1189. *The Methanolysis of Nitrophenyl Esters. Part II.*[1] *The Kinetics of the Methanolysis of 2,4-Dinitrophenyl Acetate*

By W. R. Ali, (Mrs.) Alicja Kirkien-Konasiewicz, and Allan Maccoll

The methanolysis of 2,4-dinitrophenyl acetate has been investigated both under initially neutral conditions and in the presence of the tertiary base pyridine and its methyl derivatives. For those bases with a methyl group in the 2-position (sterically hindered) first-order kinetic laws are obeyed, whilst for those bases without a 2-methyl group the reaction order is 2. In the former case, catalytic constants are given by $k_2^B = k_1/[B]$; in the latter they are given directly. For five of the reactions studied, Arrhenius parameters are reported. In the series as a whole, the rate constants are determined by a combination of base strength and steric factors, whilst for the non-sterically hindered bases the Brönsted law is obeyed.

In Part I,[1] the neutral methanolysis of picryl acetate and picryl benzoate, together with the corresponding reactions catalysed by pyridine and by its methylsubstituted homologues, have been studied. In the case of neutral methanolysis, picryl acetate was shown to yield exclusively picric acid (acyl–oxygen fission), whereas picryl benzoate gave both picric acid (acyl–oxygen fission) and 2,4,6-trinitroanisole (aryl–oxygen fission) which was itself slowly converted into picric acid. For the base-catalysed reactions, only the route leading to picric acid (*i.e.*, acyl–oxygen fission) was followed. The order of the catalytic constants k_2^B (B = pyridine, py; 2-picoline, pic; 2,6-lutidine, lut; and 2,4,6-collidine, col.) was $k_2^{py} > k_2^{col} > k_2^{pic} > k_2^{lut}$. The basic dissociation constants (in water) are in the order $K_B^{col} > K_B^{lut} > K_B^{pic} > K_B^{py}$, and so both specific base-catalysis and general base-catalysis may be excluded as possible mechanisms. It was concluded that the mechanism was in fact nucleophilic catalysis, with a combination of basic strength and steric hindrance determining the catalytic constant.

No previous work has appeared on the methanolysis of 2,4-dinitrophenyl acetate,

---

[1] Part I, A. M. Kirkien-Konasiewicz and A. Maccoll, *J.*, **1964**, **1267**.

although Kirsch and Jencks[2] reported a rate of neutral hydrolysis at 25° of 1×10^{-5} sec.$^{-1}$, the rate being independent of the presence of hydrochloric acid. These authors also studied the reaction catalysed by hydroxide ions and by imidazole. Bender and Turnquest[3] studied the hydrolysis in 5% dioxan–water catalysed by imidazole, quinoline, and acetate ions, and Bender and Neveu[4] reported the pyridine-catalysed hydrolysis.

The present Paper describes an investigation of the methanolysis of 2,4-dinitrophenyl acetate, the object being to see the way in which the rate of methanolysis (both neutral and catalysed) varies with the nature of the phenyl group. Since 2,4-dinitrophenyl acetate undergoes very rapid hydrolysis in the presence of strong bases, runs could not be followed by titration of the 2,4-dinitrophenol formed, unless prior separation of this component from the reaction mixture was achieved. This was done by a modification of the method of Olivier and Berger,[5] which also enabled the unreacted ester to be simultaneously estimated. Conductance measurements were also used to follow the rate of methanolysis.

EXPERIMENTAL AND RESULTS

2,4-Dinitrophenol, obtained from a commercial sample by twice recrystallising from water and drying over silica gel in a vacuum desiccator, had m. p. 112·5° (lit.,[6] 113°). 2,4-Dinitrophenyl acetate was prepared[7] and after two recrystallisations from light petroleum gave a nearly colourless product, m. p. 71—71·5° (lit.,[7] 72°) (Found: C, 42·6; H, 2·6; N, 12·0; O, 42·5. Calc. for $C_8H_6N_2O_6$: C, 42·5; H, 2·7; N, 12·0; O, 42·5%). AnalaR grade methanol was distilled through a 3-ft. column packed with glass helices, and the middle 80% fraction collected, having an average specific conductance of 4×10^{-6} mho cm.$^{-1}$ at 45°. Commercial samples of bases were distilled under reduced pressure, the middle 80% being retained. All kinetic experiments were done in a thermostat which maintained the temperature to within ±0·05°.

The reaction (1) was followed both by measuring the variation of conductance with time as described in Part I, and also by a chemical method which was essentially a modification of that of Olivier and Berger.[5] The chemical method depended upon a separation of the unreacted ester from the phenol, both of which were estimated. 5 or 10 ml. (depending upon initial concentration) of the reaction mixture was pipetted into an ice-cold mixture of 2% potassium sulphate (100 ml.) and carbon tetrachloride (30 ml.) in a glass-stoppered flask. After shaking, the layers were carefully separated and the carbon tetrachloride was washed several times with water (20 ml.). The aqueous layer containing the phenol and methyl acetate was immediately titrated (phenolphthalein) with standard sodium hydroxide (~N/30). Under the conditions used, the methyl acetate did not undergo hydrolysis. The carbon tetrachloride layer contained unreacted ester and up to 10% of methyl acetate. After standing for 20 hr. in contact with standard sodium hydroxide (~N/30) with occasional shaking, 1 mole of ester required 2 moles of base for neutralisation. Table 1 shows the results of a run done

$$2,4\text{-}(NO_2)_2C_6H_3{\cdot}O{\cdot}COMe + MeOH \longrightarrow 2,4\text{-}(NO_2)_2C_6H_3{\cdot}OH + MeO{\cdot}COMe \qquad (1)$$

TABLE 1

The stoicheiometry of the reaction

Time (min.)	5	18	32	46·3	60	75	95	119	140	160	186
[Ester] (mmoles l.$^{-1}$)	16·46	14·97	13·82	12·82	11·80	11·10	10·05	9·25	8·45	7·85	7·40
[Phenol] (mmoles l.$^{-1}$)	3·97	4·87	5·97	7·09	8·08	8·90	9·57	10·68	11·40	11·96	12·55
[Ester] + [Phenol] (mmoles l.$^{-1}$)	20·43	19·84	19·79	19·91	19·88	20·00	19·62	19·93	19·85	19·81	19·95

---

[2] J. F. Kirsch and W. P. Jencks, *J. Amer. Chem. Soc.*, 1964, **86**, 837.

[3] M. L. Bender and B. W. Turnquest, *J. Amer. Chem. Soc.*, 1957, **80**, 1656.

[4] M. L. Bender and M. C. Neveu, *J. Amer. Chem. Soc.*, 1958, **80**, 5388.

[5] S. C. J. Olivier and G. Berger, *Rec. Trav. chim.*, 1927, **40**, 609.

[6] I. Heilbron, " Dictionary of Organic Compounds," Eyre and Spottiswoode, London, 1934.

[7] J. J. Blanksma, *Chem. Weekblad*, 1909, **6**, 725.

with 20 mmoles $l.^{-1}$ of ester and 20 mmoles $l.^{-1}$ of pyridine at 45°. The sum of the concentrations of phenol and ester is constant, verifying the proposed stoicheiometry. Similar behaviour was noted with the other bases.

Reactions in the presence of 2-picoline, 2,6-lutidine, and 2,4,6-collidine followed a first-order law (Figure 1), whereas those in the presence of pyridine, 3-picoline, and 4-picoline followed a second-order law (Figure 2). In the former case, the catalytic constants (k_2^B) were obtained by dividing the first-order rate coefficient, k_1, less the rate coefficient of the neutral reaction, k_1^N, by the base concentration, or from the slope of a k_1 against [Base] plot (Figure 3); in the last case they were obtained directly.

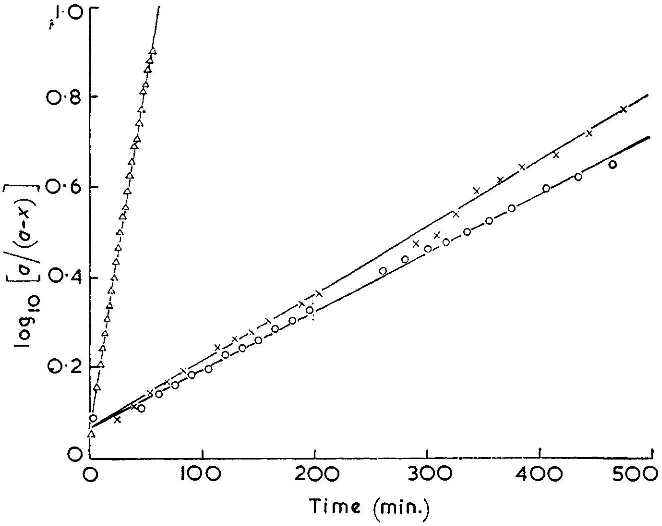

FIGURE 1. First-order (45°) plots for 2-picoline (×), 2,6-lutidine (○), and 2,4,6-collidine (△)

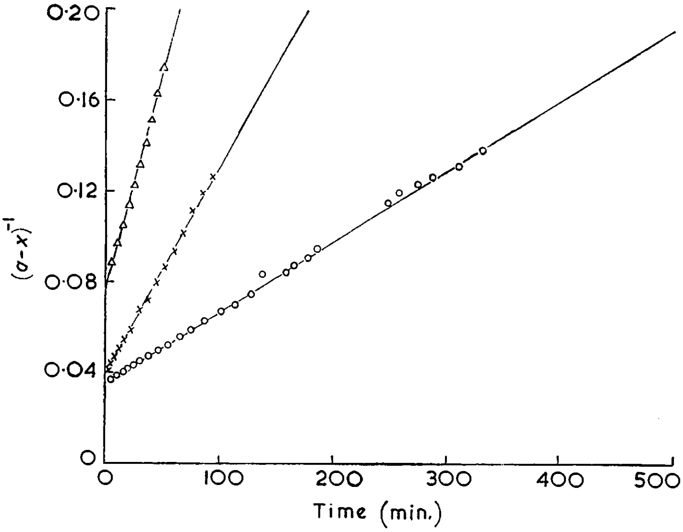

FIGURE 2. Second-order plots (45°) for pyridine (○), 3-picoline (×), and 4-picoline (△)

The Neutral Methanolysis.—The variation of the rate constant with temperature is shown in Table 2. Except at 64·8°, all the runs were done in duplicate by the chemical method; at that temperature there were in addition two conductance runs. These values were in good agreement with the Arrhenius equation $\log_{10}k_1^N = 6{\cdot}648 - 18{,}790/2{\cdot}303RT$.

Catalysis by 2-Picoline, 2,6-Lutidine, and 2,4,6-Collidine.—In all cases, runs were done by both the conductance and chemical methods. The first-order character of the reactions at constant base concentration follows from the linearity of the log-plots (Figure 1), and also from the lack of dependence of the first-order rate coefficients upon initial ester concentration (Table 3) in the case of catalysis by 2-picoline. The constancy of $k_2^B = (k_1 - k_1^N)/[B]$ as [B] is varied is shown in Table 4 for the same reaction. The proposed kinetics are thus verified. Similar behaviour was observed for the other bases. The variation of the rate constants with temperature is shown in Table 5, together with the parameters of the Arrhenius equations. All the tabulated values were calculated by the method of least squares.

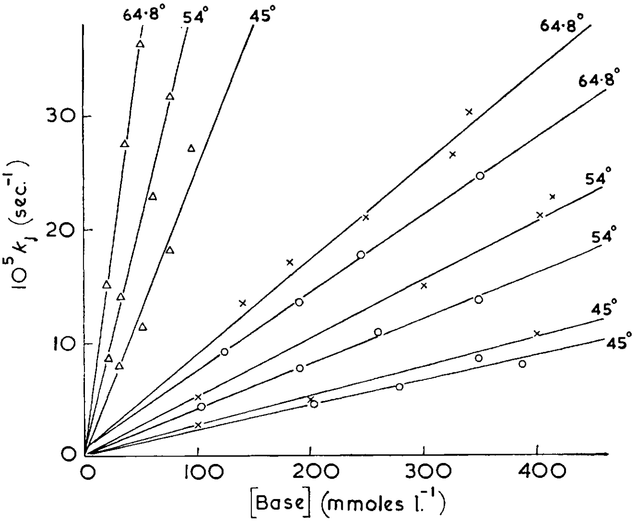

FIGURE 3. A plot of k_1 against [B] for 2-picoline (×), 2,6-lutidine (○), and 2,4,6-collidine (△)

TABLE 2

The variation of the rate of the neutral reaction with temperature

Temp.	45·0°	50·0°	55·0°	60·0°	64·8°
[Ester] (mmoles l.$^{-1}$)	22·1	20·4	24·9	22·1	19·0
	25·0	25·0	26·4	26·8	24·1
$10^6 k_1^N$ (sec.$^{-1}$)	1·84	2·23	4·64	6·45	10·59

Catalysis by Pyridine and 3- and 4-Picoline.—As has been noted earlier (Figure 2), catalyses by these bases follow a second-order rate law that is first-order in ester and first-order in base.

TABLE 3

First-order rate coefficients for methanolysis catalysed by 2-picoline

Temp.	[Ester] (mmoles l.$^{-1}$)	[2-Picoline] (mmoles l.$^{-1}$	$10^5 k_1$ (sec.$^{-1}$)	$10^4 k_2^B$ (l. mole^{-1} sec.$^{-1}$)
45·0°	76·0, 87·0	100	2·76	2·58
	12·4, 19·9	200	4·98	2·40
	11·9, 19·8	400	10·73	2·64
54·7	8·7, 12·6, 75·9	100	5·25	4·79
	6·8, 11·8	300	14·98	4·83
	10·1, 25·0, 44·6	403	21·15	5·01
	10·9	415	22·78	5·38
64·8	23·2, 49·6	181·4	16·99	8·78
	28·9, 30·1	251·2	21·02	7·95
	7·3, 18·5	268	20·00	7·07
	10·4	329	26·65	7·78
	23·1, 47·4	344·5	30·33	8·50

TABLE 4

The lack of dependence of the catalytic constants on base concentration (64·8°)

[2-Picoline] (mmoles l.$^{-1}$)	181·4	251·2	258	329	344·5
$10^4k_2^{\mathrm{B}}$ (l. mole^{-1} sec.$^{-1}$)	8·78	7·95	7·07	7·78	8·50

TABLE 5

The temperature variation of k_2^{B}

	Temp.				
	45·0°	54·7°	64·8°	Log *A*	*E* (kcal. mole^{-1})
	Base: 2-picoline				
$10^4k_2^{\mathrm{B}}$ (l. mole^{-1} sec.$^{-1}$)	2·69	5·21	7·70	4·90	11·72
	Base: 2,6-lutidine				
$10^4k_2^{\mathrm{B}}$ (l. mole^{-1} sec.$^{-1}$)	2·07	4·09	6·68	5·06	12·70
	Base: 2,4,6-collidine				
$10^4k_2^{\mathrm{B}}$ (l. mole^{-1} sec.$^{-1}$)	27·3	42·8	70·1	4·34	10·20

TABLE 6

The pyridine-catalysed methanolysis (45·0)

[Pyridine] (mmoles l.$^{-1}$)	[Ester] (mmoles l.$^{-1}$)	Number of runs *	$10^3k_2^{\mathrm{B}}$ (l. mole^{-1} sec.$^{-1}$)
20	48·5—50	2C, 14P	6·61
30	30	2C, 4P	5·85
50	27—50	1C, 5P	5·33
100	35—100	1C, 3P	5·58
150	33	2P	4·62

* C = chemical, P = conductance.

TABLE 7

The 3- and 4-picoline-catalysed methanolysis at 45°

3-Picoline

[Ester] (mmoles l.$^{-1}$)	15·0	17·8	20·1 *	24·7	25·1	34·9
[3-Picoline] (mmoles l.$^{-1}$)	14·9	25·0	20·1	35	25·0	35
$10^3k_2^{\mathrm{B}}$ (l. mole^{-1} sec.$^{-1}$)	16·3	15·1	16·7	13·0	15·1	17·0

4-Picoline

[Ester] (mmoles l.$^{-1}$)	10	14·7	20	20·1 *	25	30·4	30	40
[4-Picoline] (mmoles l.$^{-1}$)	10	20	20	20·1	30·5	30·5	40	30
$10^3k_2^{\mathrm{B}}$ (l. mole^{-1} sec.$^{-1}$)	45·8	27·3	34·3	32·3	25·6	29·7	35·8	34·4

* Runs done by the chemical method.

The lack of dependence of the rate coefficients in the case of pyridine upon the concentration of both ester and base is shown in Table 6.

Investigations of the temperature variation of the rate constants gave $10^3k_2^{\mathrm{B}}$: 45°, 5·60; 54·0°, 9·36; and 64·8°, 21·7 l. mole^{-1} sec.$^{-1}$. The rate constants fitted the Arrhenius equation $\log k_2^{\mathrm{B}} = 7{\cdot}82—14{,}700/2{\cdot}303\boldsymbol{RT}$.

For 3- and 4-picoline, runs were done at 45°. Again catalysis by these compounds followed second-order kinetics, the results being shown in Table 7.

The mean values of $10^3k_2^{\mathrm{B}}$ from Table 7 are 15·0 and 31·3 for 3- and 4-picoline, respectively, excluding the value at 10 mmoles l.$^{-1}$ of base in the latter case.

DISCUSSION

It is interesting to compare the rate constant of the neutral methanolysis with that of picryl acetate.[1] At 45°, the rate constant for the latter compound is 2700 × 10^{-6} sec.$^{-1}$ (estimated from the value at 44·6°) while for the former it is 1·84 × 10^{-6} sec.$^{-1}$. The additional nitro-group in the picryl compound thus increases the rate of methanolysis by a factor of about 1500. The surprising feature, however, is that the effect is not in the activation energy, but mainly in the pre-exponential term of the Arrhenius equation. The values are picryl acetate, $E = 21{\cdot}75$ kcal. mole^{-1} and $\log A = 12{\cdot}24$; 2,4-dinitrophenyl acetate, $E = 18{\cdot}8$, $\log A = 6{\cdot}65$. This might suggest that a different mechanism of neutral methanolysis is involved in the two cases. However, it could be that the transition state in the case of the picryl ester is more lightly solvated than in the case of the 2,4-dinitrophenyl ester, because charge delocalisation would be greater in the picryl ester. This could explain the higher activation energy and higher A-factor in the former case, since the solvation energy would be less and the solvation entropy of the transition state greater. Kirsch and Jencks [2] measured the rate of neutral hydrolysis of 2,4-dinitrophenyl acetate (at ionic strength 1) at 25° and obtained a value of $1{\cdot}1 \times 10^{-5}$ sec.$^{-1}$. From the results in Table 2 the value for neutral methanolysis at this temperature can be estimated as $\sim 3 \times 10^{-7}$. Thus, hydrolysis is faster than methanolysis by a factor of about 30, a value greater than that found for picryl acetate, which gave a factor of 5 for the rate of hydrolysis in 50% aqueous acetone compared with that of methanolysis.

The results (Table 5) show that the A-factors for the catalysed reactions are also low, but that catalysis arises in the main from a considerable lowering of the activation energy. The pK_b values [8] relevant to a discussion of the base-catalysed methanolysis are given in Table 8, along with the catalytic constants at 45°. Two conclusions follow from Table 8.

TABLE 8

Basic strengths (pK_b) and catalytic constants (k_2^B)

Base	Pyridine	2-Picoline	3-Picoline	4-Picoline	2,6-Lutidine	2,4,6-Collidine
pK_b	8·78	8·04	8·35	8·02	7·28	6·55
$10^4 k_2^B$ (l. mole^{-1} sec.$^{-1}$)	56·0	2·69	150	313	2·07	27·3

In the first place, there is no general relationship covering all the bases studied, between basic strengths and catalytic constant. Secondly, for a restricted series of bases, namely pyridine, 3-picoline, and 4-picoline, the catalytic constant increases with basic strength in a regular manner. The important point about this series is that they are not sterically hindered, the methyl group being remote from the reaction centre. For this reason, discussion of the relationship between catalytic constant and basic strength will be developed separately for non-sterically hindered and for sterically hindered bases.

Non-sterically Hindered Bases.—As has been noted earlier, reactions in the case of pyridine, 3-picoline, and 4-picoline followed second-order kinetics, which implies that one molecule of base is removed for each molecule of ester undergoing methanolysis. Curving first-order plots in the case of the pyridine-catalysed hydrolysis of acetic anhydride were observed by Bafna and Gold,[9] and were attributed to protonation of the catalyst, with consequent inactivation. A similar bending effect was noticed in the pyridine- and 3- and 4-picoline-catalysed hydrolyses of *p*-nitrophenyl acetate, by Bender and Turnquest.[3] Second-order kinetics, that is first-order in ester and first-order in base, were observed in the methanolysis of picryl acetate and benzoate, catalysed by pyridine, 2-picoline, 2,6-lutidine, and 2,4,6-collidine,[1] and this could be explained by protonation of the base by the picric acid formed in the reaction. The acid dissociation constant of picric acid, is, however, much greater than that for 2,4-dinitrophenol, values of K_a being $1{\cdot}7 \times 10^{-1}$ and 1×10^{-4}, respectively. Supporting evidence for the importance of steric hindrance in determining the properties of bases comes from a chromatographic study by Klemm and Airee [10] of the retention times of Lewis bases on activated alumina. The relevant results are set out in Table 9. The retention time decreases with successive substitution at the 2- or the 6-position; it appears roughly independent of substitution at the 3- and the 5-position.

---

[8] R. J. L. Andon, J. P. Cox, and E. F. G. Herrington, *Trans. Faraday Soc.*, 1954, **50**, 918.

[9] S. L. Bafna and V. Gold, *J.*, 1953, 1406.

[10] L. H. Klemm and S. R. Airee, *J. Chromatography*, 1964, **13**, 40.

TABLE 9

Retention times of methyl-substituted pyridines on alumina

Base	pK_b	B. p.	t_R (min.)	Base	pK_b	B. p.	t_R (min.)
Pyridine	8·78	116°	180	2,6-Lutidine ...	7·28	143°	1
2-Picoline	8·04	129	14	3,5-Lutidine ...	7·60	171	180

A further property of the non-sterically hindered bases is that catalysis follows the Brönsted law. Hence, a plot of log k_2 against K_a should yield a straight line of slope α. Such a straight line gives a slope of 0·92. The Brönsted law was deduced for the case of general base-catalysis, but evidence has accumulated to show that it may also be followed in the case of nucleophilic catalysis. Thus Bender [11] gives a summary of reactions for which a linear free-energy relationship for similar nucleophiles is obeyed. Bunnett [12] states that a slope of about 0·8 for the Brönsted plot is characteristic of nucleophilic catalysis. Again, Jencks and Carriuolo [13] state that the slopes of the Brönsted plots for nucleophilic catalysis of a similar chemical class are invariably in the range 0·7—0·8, while slopes lower than this would indicate general base-catalysis. Feather and Gold [14] studied the quantitative behaviour of sterically hindered bases, and showed that the Brönsted law holds for a series of bases having comparable steric hindrance. The general conclusion to be drawn from the results reported here for the non-sterically hindered bases is that the mechanism is nucleophilic catalysis, despite the fact that the observed slope (0·92) is rather higher than is usually encountered.

Sterically Hindered Bases.—In this case we have the series 2-picoline, 2,6-lutidine, and 2,4,6-collidine. It will be seen from Table 8 that, whilst the basic strengths are in the order $K_b^{col} > K_b^{lut} > K_b^{pic}$, the order of catalytic constants is $k_2^{col} > k_2^{pic} > k_2^{lut}$. This is the same order as has been previously observed for picryl acetate and benzoate.[1]

A rough estimate of the steric effects of the 2- and 6-methyl groups in the base can be made by assuming that the Brönsted law obtained in the case of the non-sterically hindered bases applied in the case of the sterically hindered ones. This would give $10^4k_2^{2\text{-pic}} = 242$, $10^4k_2^{lut} = 1500$, and $10^4k_2^{col} = 8800$ l. mole^{-1} sec.$^{-1}$. Taking the ratio of the calculated to the observed values of these, it is found that a singe methyl (in the 2-position) reduces the rate by a factor of 1/100, whilst the two methyls (in the 2,6-position) reduced it by a factor of 1/750. In the case of catalysis by 2,4,6-collidine, the factor is 1/300, the rate constant being increased by the additional 4-methyl group. Further work is necessary before an accurate measure of steric hindrance in these systems can be made.

The general conclusion to be drawn from this work is that catalysis by the methylpyridines is determined by two factors. The first is the basic dissociation constant of the base, and the second is steric hindrance produced by methyl substitution at the 2- or the 6-position. For non-sterically hindered bases, the Brönsted law is followed, and it is possible, though not proven here, that the same would hold for bases of an equal degree of steric hindrance. The general mechanism is nucleophilic catalysis, modified by steric effects.

The authors acknowledge the loan of equipment by Professor L. J. Haynes. W. R. A. acknowledges a Shell Research Grant which enabled the work to be done, and the Department of Chemical Engineering for working facilities. Helpful discussions with Professor C. A. Bunton and Professor Sir Christopher Ingold, F.R.S., are gratefully acknowledged.

DEPARTMENT OF CHEMISTRY, COLLEGE OF ARTS AND SCIENCE,
UNIVERSITY OF THE WEST INDIES,
ST. AUGUSTINE, TRINIDAD.
WILLIAM RAMSAY AND RALPH FORSTER LABORATORIES, UNIVERSITY COLLEGE,
GOWER STREET, LONDON W.C.1.

[*Received, February 24th,* 1965.]

---

[11] M. L. Bender, *Chem. Rev.*, 1960, **60**, 53.
[12] J. F. Bunnett, *Ann. Rev. Phys. Chem.*, 1963, **14**, 274.
[13] W. P. Jencks and J. Carriuolo, *J. Amer. Chem. Soc.*, 1961, **83**, 1743.
[14] J. A. Feather and V. Gold, *Proc. Chem. Soc.*, 1963, 306.