56. *Mechanism of Substitution at a Saturated Carbon Atom. Part V. Hydrolysis of* tert.*-Butyl Chloride.*

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THE nucleophilic substitution theory of Hughes, Ingold, and Patel (J., 1933, 526) was, in the first instance, applied to the fission of organic cations, but, as predicted at the time, it can be equally successful in explaining the analogous reactions of neutral molecules. One of the substitutions referred to in this connexion was the hydrolysis of alkyl halides: $\mathrm{OH'} + \mathrm{Alk{\cdot}Hal} \longrightarrow \mathrm{Alk{\cdot}OH} + \mathrm{Hal'}$. In its application to this reaction the theory recognised a bimolecular mechanism involving the attack of the carbon–halogen link by hydroxide ions, and also a unimolecular mechanism kinetically dependent on the ionisation of the alkyl halide. It was anticipated that there would be a change over from the bimolecular to the unimolecular mechanism towards the right-hand end of a series of alkyl halides arranged in order of increasing electron-release of the alkyl groups; *e.g.*, as shown in Series i of Part III. It was also expected that, from the left of such a series, where the bimolecular mechanism takes control, to the point at which the mechanism changes, the absolute velocity of the reactions of corresponding halides (*e.g.*, chlorides) should decrease; and that, from the point at which the unimolecular mechanism becomes dominant, towards the right, the absolute velocity should increase.

It is known (preceding paper) that the hydrolysis of methyl and ethyl halides is bimolecular, and that the reactions of the ethyl halides are slower than those of the methyl halides. It is also known that *iso*propyl halides are hydrolysed slowly (Part IV, preceding paper), whilst *tert.*-butyl halides are hydrolysed rapidly (Butlerow, *Annalen*, 1869, **144**, 33; Dobbin, J., 1880, **37**, 237; Strauss, *Annalen*, 1909, **370**, 366; Michael and Leupold, *ibid.*, 1911, **379**, 263). The existing evidence is therefore consistent with the theory, provided that there really be a change of mechanism somewhere between the ethyl and the *tert.*-butyl group. The author has now proved that the anticipated change of kinetic type occurs: the hydrolysis of *tert.*-butyl chloride is unimolecular.

This hydrolysis is therefore a reaction of the type labelled (S_N1) in the previous paper: the measured rate is the rate of ionisation of the halide. The opportunity has been taken to measure the critical energy (Arrhenius) of the reaction: the critical energy of an ionisation has thus been determined.

tert.-Butyl chloride is but sparingly soluble in water, and the kinetics were therefore studied in aqueous alcohol and aqueous acetone. The usual tests relating to reaction order were applied, thus establishing the unimolecular nature of the hydrolysis. Experiments have been carried out in aqueous media of diverse composition, and in three solvents measurements were performed at different temperatures.

A clear indication of the unimolecular nature of the reaction is obtained in experiments in which *tert.*-butyl chloride was taken in such large excess that its concentration did not appreciably change during the reaction. The velocity in dilute alkaline solution was then constant and independent of the concentration of the alkali; furthermore, when all the alkali was neutralised by the halogen acid formed, the reaction continued with the same velocity in the acid solution. This is shown in Table I, the first three columns of which are self-explanatory; col. 4 gives the average fall in titre per hour in alkaline solution, and col. 5 the average rise in titre for the same period in acid solution. The figures in both these columns relate to 10 c.c. of the reaction mixture and are expressed in c.c. of 0·05*N*-acid and -alkali. The temperature was 25·0°.

TABLE I.

Mols. halide per mol. KOH.	Solvent: Aq. EtOH EtOH, % by vol.	Range of readings: alkali → acid (in normality).	Speed in alkaline solution.	Speed in acid solution.
61	80	0·045 → 0·040	4·96	4·92
57	90	0·048 → 0·060	2·05	2·01

In the presence of a slight excess of potassium hydroxide, the velocity is independent of the concentration of the alkali and a good unimolecular constant is obtained. Under identical conditions of medium and temperature, the same constant is obtained in the complete absence of alkali, *i.e.*, in a solution which, as the reaction progresses, becomes more and more acidic. This is illustrated in Expts. 1 and 2 of Table II. The medium was 70% alcohol, the temperature 25·0°.

TABLE II.

Expt. No.	1.	2.	3.	4.	5.
[Halide], *M*	0·0510	0·0465	0·0824	0·1322	0·1746
[KOH], *N*	0·0571	—	—	—	—
k_1 (hr.$^{-1}$)	0·145	0·147	0·145	0·141	0·137

In dilute solutions the velocity constant is, within the limits of experimental error, independent of the initial concentration of the alkyl halide; but, at the higher concentrations, its value shows a decided decrease. The concentration employed in Expt. 5 (Table II), where the effect is most marked, corresponds to 2 c.c. of *tert.*-butyl chloride in 100 c.c. of the reaction mixture, and as the reaction is particularly sensitive to changes in the medium, the decrease in the velocity constant is undoubtedly to be attributed to an effect of medium.

More detailed reference may now be made to the effect of medium on the reaction. The result of regularly increasing the proportion of water in an aqueous-alcoholic solvent is to cause a very marked increase in speed, as shown below (temperature = 25·0°):

EtOH, % by vol.	90	80	70	60	50	40
[Halide], *M*	0·0755	0·0762	0·0824	0·0735	0·0810	0·0306
k_1 (hr.$^{-1}$)	0·00616	0·0329	0·145	0·453	1·32	4·66

This is consistent with our views regarding the mechanism of the reaction, *viz.*, that the speed is governed by the ionisation of the halide. It is in marked contrast to the effect of replacing alcohol by water in the hydrolysis of primary alkyl halides and in the decomposition of the dimethyl-*tert.*-butylsulphonium cation (cf. Part IV).

The variation of the velocity constant, in 80% alcohol, with temperature is shown in the following table:

Temp.	8·0°	16·0°	25·0°	35·0°	45·0°
$k_1 \times 10^3$ (hr.$^{-1}$), obs.	3·12	9·76	32·9	117	374
,, ,, calc.	3·10	9·71	32·9	117·5	380

In accordance with the Arrhenius equation, $k = Be^{-E/RT}$, the plot of log k_1 against $1/T$ is linear, giving an energy of activation $E = 23{,}060$ cals.; and the constants are in good agreement with the equation $\log_e k_1 = 35{\cdot}56 - 23{,}060/RT$. Similar results were obtained in 50% alcohol. The plot of log k_1 against $1/T$ is again linear, $\log_e k_1 = 39{\cdot}03 - 22{,}920/RT$, giving $E = 22{,}920$ cals.:

Temp.	8·0°	16·0°	25·0°
k_1 (hr.$^{-1}$), obs.	0·127	0·397	1·32
,, calc.	0·127	0·397	1·32

The velocity constants in 80% acetone are $k_{35°} = 2{\cdot}39 \times 10^{-2}$ and $k_{45°} = 7{\cdot}63 \times 10^{-2}$ (hr.$^{-1}$), giving an energy of activation of 22,600, and the general expression $\log_e k_1 = 33{\cdot}23 - 22{,}600/RT$.

It will be observed that, although the velocity constant is decreased 40-fold in passing from 50% alcohol to 80% alcohol, and 200-fold in passing from the former medium to 80% acetone, the value of E varies but slightly in the examples studied. The variation is almost entirely accounted for in the $\log_e B$ term. Discussion is postponed pending the results of further experiments.

Experiments will be reported later showing the effect of alkyl substitution and of halogen replacement on the critical energy of ionisation, and the attempt is being made to trace its dependence on the carbon–halogen bond energies through study of unimolecular hydrolyses analogous to the one herein discussed.

EXPERIMENTAL.

tert.-Butyl chloride, prepared by Norris's method (*Amer. Chem. J.*, **1907**, **38**, **641**), was carefully fractionated, and the fraction of constant b. p. 50·9°/762 mm. was used.

Hydrolysis of tert.*-Butyl Chloride in Water.*—Butlerow's experiments (*loc. cit.*) on the production of *tert.*-butyl alcohol were confirmed. Interaction was effected by shaking for 24 hours at room temperature. The solution was then neutralised with sodium carbonate, the alcohol salted out with sodium chloride, separated, dried over anhydrous sodium carbonate, and distilled. A product, b. p. 82·5°, was obtained in good yield. It was freed from traces of water by further distillation, first from fused barium oxide, and then from dissolved sodium, and was finally obtained as a white hygroscopic solid, m. p. 25°, identified by comparison with an authentic specimen. It is important to note that no olefin could be detected under the conditions of the kinetic experiments.

Kinetic Measurements.—*Purification and preparation of media.* Ethyl alcohol was lime-dried and fractionated. Acetone was purified by the sodium iodide method (Shipsey and Werner, J., **1913**, **103**, **1255**), dried over calcium chloride, and fractionated. The aqueous media were made up from the pure components by volume. Any possible errors introduced in making up the solutions were eliminated in the comparative experiments by keeping a good stock and drawing from the same sample.

Methods. In the first experiments, weighed amounts of *tert.*-butyl chloride were dissolved in the appropriate medium in a well-stoppered standard measuring flask, and diluted to the mark at the temperature of the thermostat. This procedure has the disadvantage that considerable time elapses, and, in some experiments, considerable reaction takes place, before measurements can be taken. Experience showed that the production of hydrogen chloride was quantitative. In some cases, therefore, the weighing was omitted altogether, and the method was simply to dissolve an approximately measured volume of the chloride in the medium, both being at the working temperature before admixture. The concentration at any time can then be deduced from the value of the titre at that time compared with that at infinite time. 5 C.c. were usually withdrawn, and the reaction was stopped by running it into alcohol, a standardised procedure being adopted to minimise indicator errors. The residual alkali (in the experiments in alkaline solution) was titrated with standard acid, and the hydrochloric acid (in the experiments in initially neutral solution) with standard alkali. Lacmoid was used as indicator.

The following selections of detailed experiments will serve to illustrate the nature of the results from which the foregoing constants have been taken. Except where otherwise specified, t is the time in hrs., x or $a - x$ the titre of 5 c.c. of the solution expressed in c.c. of $N/40$-alkali or -acid respectively, and k_1 the unimolecular velocity constant in hrs.$^{-1}$.

Temp. 25·0°. Medium 70% EtOH.

(*a*) [Chloride] = 0·0510N, [KOH] = 0·0510N.

t.	$a - x$.	10^3k_1.	t.	$a - x$.	10^3k_1.
0·5	9·48	146	4·0	5·70	145
1·0	8·83	144	5·0	4·92	146
1·5	8·23	143	6·0	4·28	145
2·0	7·63	145	8·0	3·13	147
3·0	6·63	143	10·0	2·30	149

(*b*) [Chloride] = 0·0465N, [KOH] = 0.

t.	x.	10^3k_1.	t.	x.	10^3k_1.
0·5	0·65	145	4·0	4·18	149
1·0	1·28	148	5·0	4·88	149
1·5	1·85	148	6·5	5·70	146
2·0	2·38	148	8·0	6·40	146
3·0	3·32	147	10·0	7·22	149

Temp. 25·0°.

Medium 80% EtOH; [Halide] = 0·0761*N*.

t.	x.	10^4k_1.	t.	x.	10^4k_1.
4·0	1·87	328	29·5	9·45	328
8·5	3·72	329	37·0	10·77	332
12·0	5·00	332	48·5	12·12	327
23·0	8·12	331	60·5	13·12	327

Medium 50% EtOH; [Halide] = 0·0810*N*.

t (min.).	x.	10^2k_1.	t (min.).	x.	10^2k_1.
10	3·20	132	50	10·80	132
20	5·75	131	70	12·72	132
30	7·86	133	90	13·95	131
40	9·38	130			

Temp. 8·0°, Medium 80% EtOH.

[Halide] = 0·0939*N*.

t.	x.	10^5k_1.	t.	x.	10^5k_1.
35·5	1·98	311	193·5	8·50	311
73·5	3·82	310	276·5	10·88	313
126·5	6·08	309	349·5	12·58	317

Temp. 35·0°, Medium 80% Acetone.

[Halide] = 0·0600*N*.

t.	x.	10^4k_1.	t.	x.	10^4k_1.
7	1·85	239	48	8·20	239
15	3·60	237	80	10·30	244
30	6·10	236			

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