

Mechanism of Substitution at a Saturated Carbon Atom. Part XXXIX.
Nucleophilic Substitutions in Tertiary Alkyl Halides by Hydroxylic
Reagents in Nitromethane Solvent.*

By EDWARD GELLES, E. D. HUGHES, and C. K. INGOLD.

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The reactions of *tert.*-butyl bromide with water, ethyl alcohol, and phenol, each alone, and in mixtures, in solvent nitromethane, with pyridine to limit the acidity, have the kinetic characteristics of unimolecular processes, involving a slow formation, and fast subsequent reactions, of the carbonium ion. With larger concentrations of substituting agents the rates rise linearly, and without mutual effects when mixtures of reagents are used. This is attributed to the electrophilic catalysis of ionisation, since the effect follows the acidity order, PhOH > HOH > EtOH. With still larger concentrations of water, a further acceleration sets in, which is ascribed to a macroscopic solvent effect.

The reactions of triphenylmethyl chloride with pyridine and the same reagents in nitromethane have kinetics which point to a mechanism derived from the same two stages with a reversed rate order, though now pyridine forms complexes with the carbonium ion. With increasing reagent concentrations, the rates rise linearly and without mutual terms, but now in the nucleophilic order, EtOH > HOH > PhOH, as would be expected if attack upon a preformed cation is rate-controlling, since then the reagents can only function as nucleophiles.

A summary is given of the possible modes of action of hydroxylic reagents on alkyl halides in solvolysis, and in non-solvolytic substitutions in polar and non-polar solvents. Kinetic consequences are indicated. Reference is made to the work of C. G. Swain in solvent benzene.

SUBSEQUENTLY to our earlier work on nucleophilic substitution in hydroxylic solvents, we took up the study of non-solvolytic substitution in aprotic polar solvents. A number of such reactions in solvent sulphur dioxide have already been described (*J.*, 1940, 1011, 1017; *J.*, 1954, 634, 642, 647). Our first reports on substitutions in nitromethane as solvent are now presented.

Interest in the mechanism of unimolecular reactions has led us to begin work in nitromethane (as we began it in sulphur dioxide) by examining reactions of some alkyl halides which have a known tendency to use that mechanism. We now report on certain reactions of *tert.*-butyl bromide and of triphenylmethyl chloride.

This paper relates specifically to the use, as nucleophilic substituting agents for these

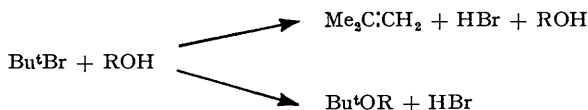
* Part XXXVIII, *J.*, 1954, 647.

alkyl halides, of hydroxylic substances, the examples being water, ethyl alcohol, and phenol. Their special interest is that, had they been used as solvents, they would have effected solvolytic substitution. By investigating such non-solvolytic substitutions in nitromethane, we hoped to cast on the mechanism of solvolytic substitution a light which might not be unduly indirect for the following reason.

It is likely that, although no aprotic solvent can in general rival the best hydroxylic solvents in capacity for electrostatic solvation, nitromethane, owing to its large dipole moment and small molecular volume, comes nearer to doing so than do most other non-hydroxylic solvents. Thus nitromethane seemed to be a solvent in which we might study the specific actions of hydroxylic substituting agents, introduced as solutes, with relatively little interference from an assumption by such reagents of those non-specific functions of electrostatic solvation which we wanted still to belong to the solvent. The hope that specific actions by the hydroxylic compounds would stand sufficiently isolated to be elucidated, directed that our first use of nitromethane as solvent for nucleophilic substitution should be turned to this particular account.

(1) *Reactions of tert.-Butyl Bromide.*—The reactions studied were those of the alkyl halide with pyridine, and with water, ethyl alcohol, and phenol, separately and as mixtures, without or with added pyridine, and in some cases with an added salt. Experiments with comparable concentrations of the reactants enabled the kinetic order with respect to each to be established. Experiments were also made over a range of much higher concentrations of the hydroxyl compounds.

The chemical changes, as confirmed by analysis or isolation of the products, consisted of simultaneous elimination and substitution :



where ROH stands for HOH, EtOH, or PhOH. The reactions were kinetically followed usually by the developed acid, but also sometimes by the formed bromide ion, the two methods giving identical results. With pyridine as reagent, and in the absence of hydroxy-compounds, the sole reaction is elimination, which with excess of pyridine goes to completion. In the absence of pyridine the reactions with the hydroxyl compounds come to equilibrium after only a small amount of change. But in the presence of a small excess of pyridine they run to completion, the acid and bromide ion appearing as pyridinium bromide. The main reaction is now one of substitution (including C-substitution in the case of phenol). The rates of all the reactions were independent of the pyridine concentration, as is illustrated for hydrolysis in Table 1.

TABLE 1. *First-order rate constants (k_1 in sec.⁻¹) of reaction of tert.-butyl bromide with water (or with water and ethyl alcohol) in nitromethane at 25.0° : illustrating invariance of rate with changing pyridine concentration.*

Run no.	(Initially, [Bu ^t Br] ~ 0.07M.)						
	7	10	5	6	11	28	26
[H ₂ O] ₀	0.61	0.61	1.00	1.00	1.00	1.11	1.11
[EtOH] ₀	—	—	—	—	—	0.33	0.33
[Pyridine] ₀	0.00	0.075	0.00	0.075	0.11	0.00	0.075
10 ⁵ k ₁	1.07	1.06	1.64	1.67	1.67	2.16	2.21

The initial specific rates of destruction of *tert.*-butyl bromide by all the reagents were independent of the initial concentration of the alkyl halide over the investigated range of 0.02—0.07M, as is illustrated for hydrolysis in Table 2. The overall reactions are thus of the first order with respect to the alkyl halide. In all the experiments cited later in this section the initial concentration of alkyl halide was kept within this range, whilst the concentration of added pyridine was standardised at 0.075M.

Except in special circumstances which will be noted, all individual runs were well

represented by the first-order rate law. This was true, not only for runs, such as those entered in Tables 1 and 2, in which the substituting agent was in large and nearly constant

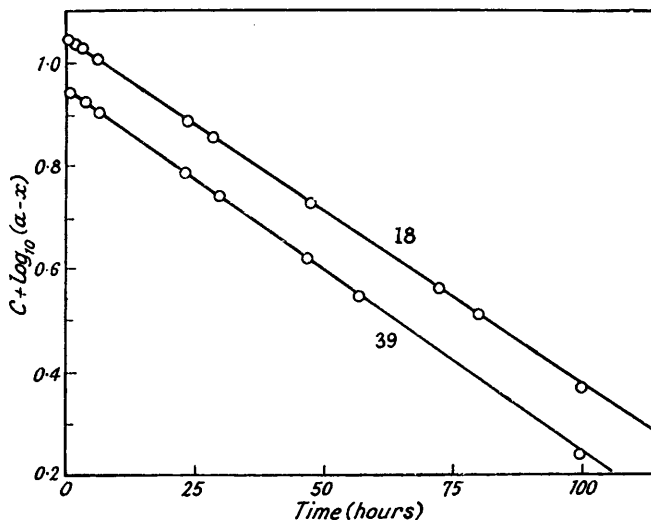
TABLE 2. Initial specific rates (k_1 in sec^{-1}) of reaction of tert.-butyl bromide with water in nitromethane at 25.0° : illustrating invariance of the specific rate with changing concentration of the alkyl halide.

(Initially, $[\text{H}_2\text{O}] = 1.00\text{M}$; [pyridine] from 0.00 to 0.11M.)

Run no.	16	15	14	11
$[\text{Bu}^t\text{Br}]_0$	0.0212	0.0350	0.0456	0.0691
$10^5 k_1$	1.69	1.70	1.70	1.67

excess, but also for experiments in which the reagent was in concentration comparable to that of the alkyl halide. This is illustrated in Fig. 1 by plots, covering the first 80% of each of two runs, of the logarithm of the concentration of surviving alkyl halide *versus* the

FIG. 1. Kinetic course of reactions of tert.-butyl bromide in nitromethane at 25.0° .



Run 18: Initially, $[\text{Bu}^t\text{Br}] = 0.069\text{M}$, [pyridine] = 0.075M , $[\text{H}_2\text{O}] = 0.035\text{M}$.
 Run 39: Initially, $[\text{Bu}^t\text{Br}] = 0.069\text{M}$, [pyridine] = 0.075M , $[\text{EtOH}] = 0.107\text{M}$.

time. In one run the substituting agent is water present in moderate deficit, and in the other it is ethyl alcohol in moderate excess. Taking into account our knowledge, derived from isolation of products, that the actual amount of substitution in these conditions, as in all those we examined, approaches the stoichiometric maximum, we have to conclude from linear plots such as those illustrated, not only that all reactions are of first order in the alkyl halide, but also that the substitutions are of zeroth order in the substituting agents.

The small deviations shown by the last points in Fig. 1 probably arise from a positive salt effect, which can, indeed, be brought out much more strongly by adding a salt, such as tetraethylammonium bromide, the rate then increasing from the outset, as is illustrated for alcoholysis in Fig. 2. Though we did not develop the study of salt effects quantitatively, the rate changes are certainly large enough to be understood as ionic-strength effects in unimolecular substitution. The relative retardations shown by the last few points in the most saline of the runs illustrated in Fig. 2, probably represent a small mass-law effect in the unimolecular mechanism, since it is here, if anywhere, that one would expect to find such retardations, namely, when the concentration of bromide ion is high, and nearly all the substituting agent has been used up, so that an appreciable proportion of formed carbonium ions fails to be collected by the substituting agent before it reunites with bromide ion.

When the concentration of hydroxylic substituting agent is made much larger than that of the alkyl bromide, say 10—50 times larger, then the first-order rate constant rises substantially, *e.g.*, by 2—7 times. This is illustrated in Table 3, for the reagents water, ethyl alcohol, and phenol, employed separately, and for the three possible types of binary mixtures of them.

The functional forms of the relations between rate and the concentrations of the three reagents, when used separately, are shown in Fig. 3. At low reagent concentrations, the main part of the rate is independent of the reagent: that is why we observe first-order rate-laws in these conditions. At high concentrations, the reagents are in constant excess, and we inevitably find first-order laws. Only in a few intermediate cases, indicated by the asterisks in Table 3, do we observe a slight falling-off in the first-order constants, suggesting

TABLE 3. *First-order rate-constants (k_1 in sec.^{-1}) of reactions of tert.-butyl bromide in nitromethane at 25.0°: variation with concentration of the substituting agent.*

(Initially, $[\text{Bu}^t\text{Br}] = 0.02\text{--}0.07\text{M}$, $[\text{pyridine}] = 0.075\text{M}$.)

		<i>Substituting agent: H₂O</i>							
Run no.	13, 17	18	45	42	38	10	44	11, 14—16	29, 30
$[\text{H}_2\text{O}]_0$	0.00	0.035	0.075	0.133	0.435	0.61	0.70	1.00	1.10
$10^5 k_1$	0.395	0.43	0.47 *	0.53	0.84	1.06	1.195	1.69	1.90
		<i>Substituting agent: EtOH.</i>							
Run no.	13, 17	39	21	20	37	22	43		
$[\text{EtOH}]_0$	0.000	0.107	0.330	0.67	1.00	1.33	1.59		
$10^5 k_1$	0.395	0.455	0.565	0.74	0.905	1.06	1.18		
		<i>Substituting agent: PhOH.</i>							
Run no.	13, 17	55	56	57					
$[\text{PhOH}]_0$	0.000	0.063	0.160	0.318					
$10^5 k_1$	0.395	0.525 *	0.825	1.26					
		<i>Substituting agent: H₂O + EtOH.</i>							
Run no.	40	38	41	24	23	26	25	34	27
$[\text{H}_2\text{O}]_0$	0.10	0.11	0.22	0.50	1.00	1.10	1.10	1.10	1.10
$[\text{EtOH}]_0$	0.23	0.23	1.00	1.00	1.00	0.33	0.67	1.00	1.33
$10^5 k_1$	0.615	0.615	0.135	1.59	2.56	2.21	2.48	2.63	2.88
Calc.	0.625	0.63	1.13	1.42	2.20	2.07	2.24	2.41	2.56
		<i>Substituting agent: H₂O + PhOH</i>				<i>Substituting agent: EtOH + PhOH</i>			
Run no.	51	62			Run no.	65	66		
$[\text{H}_2\text{O}]_0$	0.10	0.10			$[\text{EtOH}]_0$	0.33	0.67		
$[\text{PhOH}]_0$	0.16	0.32			$[\text{PhOH}]_0$	0.32	0.16		
$10^5 k_1$	0.925	1.37			$10^5 k_1$	1.40	1.18		
Calc.	0.94	1.37			Calc.	1.43	1.18		

* Initial value: k_1 drops by a few units % as reaction proceeds.

that the reaction has an appreciable dependence on the reagent, and is being affected by the fall in its concentration with time.

As Fig. 3 shows, the rates increase linearly with the reagent concentration, except that, in the case of water, this simple relation holds only up to 0.5M, after which a steeper increase sets in. The linear rates at 25° are represented by the equations

$$\left. \begin{aligned} 10^5 k_1^{\text{H}_2\text{O}} &= 0.40 + 1.02 [\text{H}_2\text{O}] \\ 10^5 k_1^{\text{EtOH}} &= 0.40 + 0.50 [\text{EtOH}] \\ 10^5 k_1^{\text{PhOH}} &= 0.40 + 2.75 [\text{PhOH}] \end{aligned} \right\} \dots \dots \dots (1)$$

In the lower three sections of Table 3, rows of figures headed "Calc." are given, which represent rates for binary mixtures of substituting agents, as calculated from the formula

$$k_1 = k_1^{\text{ROH}} + k_1^{\text{R'OH}} - 0.40 \times 10^{-5} \dots \dots \dots (2)$$

where ROH, R'OH = HOH, EtOH, PhOH. The agreement is good, provided that water, if present, is in concentration below 0.5M. This must mean that, for the concentration

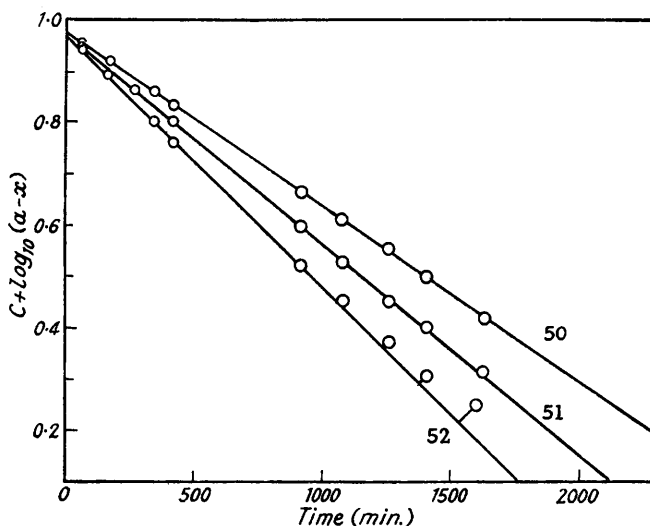
ranges over which the separate reagents affect the rate linearly, the rate for any mixture of them is given by an additive expression without "mutual" terms:

$$10^6 k_1 = 0.40 + 1.02 [\text{H}_2\text{O}] + 0.50 [\text{EtOH}] + 2.75 [\text{PhOH}] \quad \dots \quad (3)$$

When the mixture of substituting agents contains water in concentrations from 0.5M upward, so that, if the water were there as the only substituting agent, it would produce rates in excess of the appropriate linear rates, then the observed rates for the mixed reagents are always higher than those calculated from equation (2), even though k_1^{HOH} , as used in this equation, is now taken from the experimental rate curve for water, and thus allows for the extra rate of the water reaction when water is in high concentration. It thus appears that water, when in concentration above 0.5M, has the power, not only of sharpening its influence on the rate of its own reaction, but also of accelerating the reaction of an independent substituting agent.

A brief study has been made of the temperature effect on rate, and of its analysis in terms of the Arrhenius equation, for the reaction with water in a concentration within the

FIG. 2. Salt effects in reactions of *tert.*-butyl bromide in nitromethane at 40.0°.



(All runs have, initially, $[\text{Bu}^t\text{Br}] = 0.035\text{M}$, $[\text{pyridine}] = 0.075\text{M}$, $[\text{EtOH}] = 0.039\text{M}$, whilst $[\text{NEt}_4\text{Br}]$ is 0.000M in run 50, 0.045M in run 51, and 0.110M in run 52.)

range of its linear kinetic effect. The results are summarised in Table 4. These data are compared in the following paper with corresponding figures for some other substitution reactions of *tert.*-butyl bromide in nitromethane.

TABLE 4. Arrhenius parameters of the rates of reaction of *tert.*-butyl bromide in nitromethane with water (B_1 in sec^{-1} , E in kcal./mole).

Run no.	$[\text{H}_2\text{O}]$	T	$10^6 k_1$	$\log_{10} B_1$	E
70	0.125	273.1°	0.0206	9.76	20.6
42, 45	„	298.1	0.519		
76	„	313.1	2.70		

Products of the elimination, and of the three substitutions, at 25° and at 40°, were separated and identified by standard methods from completed reactions, conducted in conditions similar to those of typical kinetic experiments, except that the scale, and in some cases the concentrations, were somewhat larger. Liquids, isolated by distillation through an efficient column of small hold-up, were identified by b. p. and refractive index. The

following example will illustrate the dominance of substitution in the presence of an equivalent or more of substituting agent. From *tert.*-butyl bromide (2.3 g.) and pyridine and water in equivalence ($\sim 0.3M$) at 40° in nitromethane, 0.95 g. of *tert.*-butyl alcohol, b. p. 82.8° , n_D 1.388, was isolated: this yield is 75% of the theoretical.

(2) *Reactions of Triphenylmethyl Chloride.*—When this substance is dissolved in nitromethane, the characteristic greenish-yellow colour of the carbonium ion appears to be produced instantly. Bentley, Evans, and Halpern have shown (*Trans. Faraday Soc.*, 1951, **47**, 711) that this colour arises from the conversion of a small proportion of the solute molecules into ion-pairs, $\text{Ph}_3\text{CCl} \rightleftharpoons \{\text{Ph}_3\text{C}^+\text{Cl}^-\}$, the proportion of ion-pairs formed at 0° , for instance, being 0.032%, independently of concentration.

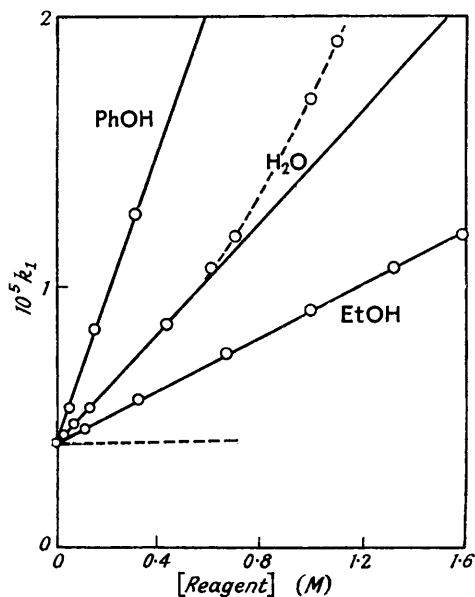


FIG. 3. First-order rate-constants for reactions of *tert.*-butyl bromide in nitromethane at 25.0° , as functions of the concentrations of the substituting agents.

When pyridine is added to such solutions, the colour is discharged instantly. No acid (*i.e.*, pyridinium ion) is developed.

When water, ethyl alcohol, or phenol is added to a solution of triphenylmethyl chloride in nitromethane, substitutions occur (including *C*-substitution in the case of phenol),



as can be followed by the development of acid. However, these reactions reach equilibrium after only a small percentage conversion. Thus, with initial concentrations $[\text{Ph}_3\text{CCl}] = 0.0211M$, and $[\text{EtOH}] = 0.0248M$, the concentration of acid developed at equilibrium is $0.0033M$, corresponding to a 16% conversion.

On addition of water, ethyl alcohol, or phenol, or mixtures of them, to a solution of triphenylmethyl chloride and an excess of pyridine in nitromethane, the above substitutions proceed to completion. The reactions in these conditions have been followed kinetically at 0° , by noting the development of acid. Their rates are of the order of 100–1000 times greater than those of the corresponding reactions of *tert.*-butyl bromide.

Early in our kinetic investigation it was established, for the three substitutions with single substituting agents, that the rates are independent of the concentration of previously introduced pyridine, and that the specific rates are independent of the initial concentration of triphenylmethyl chloride. Individual runs followed first-order rate-laws to a good approximation, not only when the concentration of substituting agent was relatively high and therefore almost constant, but also when it was low, and, in particular, when, for water or phenol, it was comparable to the concentration of the triphenylmethyl chloride.

Thus reactions were occurring which are of first order in the alkyl halide and of zeroth order in the substituting agent. However, a range of intermediate reagent-concentrations could be found, easily in the case of ethyl alcohol, with some difficulty in that of water, and hardly at all in that of phenol, for which the first-order rate-constants fall off with the progress of reaction, thus indicating the presence of a component process which depends on the concentration of the substituting agent. All these results are so similar to those already described for the reactions of *tert.*-butyl bromide that separate illustration is omitted.

In contrast to the reactions of *tert.*-butyl bromide, those of triphenylmethyl chloride showed no salt effects, a clear indication that, despite a general similarity, the detailed mechanisms of substitution of the two alkyl halides are not the same. In illustration, Table 5 is given, which shows the absence of an effect of added tetraethylammonium chloride on the rate of the reaction of triphenylmethyl chloride with ethyl alcohol in the presence of pyridine.

TABLE 5. *First-order rate-constants (k_1 in sec.⁻¹) of triphenylmethyl chloride with ethyl alcohol in the presence of pyridine in nitromethane at 0.0°: absence of a salt effect.*

(Initially, [EtOH] = 0.0232M, [pyridine] = 0.062M.)			
Run no.	103	104	105
[Ph ₃ CCl] ₀	0.0197	0.0210	0.0197
[NEt ₄ Cl] ₀	None	0.0795	0.1590
10 ⁵ k ₁	13.1	12.8	13.1

When the concentrations of the substituting agents are considerably increased, the rate constants rise, as is shown in the upper sections of Table 6. Up to a point, this result qualitatively resembles that obtained for the reactions of *tert.*-butyl bromide; but the order in which the three substituting agents then stood, with respect to the sensitivity of the rate to their concentration, is now found to be inverted.

TABLE 6. *First-order rate-constants (k_1 in sec.⁻¹) of reactions of triphenylmethyl chloride in nitromethane at 0.0°: dependence on concentration of the reagent.*

(Initially, [Ph ₃ CCl] = 0.02—0.05M, [pyridine] = 0.05—0.07M.)							
Substituting agent: H ₂ O.			Substituting agent: PhOH				
Run no.	113	114	115	Run no.	116	117	118
[H ₂ O] ₀	0.043	0.097	0.209	[PhOH] ₀	0.044	0.173	0.255
10 ⁵ k ₁	9.5 *	15.8	32.0	10 ⁵ k ₁	5.3	7.7	8.8
Substituting agent: EtOH.							
Run no.	103	106, 107	108	110	111	112	
[EtOH] ₀	0.023	0.025	0.052	0.062	0.125	0.255	
10 ⁵ k ₁	13.1 *	17.5 *	28.1	34.3	68	140	
Reagent: H ₂ O + EtOH.		Reagent: H ₂ O + PhOH.		Reagent: EtOH + PhOH.			
Run no.	121	Run no.	122	Run no.	120	119	
[H ₂ O] ₀	0.097	[H ₂ O] ₀	0.097	[EtOH] ₀	0.025	0.048	
[EtOH] ₀	0.103	[PhOH] ₀	0.044	[PhOH] ₀	0.025	0.044	
10 ⁵ k ₁	69	10 ⁵ k ₁	17.7	10 ⁵ k ₁	16.0 *	28.0	
Calc.	68	Calc.	17.1	Calc.	17.0	29.1	

* From initial part of run: the constants fall as reaction continues.

Within the ranges of concentration investigated (up to 0.25M), the increases of reaction-rate with increasing reagent concentration were substantially linear, as illustrated in Fig. 4. For the three substituting agents, separately employed, the first-order rate-constants at 0° are given approximately by the following equations:

$$\left. \begin{aligned} 10^5 k_1^{\text{HOH}} &= 4.0 + 125 [\text{H}_2\text{O}] \\ 10^5 k_1^{\text{EtOH}} &= 4.0 + 500 [\text{EtOH}] \\ 10^5 k_1^{\text{PhOH}} &= 4.0 + 25 [\text{PhOH}] \end{aligned} \right\} \dots \dots \dots (4)$$

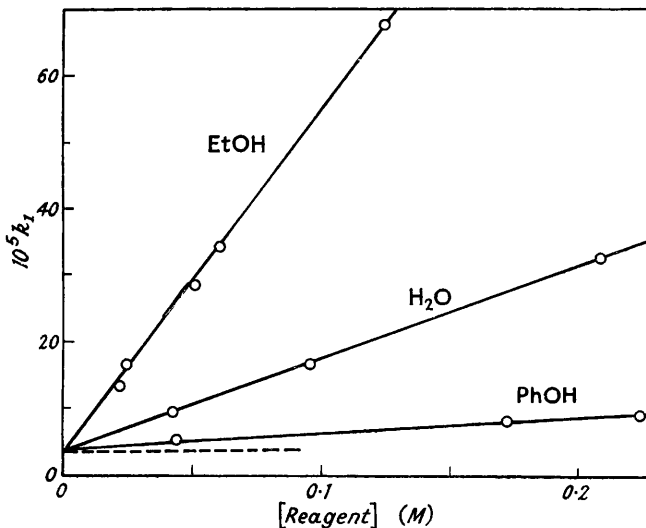
The lower sections of Table 6 record some rate-constants for the total reactions which were observed when various pairs of substituting agents were acting together. The

adjacent figures labelled "Calc." are the corresponding rates as calculated from equation (5) :

$$k_1 = k_{1,ROH} + k_{1,R'OH} - 4.0 \times 10^{-5} \dots \dots \dots (5)$$

where ROH, R'OH = HOH, EtOH, PhOH. The general agreement between the observed and the calculated rates allows us to conclude that, over the investigated range of reagent concentrations, the rate-constant of the total reaction of triphenylmethyl chloride with

FIG. 4. *First-order rate-constants for reactions of triphenylmethyl chloride in the presence of pyridine in nitromethane at 0.0°, as functions of the concentrations of the substituting agents.*



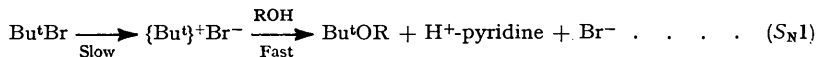
any mixture of the three substituting agents could be calculated from an additive expression without "mutual" terms :

$$10^5 k_1 = 4.0 + 125 [H_2O] + 500 [EtOH] + 25 [PhOH] \dots \dots \dots (6)$$

DISCUSSION

(3) *Reactions of tert.-Butyl Bromide : Electrophilic Catalysis of Ionisation.*—The observations presented in Section (1) leave no doubt that all the investigated reactions of *tert.*-butyl bromide in nitromethane, *i.e.*, the elimination, and the three substitutions with hydroxylic substituting agents, follow the familiar *E1* and *S_N1* mechanisms. The first-order kinetics, the fact that the products can be changed without a change of rate, and the observed ionic strength and mass-law effects, all point to this conclusion. The essential function of the pyridine in all these reactions seems only to be that it allows them to go much further forward, by replacing the formed hydrogen bromide by the more weakly acidic pyridinium ion.

We have, then, basically, two-stage processes, the first stage rate-controlling, and the second product-forming. For substitution they may be represented thus :

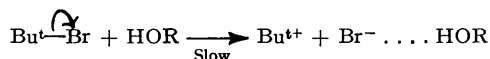


Against this background, it has to be considered why large concentrations of the substituting agents increase the first-order rate, the increases being linear over considerable ranges of reagent concentration. The linear curves in Fig. 3 are of a kind which Bird, Hughes, and Ingold looked for, but did not find, in their work on the Menshutkin reactions of *m*-chlorobenzhydryl chloride (*J.*, 1954, 634) ; and, as is shown by their discussion of the

observed, more complicated kinetic relations, the essential meaning of the present linear curves must be that *one* molecule of the reagent is involved *at close range* in the transition states of the rate-controlling processes. The absence of "mutual" terms from the equation for the rates with mixtures of substituting agents (equation 3) confirms the conclusion that only one hydroxylic molecule is involved.

Now this strictly kinetic conclusion might be chemically specialised in either of two possible ways. One trial specialisation would be that, superposed on the S_N1 substitution, an S_N2 substitution is taking place, or, in other words, that in some of the individual molecular acts of substitution, the substituting agent is attacking the carbon end of the breaking carbon-halogen bond. But, if this were true, the order in which the substituting agents should stand with respect to their kinetic effects should be the order of their nucleophilic power, $\text{EtOH} > \text{HOH} > \text{PhOH}$, *i.e.*, the inverse of the order of their acidity. Actually, as is shown in Fig. 3, or by the coefficients in equations (1) and (3), the reagents stand in the opposite order, *i.e.*, in the order of their acidity, $\text{EtOH} < \text{HOH} < \text{PhOH}$, the relevant coefficients being in the ratios 1 : 2 : 5.5.

This makes it clear that the alternative specialisation is the correct one: the hydroxyl compounds are intervening in the rate-controlling process by virtue of those structural features which make them acids: in some of the transition states of ionisation of the alkyl halide, they are hydrogen-bonding with the halogen, and thus assisting the electron transfer and the covalency disruption:



The hydrogen-bonding, although electrostatic, is a short-range interaction, and hence must produce an integral kinetic order, unlike interactions of longer range in which the positional requirements of the reagent are less well defined. To summarise, we are observing here an electrophilic catalysis of unimolecular nucleophilic substitution, quite similar to that described before for strongly acid catalysts, and for catalysing silver and mercuric ions in hydroxylic media.

Within the range of the linear kinetic effects, no hydroxylic molecule other than that just discussed can be involved in any way in the transition state of ionisation: its solvation shell must consist (as we hoped when choosing nitromethane for solvent) exclusively of nitromethane molecules. But water is peculiar in that a more-than-linear acceleration sets in when its concentration exceeds 0.5M, such extra acceleration affecting the total reaction of the alkyl halide, even though a part of that reaction may end by involving a substituting agent other than water. We ascribe this extra acceleration to a macroscopic solvent effect. Water is more solvating than either of the other two hydroxyl compounds, and, when a solvent, is much more strongly ionising. Thus it is to be expected that, when its volume concentration reaches units per cent., occasions will arise in which a molecule of water, or even more than one, intrudes among the nitromethane molecules in the general solvation shell of a transition state. The fact that we find this effect with water, which, whilst it is outstanding as a polar solvent, is neither the most acid nor the least acid of the three hydroxy-compounds, supports this interpretation.

(4) *Reactions of Triphenylmethyl Chloride: Fast Ionisation and a Slow Subsequent Step.*—It has been found by other workers in these laboratories that triphenylmethyl chloride in nitromethane undergoes halide-ion exchange immeasurably rapidly. We also have optical evidence that triphenylmethyl chloride in nitromethane establishes equilibrium with its ions practically instantaneously. Thus, there can be no doubt that the ionisation of triphenylmethyl chloride in nitromethane occurs extremely readily, and that the carbonium ion is instantly and unrestrictedly available to any reaction requiring it.

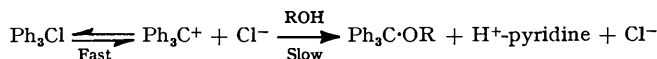
With reference to the kinetic studies, described in Section 2, of the reactions of triphenylmethyl chloride in the presence of pyridine with hydroxylic substituting agents in nitromethane, it follows from the above considerations that, if we try to build a reaction scheme based on ionisation, employing the usual two stages of the unimolecular mechanism of substitution, we cannot make the ionisation stage rate-controlling. But, in view of the

outstanding thermodynamic stability of the triphenylmethyl cation, we might try to make rate-controlling its interaction with the substituting agent.

Support is given to this idea by the absence of salt effects. That shows that the rate is not controlled by the ionisation of a neutral molecule, and, furthermore, that it is controlled by a process having the same number of ionic charges on both sides of the chemical equation.

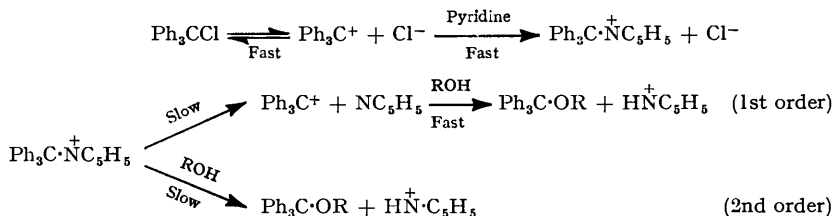
Further support for the same outlook may be derived from the linear accelerations observed with the higher concentrations of substituting agents. The linearity of these effects, and the absence of "mutual" terms from the rates given by mixtures of the substituting agents (equation 6), prove that only one hydroxylic molecule is involved in the rate-controlling process. Now, as can be seen in Fig. 4, and by the coefficients in equations (4) and (6), the order in which the three substituting agents stand with respect to these kinetic effects is just the reverse of the order found for the reactions of *tert.*-butyl bromide. The present order is neither that of the acidities of the reagents, nor that of their ionising power, but it is that of their nucleophilic power, $\text{EtOH} > \text{HOH} > \text{PhOH}$: the kinetic coefficients diminish along this series in the ratios 20 : 5 : 1. When these substituting agents attack a *pre-formed* cation, they can only do so as nucleophilic reagents, and our hypothesis that such an attack controls the measured rate requires that the accelerating effects should stand in this order.

If we now try to set up the type of mechanism considered in its simplest conceivable form, *i.e.*, as an $\text{S}_{\text{N}}1$ mechanism, except for a reversed order of rates,



we see at once that, in this form, it is inadequate for the following reasons. First, it does not account for the instantaneous discharge of the colour of the carbonium ion when pyridine is added to a solution of triphenylmethyl chloride in nitromethane. It thus appears that pyridine forms a complex almost instantaneously with the carbonium ion. Secondly, as the second and fast step in an ordinary unimolecular non-solvolytic substitution is bimolecular, so we have written the above second and slow step as bimolecular; and thus the above mechanism does not allow for the fact that, with low concentrations of substituting agents, the overall reaction is essentially of first-order.

These difficulties disappear if we include the complexing of the carbonium ion with pyridine in the fast preliminary process, as follows :

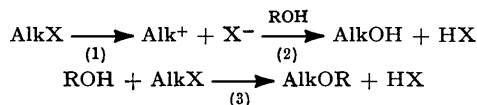


All the qualitative and kinetic observations are accommodated in this scheme, and we think that they are sufficiently varied and extensive to allow us to regard it as well-founded. It follows from it, that the use of a stronger complexing agent than pyridine should lead to diminished rates of reaction with the hydroxyl compounds; and we have verified that, on replacement of pyridine with triethylamine, these reactions are, indeed, rendered too slow for measurement.

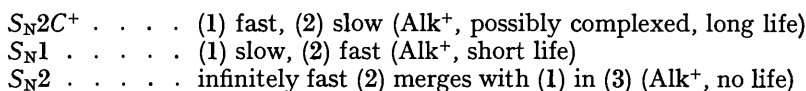
(5) *Functions of Hydroxylic Molecules in Solvolytic and Non-solvolytic Substitutions with Hydroxylic Reagents.*—The deductions of Sections 3 and 4 are probably all that, strictly logically, we should draw. Yet, although our experiments relate to non-solvolytic reactions, they do offer suggestions as to what specific functions hydroxylic molecules may assume in the solvolytic substitutions of alkyl halides, in addition to the general function of providing a solvating medium. Similarly, our results suggest by what molecular

processes kinetics may be determined in reactions of alkyl halides with hydroxylic molecules in less polar solvents than nitromethane, and even, by a long extrapolation, in non-polar solvents.

Taking as basis the separate chemical processes involved in S_N1 and S_N2 substitutions,



we can envisage three well-defined mechanisms, as set out below, although transitional situations between the first and second, and between the second and third, are obviously possible :



The first of these has hitherto been less fully considered than the others, but a large field for it exists in *pseudo*-base chemistry, *e.g.*, in slow basications of rapidly ionising *pseudo*-salts.

The ways in which a hydroxylic molecule, whether solvent or solute, might enter the rate-controlling steps of these processes are as follows :

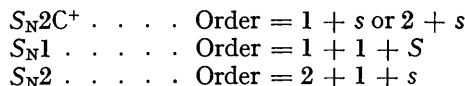
S_N2C^+ , as nucleophilic substituting agent, and by a general solvent effect ;

S_N1 , as electrophilic catalyst, and by a strong general solvent effect ;

S_N2 , as nucleophilic substituting agent, and as electrophilic catalyst, and also by a general solvent effect.

In solvolysis, the functions listed will determine rate, but not kinetic order, and thus, as we have pointed out before, less direct methods than the determination of kinetic form have to be applied in seeking to distinguish them.

In substitution conducted non-solvolytically, the various modes of action of the hydroxylic reactants could give rise to the following kinetic orders, which are here additively itemised in the sequence of the reagent functions set out above :



The point of the itemisation is that (as has been illustrated in this paper) the onset of the different contributions to the observed total order may become appreciable at different concentrations of the hydroxy-compound. The symbols S and s stand for any apparent order, often non-integral, arising from a general co-solvent function. It might be unobservable. Its importance for the two well-known mechanisms should follow the sequence $S_N1 > S_N2$. It should be more important in weakly polar than in strongly polar solvents.

Swain and his co-workers (*J. Amer. Chem. Soc.*, 1948, **70**, 1119, 2989; 1950, **72**, 2794; 1951, **73**, 2813) have studied the reactions of several alkyl halides with hydroxylic reagents in solvent benzene, and have carried over conclusions, drawn from results obtained in such conditions, directly to the problems of solvolysis—a dubious proceeding in itself, but one which can, we think, be made somewhat more secure by the use of results for polar aprotic solvents, such as nitromethane, as a stepping-stone. One sees from the above statement of possible reaction orders, that Swain's observation of orders of 3 does not necessitate the conclusions which were drawn, *viz.*, that what we have classified as the bimolecular and unimolecular mechanisms of nucleophilic substitution are identical, and are one-stage termolecular processes. When a solvent is made less polar, until it finally becomes non-polar, the mechanism itself is expected to shift in the direction $S_N2C^+ \longrightarrow S_N1 \longrightarrow S_N2$. Mechanism S_N1 , supposing that, for some particular alkyl halide, any mechanistic change

did not go beyond that point, might build up an overall order of 3 with the aid of its large co-solvent effect. Mechanism S_N2 , intrinsically more probable in a fully non-polar solvent, could hardly fail to give an order of 3 at lower reagent concentrations than would bring in a general co-solvent effect. These explanations, the second of which, already offered by Hughes (cf. Ingold, "Structure and Mechanisms in Organic Chemistry," Cornell Univ. Press, 1953, p. 356), is preferred, assume no reagent function which was not illustrated by us in or before 1940.*

EXPERIMENTAL

Materials.—Nitromethane, dried with calcium chloride, and, after refluxing under nitrogen, with magnesium perchlorate, was fractionally distilled, the middle one-third, b. p. 100.3—100.5°, being accepted. As used in the kinetic experiments, it had a water content, estimated by the Karl Fischer method, of less than 0.02%. "AnalaR" phenol was crystallised from light petroleum, while *tert.*-butyl bromide, triphenylmethyl chloride, ethyl alcohol, pyridine, tetraethylammonium chloride and bromide, and the acetone used in the analytical procedure, were purified by methods which have been described in papers from this laboratory. Carbonate-free standard sodium hydroxide was checked periodically against constant-boiling hydrochloric acid.

Kinetic Measurements.—For most of the runs, reaction mixtures, made up to 50 c.c. in glass-stoppered flasks, were prepared, either by direct weighing, or by the previous preparation by weighing of separate standard solutions in nitromethane of the reactants, which were mixed with the aid of automatic pipettes (error $\pm 0.02\%$). Thermostats were set to 0°, 25°, and 40° to within $\pm 0.02^\circ$. Aliquots of 5 c.c., withdrawn by means of an automatic pipette, attached to the flask, jacketted with the thermostat liquid as necessary, and operated by pressure of dry nitrogen, were delivered into 70 c.c. of acetone at 0°, and titrated with aqueous sodium hydroxide using lacmoid as indicator.

Some of the runs at 40° were conducted by the sealed-tube method, but rather as a check upon the standard method than as a necessity. Determinations of acid were in some cases checked by determinations of halide ion. Initial concentrations of alkyl halide, as given by weighing, were checked against the final titres, and in some cases also by decomposing an aliquot portion with aqueous acetone, and subsequently measuring either the acid or the halide ion. All these checks were satisfactory. Rate constants for the reactions of *tert.*-butyl bromide are probably good to ± 2 —3%, whilst those for the faster reactions of triphenylmethyl chloride are rather less reliable.

Products.—The method of examination is indicated, and an example is given, at the end of Section I.

This paper has benefited considerably from discussions with Dr. P. B. D. de la Mare and Dr. Y. Pocker, whom we thank.

WILLIAM RAMSAY AND RALPH FORSTER LABORATORIES,
UNIVERSITY COLLEGE, GOWER ST., LONDON, W.C.1.

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* We have used the past tense in referring to Swain's conclusions, since it is not quite clear whether or not they are still maintained. Swain, Scott, and Lohmann (*J. Amer. Chem. Soc.*, 1953, **75**, 136) recently observed large common-ion retardations, as well as strong non-common-anion interventions without rate-change, in the aqueous solvolysis of triphenylmethyl halides; and they explained these phenomena exactly as we would explain them. However, the brevity of their paper did not permit them either to refer to our precisely similar demonstrations and conclusions of 1940 relating to benzhydryl halides, with an explicit prediction of similar effects for triphenylmethyl halides, or to discuss the bearing of their new results on the previous conclusions of Swain already mentioned.