231. *Electrophilic Catalysis in Nucleophilic Substitution and Elimin-*
ation. Part I. Kinetics and Mechanism of Reaction of tert.-*Butyl*
Bromide with Alcohols, Phenols, and Carboxylic Acids in Nitro-
methane.

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Measurements are reported on the kinetics of reaction of *tert.*-butyl bromide with a variety of alcohols, phenols, and carboxylic acids in nitromethane. Superimposed on a common zero-order component with respect to hydroxylic reagent, the alcohols show a linear catalysis up to about 1·5M. From the linear slopes the catalytic order is found to be: $PhCH_2\cdot OH >$ $MeOH > EtOH > Pr^nOH > Bu^nOH \sim Pr^iOH > Bu^sOH > Bu^tOH$.

With phenols, departures from linearity occur above *ca.* 0·3M and at lower concentrations the catalytic order is: $p\text{-}NO_2\cdot C_6H_4\cdot OH > p\text{-}$ $CN\cdot C_6H_4\cdot OH > p\text{-}I\cdot C_6H_4\cdot OH > p\text{-}Br\cdot C_6H_4\cdot OH > p\text{-}Cl\cdot C_6H_4\cdot OH > PhOH >$ $m\text{-}CH_3\cdot C_6H_4\cdot OH > p\text{-}CH_3\cdot C_6H_4\cdot OH > p\text{-}Bu^t\cdot C_6H_4\cdot OH > p\text{-}MeO\cdot C_6H_4\cdot OH$; *i.e.*, the acididy order. Phenols have a considerably higher electrophilic capacity to assist ionisation than alcohols.

In nitromethane, acetic and benzoic acids have a lower capacity to assist the ionisation of *tert.*-butyl bromide than phenols. It is suggested that this is because at 25·0° the carboxylic acids are largely in the form of cyclic dimers in this solvent.

THE reactions of *tert.*-butyl bromide with water, ethyl alcohol, and phenol have been studied by Gelles, Hughes, and Ingold[1] in nitromethane. They showed that superimposed on the unimolecular process assisted only by solvent there is an electrophilic catalysis of ionisation which follows the acidity order $PhOH > HOH > EtOH$. We now extend their kinetic studies in an attempt to obtain a relative scale of electrophilic capacity of various hydroxylic reagents to assist the ionisation of alkyl halides in the non-hydroxylic, but polar solvent, nitromethane.

EXPERIMENTAL

Materials.—Nitromethane was dried, fractionated, and chromatographed as previously described.[2] Pyridine was purified by Burgess and Kraus's method,[3] dried (CaH_2), and fractionated, b. p. 115·2—115·6°, n_D^{25} 1·5067. *NN*-Dimethylaniline was dried (CaH_2) and fractionated, b. p. 193—194°. *N*-Methylaniline was similarly dried and fractionated, b. p. 195—196°. Aniline was dried (KOH), distilled from zinc under reduced pressure, and finally dried with calcium hydride and distilled from it, b. p. 184—184·5°, n^{25} 1·5832. Triethylamine was distilled from acetic anhydride to remove traces of primary and secondary amines, dried (CaH_2), and fractionated, b. p. 89—89·5°, n^{25} 1·3992. Tribenzylamine, recrystallised from ligroin and dried under vacuum (P_2O_5), had m. p. 92°. *tert.*-Butyl bromide and methyl, ethyl, and benzyl alcohols were purified and dried as previously described:[4,5] Bu^tBr, b. p. 73—73·5°; MeOH, b. p. 64·2—64·6°, n^{25} 1·3266; d^{25} 0·7867; EtOH, b. p. 78—78·4°, n^{25} 1·3594, d^{25} 0·7850; $Ph\cdot CH_2\cdot OH$, b. p. 205—206°, n^{25} 1·5371, d^{25} 1·0413. *n*-Propyl alcohol was dried ($CaSO_4$, then Mg activated with I_2), and fractionated through a column of 20 theoretical plates. The middle fraction had b. p. 96·8—97·2°, n^{25} 1·3835. *iso*Propyl alcohol was freed from peroxides with solid stannous chloride, dried (CaO), and fractionated as above, b. p. 82—82·6°, n^{25} 1·3747. The butyl alcohols were dried (K_2CO_3) and fractionated after filtration of the desiccant. The redistilled alcohols were treated with the appropriate butyl phthalate and fractionated: Bu^nOH, b. p. 117·5—118°, n^{25} 1·3974; Bu^sOH, b. p. 99·5—100°, n^{25} 1·3961; Bu^tOH, b. p. 82·0—82·5°, m. p. 26°, supercooled to 25°, n^{25} 1·3823. The solid phenols were recrystallised

[1] Gelles, Hughes, and Ingold, *J.*, 1954, 2918.
[2] Pocker, *J.*, 1958, 240.
[3] Burgess and Kraus, *J. Amer. Chem. Soc.*, 1948, **70**, 706.
[4] de la Mare, Hughes, Ingold, and Pocker, *J.*, 1954, 2930.
[5] Hughes, Ingold, Mok, Patai, and Pocker, *ibid.*, 1957, 1220.

from light petroleum and kept *in vacuo* over phosphoric oxide; PhOH, m. p. 43°; *p*-Cl·C$_6$H$_4$·OH, m. p. 43°; *p*-Br·C$_6$H$_4$·OH, m. p. 64°; *p*-I·C$_6$H$_4$·OH, m. p. 94°; *p*-CN·C$_6$H$_4$·OH, m. p. 113°; *p*-NO$_2$·C$_6$H$_4$·OH, m. p. 56°; *p*-Bu^t·C$_6$H$_4$·OH, m. p. 98·5°. The liquid phenols were chromatographed, dried (CaSO$_4$), and distilled: *m*-cresol, b. p. 190—191°; *p*-cresol, b. p. 201—202°, m. p. 34°; *p*-F·C$_6$H$_4$·OH, b. p. 82°/13 mm.

Kinetic Measurements.—Reaction mixtures, made up to 50 c.c. in glass-stoppered flasks, were prepared as previously described by weighing of separate standard solutions in nitromethane of the reactants. The thermostat was at 25·0° $\pm$ 0·02°. For the determination of " acid " (either as free HBr or as a salt of a weak amine with HBr), aliquot portions (5 c.c.) were run into dry acetone (50 c.c.) at $-80°$ and titrated with standard sodium methoxide (lacmoid). In the presence of strong base (*e.g.*, triethylamine) the extent of reaction was determined by titrating (lacmoid) the free base, left after various periods of heating, with a standard methanolic solution of acid. For the determination of bromide ions a potentiometric titration with silver nitrate was carried out; two methods were used for the preparation of samples withdrawn from the kinetic runs. In the first (the " extraction " method) the sample was delivered into carbon tetrachloride (40 c.c.) at $-10°$, and this solution shaken three times with 20 c.c. of ice-cold water. In the second (the " evaporation " method) the sample was run into a flask immersed in a freezing mixture, evaporated with the help of a high capacity pump, and the residue was dissolved in water.

For the determination of olefin a sealed-ampoule technique was used; the sample, freed from amine, was added to methanolic bromine at $-30°$, solid potassium iodide was introduced, and the liberated iodine titrated with thiosulphate.

Results.—In the absence of added hydroxylic reagents, the rates of pyridinium ion (" acid ") production from *tert.*-butyl bromide and pyridine in nitromethane are of the first order in alkyl halide and zero order in pyridine.[1] This observation is now extended to cover a 1000-fold variation in pyridine and a 100-fold variation in *tert.*-butyl bromide (Table 1). The replacement

TABLE 1.   *Initial first-order rate coefficients for " acid " production, k_1 (H^+) (sec.$^{-1}$), from* tert.*-butyl bromide and pyridine in nitromethane at 25·0°.*

[Bu^{t}Br]	0·020	0·020	0·020	0·020		0·002	0·020	0·200
[C$_5$H$_5$N]	0·0002	0·002	0·020	0·20		0·020	0·020	0·020
$10^5 k_1$(H$^+$)	0·369	0·366	0·367	0·365		0·370	0·367	0·361

[Bu^{t}Br] = [C$_5$H$_5$N]	0·01	0·02	0·04	0·08	0·20	0·50	1·00	2·00
$10^5 k_1$(H$^+$)	0·366	0·367	0·364	0·367	0·367	0·369	0·370	0·370

of pyridine by other weak tertiary amines (*e.g.*, *NN*-dimethylaniline and tribenzylamine) of variable steric requirements leaves the rates of " acid " production substantially the same. Also, the rates of " acid," olefin, and bromide-ion production are practically identical (Table 2), indicating that with weak tertiary amines and in the absence of hydroxylic reagents an *E*1 process is under observation. With primary and secondary amines which are relatively weak bases (*e.g.*, aniline and *N*-methylaniline) and with strong tertiary amines (*e.g.*, triethylamine) the results are substantially the same except for a small increase in rate with increasing amine concentration, which has the characteristics of a bimolecular component of the S_N2 type. Thus, while the first-order rate coefficient of olefin production (Table 2) is the same as with pyridine and independent of amine concentration, the corresponding first-order rate coefficients of acid or bromide-ion production rise linearly with amine concentration. The linear rate coefficients for the reactions in presence of pyridine, *N*-methylaniline, aniline, and triethylamine respectively at 25·0° are $10^5 k_2 = 0·367 + 0·00$[C$_5$H$_5$N], 0·367 + 0·03[Ph·NHMe], 0·367 + 0·20[Ph·NH$_2$], 0·367 + 1·2[NEt$_3$]. The second-order rate coefficients are: for methylaniline, $k_2 \sim 0·3 \times 10^{-6}$, aniline $k_1 \sim 0·2 \times 10^{-5}$, and for triethylamine $k_2 \sim 1·2 \times 10^{-5}$ sec.$^{-1}$ l. mole^{-1}. In the first two amines the substitution products are Ph·NMeBu^t and Ph·NHBu^t respectively, but with triethylamine Bu^{t}OH was recovered. This is understandable if one realises that the *tert.*-butyl group cannot form substitution products with tertiary amines; the second-order component with strong tertiary amines may conceivably be due to a bimolecular attack by CH$_2$:NO$_2^-$ (formed in the reaction CH$_3$·NO$_2$ + Et$_3$N $\rightleftharpoons$ CH$_2$:NO$_2^-$ + Et$_3\overset{+}{N}$H) on Bu^{t}Br to produce an unstable ester of *aci*-nitromethane which subsequently decomposes to *tert.*-butyl alcohol.

Reaction with alcohols, phenols, and carboxylic acids. The chemical processes in the reactions

of *tert.*-butyl bromide with hydroxylic reagents consist of simultaneous elimination and substitution. In the absence of substances which reduce the acidity of the hydrogen bromide in nitromethane these changes come to equilibrium only after a small amount of change because the reverse processes are even faster. But in the presence of a small excess of a weak tertiary amine they proceed to completion and the acid and bromide ion appear as amine hydrobromide.

TABLE 2. *First-order rate coefficients (sec.$^{-1}$) of acid, $k_1(H^+)$, bromide ion, $k_1(Br^-)$, and olefin, $k_1(olefin)$, production from tert.-butyl bromide in the presence of amines in nitromethane at 25·0°.*

Bu^{t}Br = 0·05M.

Concn.	$10^5 k_1(H^+)$	$10^5 k_1(Br^-)$	$10^5 k_1(olefin)$	Concn.	$10^5 k_1(H^+)$	$10^5 k_1(Br^-)$	$10^5 k_1(olefin)$
	Pyridine				*N*-Methylaniline		
0·02	0·367	0·370	0·364	0·20	0·367	—	—
0·20	0·370	0·368	—	1·00	0·39	0·40	—
2·00	0·365	0·370	0·360	2·00	0·430	0·43	0·365
	NN-Dimethylaniline				Aniline		
0·02	0·367	0·369	0·365	0·20	0·41	—	0·367
0·20	0·364	0·365	—	0·50	0·47	0·46	—
2·00	0·372	0·374	0·350	1·00	0·56	0·57	0·360
	Tribenzylamine				Triethylamine		
0·20	0·367	0·365	—	0·0002	0·367	—	—
2·00	0·363	0·369	0·36	0·002	0·375	—	—
				0·01	0·40	0·49	0·37
				0·02	0·61	—	—

The relation between first-order rate coefficients of " acid " production and the concentration of various hydroxylic reagents is given in Table 3. These data show that the rates

TABLE 3. *Initial first-order rate coefficients, $10^5 k_1$ (sec.$^{-1}$), for acid production in the reaction of tert.-butyl bromide with various alcohols (ROH), phenols (ArOH), and carboxylic acids (R·CO$_2$H) in the presence of pyridine in nitromethane at 25·0°. [Bu^{t}Br] = [C$_5$H$_5$N] = 0·050. When [ROH] = 0·00, $k_1 = 0·367 \times 10^5$ sec.$^{-1}$.*

[ROH]	Ph·CH$_2$·OH	MeOH	EtOH	Pr^{n}OH	Pr^{i}OH	Bu^{n}OH	Bu^{s}OH	Bu^{t}OH
0·10	0·45	0·44	0·42	0·39	0·38	0·38	0·37	0·36
0·20	0·54	0·51	0·47	0·41	0·39	0·40	0·39	0·37
0·30	0·62	0·58	0·51	0·44	0·41	0·41	0·40	0·37
0·50	0·80	0·72	0·62	0·48	0·44	0·44	0·42	0·38
0·75	1·01	0·91	0·74	0·54	0·48	0·48	—	—
1·00	1·23	1·09	0·88	0·60	0·51	0·52	0·48	0·40
1·50	1·66	1·44	1·10	—	—	—	—	—
2·00	2·09	1·83	1·38	—	0·66	0·66	0·58	0·43
2·50	2·65	2·30	—	—	0·80	0·75	0·65	—
3·00	3·35	2·70	—	—	—	0·80	0·64	0·46
4·00	—	4·00	—	1·22	0·78	0·80	0·62	0·46

[X·C$_6$H$_4$·OH]	*p*-NO$_2$	*p*-CN	*p*-I	*p*-Br	*p*-Cl	*p*-F	H	*m*-Me	*p*-Me	*p*-Bu^t	*p*-MeO
0·10	0·93	0·87	0·69	0·68	0·65	0·64	0·62	0·61	0·61	—	0·59
0·15	1·21	1·12	—	—	0·80	0·79	0·70	—	—	0·72	—
0·20	1·5	1·36	1·04	1·00	0·98	0·92	0·87	0·86	0·85	0·84	0·82
0·25	1·75	1·62	—	—	—	—	—	—	—	0·95	0·94
0·30	2·1	1·87	1·34	—	1·30	1·21	1·17	1·13	1·08	1·07	1·05
0·40	3·00	2·4	1·66	1·63	1·60	1·49	1·42	1·39	1·33	1·31	—
0·50	4·2	—	—	—	2·20	—	1·99	1·65	1·61	—	1·50
0·80	7·2	—	—	—	—	—	3·00	—	—	—	—
1·00	—	—	—	—	—	—	—	3·7	3·2	—	—

| [Ph·CO$_2$H]... | 0·04 | 0·16 | 0·32 | [Me·CO$_2$H] | 0·26 | 0·65 | 0·87 | 1·95 | 3·25 |
| $10^5 k_1$ .... | 0·41 | 0·51 | 0·69 | $10^5 k_1$ ...... | 0·56 | 0·85 | 1·18 | 1·54 | 2·65 |

increase linearly with alcohol concentration up to about 1·5M, whereupon departures from linearity occur. These departures are accelerative with methyl, ethyl, and benzyl alcohols and decelerative for *iso*propyl and *n*-, *sec.*-, and *tert.*-butyl alcohols.

With phenols the rate increase is almost linear up to between 0·3 and 0·5M (the actual value depending on the phenol), whereat a " more than linear catalysis " sets in.

Only two carboxylic acids have been examined, acetic and benzoic. Both show a lower catalytic capacity than phenols. Acetic acid was examined up to 3·25M, and the departure from linearity was apparent above *ca.* 0·80M, whereat a deceleration occurs.

The linear rate coefficients, $10^5 k_1$ (sec.$^{-1}$), for reactions in presence of alcohols respectively are 0·367 + 0·86[PhCH$_2$OH], 0·367 + 0·72[MeOH], 0·367 + 0·49[EtOH], 0·367 + 0·23[Pr^{n}OH], 0·367 + 0·15[Pr^{i}OH], 0·367 + 0·15[Bu^{n}OH], 0·367 + 0·11[Bu^{s}OH], 0·367 + 0·03[Bu^{t}OH].

With phenols, the *initial* slopes are of the form: $10^5 k_1 = 0·367 + k_2$[ArOH] from which the following catalytic coefficients, $10^5 k_2$ (sec.$^{-1}$ l. mole^{-1}) are obtained: p-NO$_2$·C$_6$H$_4$·OH 5·6, p-Br·C$_6$H$_4$·OH 3·16, PhOH 2·68, p-Bu^t·C$_6$H$_4$·OH 2·35, p-CN·C$_6$H$_4$·OH 5·0, p-Cl·C$_6$H$_4$·OH 3·10, m-Me·C$_6$H$_4$·OH 2·55, p-MeO·C$_6$H$_4$·OH 2·28 p-I·C$_6$H$_4$·OH 3·25, p-F·C$_6$H$_4$·OH 2·8, p-CH$_3$·C$_6$H$_4$·OH 2·4.

DISCUSSION

In the region of linear catalysis the order of decreasing efficiency in alcohols (EtOH = 1) is: Ph·CH$_2$·OH (1·75) > MeOH (1·47) > EtOH (1·00) > Pr^{n}OH (0·47) > Bu^{n}OH (0·30) ~ Pr Pr^{i}OH (0·30) > Bu^{s}OH (0·225) > Bu^{t}OH (~0·06). With the exception of benzyl alcohol this is the accepted order of decreasing acidity. It is unlikely that the special position of benzyl alcohol is due to a nucleophilic component. It may be that when we refer to alcohols in nitromethane, we refer to the fraction which is free to ;form hydrogen bonds (monomers) and that this fraction is particularly high in benzyl alcohol. According to its acidity, benzyl alcohol is placed after ethanol.

The " more than linear " catalysis is shown by hydroxylic reagents which, when solvents, are more ionising media towards *tert.*-butyl bromide than nitromethane. Indeed, the alcohols which at high concentration show a " less than linear " catalysis are, when solvents, poorer ionising media than nitromethane. This means that in addition to the hydrogen-bonding molecule which is responsible for the linear catalysis, one or more hydroxylic molecules intrude among the nitromethane molecules in the solvation shell of the transition state leading to a more than or less than linear increase in the ionisation rate, as the case may be.

The phenols follow at low concentration the acidity order. Indeed a linear correlation exists between the logarithm of the initial catalytic slope of a given phenol and its pK_a in water. Since the ionisation of phenols in water conforms with the Hammett equation log (K_{ArOH}/K_{PhOH}) = $\rho\sigma$, one would also expect the logarithm of the ratio of the catalytic coefficients log ($k_{2(ArOH)}/k_{2(PhOH)}$) to be directly proportional to the σ constants of the phenols.[6] This is confirmed by Table 4 where $\rho = 0·27 \pm 0·03$.

TABLE 4.

Subst.	σ	log ($k_{2(ArOH)}/k_{2(PhOH)}$)	ρ	Subst.	σ	log ($k_{2(ArOH)}/k_{2(PhOH)}$)	ρ
p-MeO	−0·268	−0·070	0·26	p-Cl	+0·0226	+0·064	0·28
p-Bu^t	−0·197	−0·057	0·29	p-Br	+0·232	+0·071	0·30
p-Me	−0·170	−0·048	0·28	p-I	+0·276	+0·83	0·30
m-Me	+0·069	+0·020	0·29	p-CN	+1·00	+0·270	0·27
p-F	+0·062	+0·018	0·29	p-NO$_2$	+1·27	+0·32	0·25

Acetic and benzoic acids show a capacity to assist the ionisation of *tert.*-butyl bromide in nitromethane which is only slightly higher than that of alcohols. A comparison with phenols on the basis of acid strength is misleading since if these carboxylic acids exist largely as cyclic dimers then they are not present under the kinetic conditions as the same species whose acid strength we determine in hydroxylic solvents.

Bartlett and Dauben [7] showed that the hydroxylic compounds which catalyse the rearrangement of camphene hydrochloride into *iso*bornyl chloride are all capable of increasing the acidity of hydrogen chloride in dioxan. Since hydrogen chloride in dioxan

[6] Hammett, " Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, 1940, p. 188; Hine, " Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, 1956, p. 72.
[7] Bartlett and Dauben, *J. Amer. Chem. Soc.*, 1940, **62**, 1339.

is present as the weaker acid, dioxanonium chloride from which the hydroxylic reagents employed by them were incapable of taking a proton, they were able to obtain a measure of the hydrogen-bonding capacity of these reagents with a chlorine atom.   Indeed, the order they obtain agrees well with the present kinetic observations, *i.e.*, p-CN·C_6H_4·OH > p-Cl·C_6H_4·OH > PhOH > p-Me·C_6H_4·OH > Me·CO_2H > MeOH > EtOH > Pr^iOH.   Thus in their case, too, acetic acid showed a catalytic capacity similar to that of alcohols.

The author is indebted to Mr. D. W. Hills for technical assistance.