[B] \gg [I.P.]$, is given by

$$K = [I.P.]/([A]-[I.P.])\,[B]. \qquad (3)$$

The optical density (O.D.) in a 1-cm spectrophotometric cell is given by

$$\varepsilon_{ip} = (O.D.)/[I.P.]. \qquad (4)$$

Combination of eqn (3) and (4) and rearrangements leads to

$$[A]/O.D. = 1/K\varepsilon_{ip}[B] + 1/\varepsilon_{ip}. \qquad (5)$$

If the product is an ion-pair, a plot of [A]/(O.D.) against 1/[B] will be a straight line with an intercept $1/\varepsilon_{ip}$ and a slope $1/K\varepsilon_{ip}$. A similar treatment assuming that the product consists of separated ions leads to the equation,

$$[A]/O.D. = O.D./K[B]\varepsilon^2 + 1/\varepsilon. \qquad (6)$$

Thus a plot of [A]/(O.D.) against (O.D.)/[B] should be a straight line.

A series of optical density measurements with triethylamine carried out on a Hitachi-Coleman 124 spectrophotometer is plotted in fig. 1. The results obey eqn (5) derived for the ion-pair product, but not eqn (6) derived for separated ions. The equilibrium constant K_{25} at 25° is 137 l. mol^{-1} and the molar absorptivity of the ion-pair ε_{ip} is 10 250 l. mol^{-1} cm^{-1}.

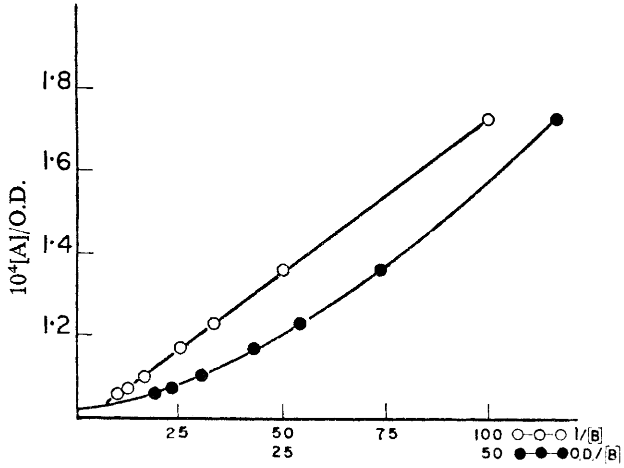

FIG. 1.—Plot of 10^4[A]/(O.D.) against the reciprocal of the base concentration (open circles) and also against (O.D.)/[B] (closed circles).

TABLE 1.—RATE CONSTANTS FOR THE REACTION OF 4-NITROPHENYLNITROMETHANES WITH TRIETHYLAMINE IN ACETONITRILE.

Initial conc. of $4\text{-}NO_2C_6H_4CH_2NO_2$ and of $4\text{-}NO_2C_6H_4CD_2NO_2 = 2\times10^{-5}$ mol $l.^{-1}$; b = initial conc. triethylamine in mol $l.^{-1}$; k_H = observed first-order rate constant for normal substrate, s^{-1}; k_D = observed first-order rate constant for deuterated substrate, s^{-1}.

temp. °C	$10^3 b$	k_H	k_D
0.0	0.5	0.53	0.33
	1.0	0.73	0.39
	1.25	0.81	—
	1.5	0.87	0.42
	2.0	—	0.47
5.0	0.5	0.69	0.42
	1.0	0.82	0.47
	1.25	0.99	—
	1.5	1.17	0.57
	2.0	—	0.60
10.0	0.5	0.86	0.53
	1.0	0.94	0.62
	1.25	1.03	—
	1.5	1.45	0.75
	2.0	—	0.83
15.0	0.5	1.02	0.58
	1.0	1.29	0.75
	1.25	1.36	—
	1.5	2.15	0.94
	2.0	—	1.08
20.0	0.5	1.43	0.83
	1.0	2.04	1.03
	1.25	2.28	—
	1.5	2.61	1.20
	2.0	—	1.41
25.0	0.5	2.09	1.02
	1.0	—	1.33
	1.25	2.33	—
	1.5	3.05	1.48
	2.0	—	1.74
30.0	0.5	2.46	1.40
	1.0	3.01	1.76
	1.25	2.94	—
	1.5	3.56	1.93
	2.0	—	2.22
35.0	0.5	2.90	1.92
	1.0	—	2.15
	1.25	3.59	—
	1.5	4.78	2.34
	2.0	—	2.52

TABLE 2.—RATE CONSTANTS FOR THE REACTION OF 4-NITROPHENYLNITROMETHANES WITH TRI-n-BUTYLAMINE IN ACETONITRILE.

Initial conc. of 4-$NO_2C_6H_4CH_2NO_2$ and of 4-$NO_2C_6H_4CD_2NO_2$ = 2×10^{-5} mol $l.^{-1}$; b = initial conc. of tri-n-butylamine in mol $l.^{-1}$; k_H = observed first-order rate constant for normal substrate, s^{-1}; k_D = observed first-order rate constant for deuterated substrate, s^{-1}.

temp. °C	$10^3 b$	k_H	k_D
0.0	0.1	0.34	—
	0.5	0.49	0.32
	1.0	0.59	0.37
	1.5	0.75	0.42
	2.0	—	0.47
5.0	0.1	0.38	—
	0.5	0.60	0.39
	1.0	0.68	0.47
	1.5	0.90	0.53
	2.0	—	0.58
10.0	0.1	0.47	—
	0.5	0.76	0.47
	1.0	0.86	0.56
	1.5	1.10	0.67
	2.0	—	0.75
15.0	0.1	0.57	—
	0.5	0.94	0.61
	1.0	1.13	0.71
	1.5	1.37	0.84
	2.0	—	0.95
20.0	0.1	0.81	—
	0.5	1.15	0.72
	1.0	1.43	0.89
	1.5	1.77	1.03
	2.0	—	1.19
25.0	0.1	1.03	—
	0.5	1.40	0.97
	1.0	1.70	1.24
	1.5	2.11	1.35
	2.0	—	1.62
30.0	0.1	1.29	—
	0.5	1.78	1.09
	1.0	2.03	1.31
	1.5	2.60	1.59
	2.0	—	1.77
35.0	0.1	1.78	—
	0.5	2.04	1.46
	1.0	2.39	1.60
	1.5	3.11	1.83
	2.0	—	2.11

A rate equation may be derived for the equilibrium shown in eqn (2). If a and b are the initial concentrations of the acid and base respectively, and $(a-x)$ and $(b-x)$ are their concentrations at a time t, then with $b \gg a$ the rate equation is

$$\mathrm{d}x/\mathrm{d}t = k_2 b(a-x) - k_{-2}x, \tag{7}$$

where k_2 and k_{-2} are the rate constants for the forward and backward reactions respectively. At equilibrium,

$$k_2 b(a-x_e) = k_{-2}x_e, \tag{8}$$

where x_e is the equilibrium concentration of the ion-pair. Combination of eqn (7) and (8) and integration yields

$$t(k_2 b + k_{-2}) = \ln\,[x_e/(x_e-x)], \tag{9}$$

or

$$x_e/(x_e-x) = \exp\,[-(k_2 b + k_{-2})t]. \tag{10}$$

The observed first-order rate constants k obtained from the experimental reaction traces are thus equal to $(k_2 b + k_{-2})$, from which k_2, the second-order rate constant of the forward reaction, can be obtained by plotting the values of k against the base concentration.

KINETIC MEASUREMENTS

The rate constants obtained for a series of experiments at different temperatures between 0 and 35°C and at various concentrations of base are shown in tables 1 and 2 for the normal and deuterated substrates reacting with triethylamine and tri-n-butylamine. The measured values of the first-order rate constants k at each concentration were plotted as $\log_{10}k$ against $1/T$ and a series of parallel straight lines was constructed. From these lines " smoothed " values of the first-order rate

TABLE 3.—SECOND-ORDER RATE CONSTANTS FOR THE PROTON AND DEUTERON TRANSFER REACTIONS

$k_{2\mathrm{H}}$ and $k_{2\mathrm{D}}$ in l. mol^{-1} s^{-1}, with standard deviations.

TRIETHYLAMINE REACTION:

temp. °C	$10^{-2}\,k_{2\mathrm{H}}$	$10^{-2}\,k_{2\mathrm{D}}$	$k_{2\mathrm{H}}/k_{2\mathrm{D}}$
0	3.99±0.48	1.12±0.03	3.56±0.43
5.0	5.02±0.57	1.42±0.05	3.53±0.41
10.0	6.66±1.7	1.94±0.03	3.43±1.18
15.0	8.30±1.1	2.48±0.03	3.33±0.45
20.0	10.30±0.81	3.20±0.01	3.22±0.25
25.0	12.2±0.94	3.92±0.21	3.12±0.24
30.0	15.2±1.2	5.04±0.14	3.01±0.25
35.0	18.0±1.7	6.22±0.29	2.89±0.28

TRI-n-BUTYLAMINE REACTION:

temp.°C	$10^{-2}\,k_{2\mathrm{H}}$	$10^{-2}\,k_{2\mathrm{D}}$	$k_{2\mathrm{H}}/k_{2\mathrm{D}}$
0	2.60±0.08	1.08±0.03	2.41±0.07
5.0	3.24±0.11	1.43±0.05	2.27±0.09
10.0	4.02±0.11	1.74±0.04	2.31±0.06
15.0	4.91±0.19	2.20±0.01	2.23±0.09
20.0	6.16±0.24	2.86±0.10	2.15±0.08
25.0	7.28±0.23	3.36±0.09	2.17±0.07
30.0	8.89±0.41	4.20±0.15	2.13±0.10
35.0	10.2±0.41	5.08±0.13	2.00±0.08

constants were obtained for each experimental temperature. The smoothed values were then plotted for each temperature against the concentration of base, and the second-order rate constants k_2 for the forward reactions were obtained from the slopes of the graphs, which were calculated by the method of least squares. Table 3 shows these constants, and also the isotopic rate ratios for the triethylamine and tri-n-butylamine reactions.

The values of $\log_{10}k_2$ were plotted against the reciprocal of the absolute temperature, and the activation parameters given in table 4 were calculated by the least-squares method. One pair of graphs is illustrated in fig. 2.

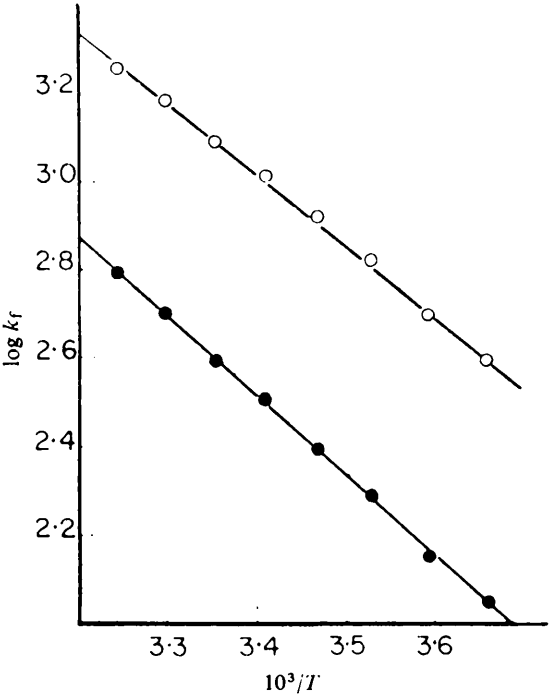

FIG. 2.—Plot of log k_f (second-order rate constant) against the reciprocal of the absolute temperature for the reaction of 4-nitrophenylnitromethanes with triethylamine in acetonitrile; normal compound, open circles; deuterated compound, closed circles.

DISCUSSION

Table 4 shows that the reactions are characterized by low activation energies and large negative entropies of activation. It is the latter which make the reactions slow enough to be measured at room temperature by the stopped-flow technique. The low activation energies are a manifestation of the weakness of the bond between the hydrogens and the aliphatic carbon atom, which in turn results from the strong electron-withdrawing power of the nitro-groups in the molecule. These activation energies are lower than that observed earlier for the proton-transfer from 4-nitrobenzyl cyanide to ethoxide ion in ethanol + ether solvent [2]; here the substrate molecule has a cyano-group attached to the aliphatic carbon, in place of the more powerful electron-withdrawing nitro-group.

The large negative entropies of activation are interpreted as an indication of a transition state which is much more strongly solvated than the initial state. Since the product is an ion-pair, there must be a certain amount of charge separation in the transition state, and the solvation shell will be held more strongly than in the initial state.

A comparison of the activation parameters shows relatively little difference between triethylamine and tri-n-butylamine. The *A*-factors for tri-n-butylamine are about 5 times smaller than for triethylamine; this difference is in the direction suggested by the steric effects of the n-butyl chains, but it is not large, and suggests that these effects are not dominant in the kinetics. If they were, a higher activation energy would be observed for tri-n-butylamine, but in fact it shows a slightly lower value than for triethylamine. It may be concluded that the amine molecule does not have to approach very close to the proton to effect the transfer. Lewis and Funderburk [3] have proposed that, since the requirement for extensive proton tunnelling is a barrier with a high curvature, reactions with considerable steric hindrance are more likely to show the phenomenon than those in which steric factors are unimportant. The relatively small steric sensitivity of the activation parameters in these reactions indicates that from this point of view the reactions are not unusually favourable for the detection of tunnelling.

TABLE 4.—ACTIVATION PARAMETERS FOR THE PROTON AND DEUTERON TRANSFER REACTIONS. E and $\Delta H^{\ddagger}$ in kcal mol^{-1}; $\Delta S^{\ddagger}$ in cal K^{-1} mol^{-1}; A in l. mol^{-1} s^{-1}; all with standard deviations. 1 cal = 4.184 J.

TRIETHYLAMINE REACTION

$E_H = 7.2 \pm 0.1$	$E_D = 8.2 \pm 0.1$	$(E_D - E_H) = 1.0 \pm 0.2$
$A_H = (2.5 \pm 0.4) \times 10^8$	$A_D = (4.5 \pm 0.5) \times 10^8$	$A_H/A_D = 0.55 \pm 0.1$
$\Delta H_H^{\ddagger} = 6.7 \pm 0.1$	$\Delta H_D^{\ddagger} = 7.7 \pm 0.1$	$(\Delta H_D^{\ddagger} - \Delta H_H^{\ddagger}) = 1.0 \pm 0.2$
$\Delta S_H^{\ddagger} = -22.1 \pm 0.4$	$\Delta S_D^{\ddagger} = -20.9 \pm 0.3$	$(\Delta S_D^{\ddagger} - \Delta S_H^{\ddagger}) = 1.2 \pm 0.4$

TRI-n-BUTYLAMINE REACTION

$E_H = 6.6 \pm 0.1$	$E_D = 7.4 \pm 0.1$	$(E_D - E_H) = 0.8 \pm 0.1$
$A_H = (5.2 \pm 0.5) \times 10^7$	$A_D = (8.8 \pm 1.0) \times 10^7$	$A_H/A_D = 0.6 \pm 0.1$
$\Delta H_H^{\ddagger} = 6.0 \pm 0.1$	$\Delta H_D^{\ddagger} = 6.8 \pm 0.1$	$(\Delta H_H^{\ddagger} - \Delta H_D^{\ddagger}) = 0.8 \pm 0.1$
$\Delta S_H^{\ddagger} = -25.2 \pm 0.3$	$\Delta S_D^{\ddagger} = -24.1 \pm 0.4$	$(\Delta S_D^{\ddagger} - \Delta S_H^{\ddagger}) = 1.0 \pm 0.5$

The isotope effects on the rate constants shown in table 3 are not by themselves indicative of proton tunnelling, in that they are not abnormally large and, in fact, are small for primary hydrogen isotope effects. However, when the isotopic difference in the activation parameters is considered (in table 4), the activation-energy isotope effect is large; for the triethylamine reaction, it is about equal to the difference in the zero-point energy of the stretching frequency of a C—H bond in the initial state relative to a C—D bond (about 1.1 kcal mol^{-1}), and for the tri-n-butylamine reaction it is about 70 % of this value. It may be concluded that the C—H and C—D bonds are to a large extent broken in the transition state.

The isotope effect on the entropy of activation is small but probably real. It is in the direction to be expected for tunnelling ($A_H/A_D < 1$). It is in the opposite direction to the isotope effect on the activation energy and thus it reduces the value of the rate ratio by about one-half, although it reduces the value of $(\Delta G_D^{\ddagger} - \Delta G_H^{\ddagger})$ by only about one-third.

Since the molecule $NO_2C_6H_4CD_2NO_2$ contains two identical deuterium atoms, only one of which is transferred, the measured isotope effect actually contains both a primary effect and a secondary effect deriving from the influence of the second deuterium atom which is not transferred. Secondary effects of this type usually give a rate change of about 12-15 %. The secondary isotope effect, therefore, is negligible compared to the primary effect.

CONCLUSIONS

The proton transfer reactions between 4-nitrophenylnitromethane and the tertiary bases triethylamine and tri-n-butylamine in acetonitrile solvent do not show marked proton-tunnelling effects. The activation parameters and isotope effects for these reactions are consistent with a relatively low and wide energy barrier and a transition state in which the C—H and C—D bonds are largely broken, giving the characteristics of an ion-pair surrounded by a tightly-held solvation shell.

The authors are grateful for financial support received from the Leverhulme Trust and the National Research Council of Canada.

[1] R. P. Bell, *The Proton in Chemistry* (Methuen, 1959), chap. 11; E. F. Caldin, *Chem. Rev.*, 1969, **69**, 135.
[2] E. F. Caldin and G. Tomalin, *Trans. Faraday Soc.*, 1968, **64**, 2814.
[3] E. S. Lewis and L. H. Funderburk, *J. Amer. Chem. Soc.*, 1967, **89**, 2322.
[4] R. G. Cooke and A. K. MacBeth, *J. Chem. Soc.*, 1938, 1024.
[5] N. Kornblum, B. Taub and H. E. Ungnade, *J. Amer. Chem. Soc.*, 1954, **76**, 3209.
[6] J. F. O'Donnell, J. T. Ayers and C. K. Mann, *Anal. Chem.*, 1965, **37**, 1161.
[7] A. I. Vogel, *J. Chem. Soc.*, 1948, 1825.
[8] *Dictionary of Organic Compounds* (Eyre and Spottiswoode, 1965), vol. 5, p. 3108.
[9] E. F. Caldin, *Fast Reactions in Solution* (Blackwell, 1964), chap. 3; H. P. Bennetto, E. F. Caldin and R. H. Holyer, unpublished work.
[10] E. A. Guggenheim, *Phil. Mag.*, 1926, **2**, 538.
[11] E. F. Caldin, M. Kasparian and G. Tomalin, *Trans. Faraday Soc.*, 1968, **64**, 2802.
[12] M. R. Crampton, *J. Chem. Soc. B*, 1967, 85.