809. *Aromatic Alkylation. Part V.* Alkylation by Aliphatic Alcohols in Aqueous Perchloric Acid.*

By V. Gold and T. Riley.

Acid-catalysed interaction of aliphatic alcohols (methyl, isopropyl, isobutyl, and t-butyl) with aromatic compounds (anisole and benzene) has been qualitatively examined. Anisole and t-butyl alcohol in aqueous perchloric acid at 25° give mainly *p*-t-butylanisole. In the approximate acid-concentration range 50—60% w/w the rate of this reaction is conveniently measurable and increases with acidity. The other alkylations appear to be less straight-forward. The acidity-dependence and mechanism of the t-butylation of anisole are discussed and compared with other acid-catalysed reactions of t-butyl alcohol.

Earlier Parts of this series have established that the velocity of diarylmethylation of reactive aromatic compounds (ArH) depends on the acidity of an acetic acid medium in the same manner as the ionisation (to form carbonium ions) of very basic diarylmethyl

---

* Part IV, *J.*, 1960, 2973.

compounds.[1] The result implies that, with various catalysts in this solvent, the transition state of the reaction is composed of the diarylmethyl cation and ArH.

The present work extends this approach to the alkylation of anisole by aliphatic alcohols in aqueous perchloric acid. These reactions differ from those previously investigated in several respects. The medium now used precludes a significant amount of esterification of the alcohol. Further, it is one for which measurements of acidity functions have been reported [2] and which has been considered in connection with the application of acidity functions to other reactions of aliphatic alcohols.[3] In addition, the carbonium ions related to aliphatic alcohols are less stable than those derived from diarylmethanols.

EXPERIMENTAL

Materials.—Acid solutions were prepared by dilution of " AnalaR " 60% perchloric acid and standardised against potassium iodate.

t-Butyl alcohol (reagent grade) was refluxed over calcium oxide for 10 hr., fractionally distilled, and further purified by two fractional freezings (m. p. 25·6°). Isopropyl and isobutyl alcohol (" AnalaR ") were refluxed successively over calcium oxide (10 hr.) and clean magnesium ribbon (6 hr.), and then fractionally distilled. " AnalaR " methanol was used without purification. The purification of anisole for kinetic experiments has been described previously.[1]

A reference specimen of *p*-t-butylanisole was prepared by methylation (dimethyl sulphate) of commercial *p*-t-butylphenol. It was purified in the same way as anisole.[1] *o*- and *p*-Isopropylanisole were prepared [4] by the reaction between anisole (28 g.), isopropyl alcohol (16·5 g.), and aluminium chloride (35 g.): the product distilling in the range 190—230° was collected and purified by the method used for anisole. Fractional distillation gave two fractions, boiling respectively (at 765 mm.) at 196—201° (8·7 g.) and 210—213° (23·5 g.). Vapour-phase chromatography showed the fractions to contain two compounds only, the major component in each fraction being contaminated with a little of the other. According to the literature *o*-isopropylanisole [5] boils at 198°/751 mm. and *p*-isopropylanisole [6] at 212°/758 mm. The analogous reaction of anisole and isobutyl alcohol [7] gave a product (b. p. 120—135°/18 mm.) which was found (vapour-phase chromatography) to be a mixture of five components. For our purpose (see below) the separation of this mixture was not essential and was not attempted.

Preparative Alkylations with Perchloric Acid as Catalyst.—These experiments were carried out with the primary object of finding experimental conditions under which a reaction of this type would proceed smoothly in homogeneous solution.

(*a*) *Experiments with benzene.* A heterogeneous mixture of benzene (45 ml.), alcohol (5 ml.), and 60% perchloric acid (200 ml.) was refluxed for 8 hr., then poured into water and extracted with ether. The extract was washed successively with water, dilute aqueous sodium hydrogen carbonate, and water, dried ($MgSO_4$), and distilled, the final fraction (10 ml.) of distillate being retained for analysis by infrared spectrometry and vapour-phase chromatography. With methanol there was considerable charring but no toluene was formed. With isopropyl alcohol there was evidence for the formation of a small amount of isopropylbenzene, and some charring; additional infrared frequencies observed in the regions 12—13 μ were probably due to polysubstitution. With t-butyl alcohol, t-butylbenzene and *p*-di-t-butylbenzene were identified among the products, but there was some charring and evidence of other unidentified products.

(*b*) *Experiments with anisole.* Mixtures of anisole (30 g.), t-butyl alcohol (10 g.), and 60% perchloric acid (100 ml.) were either (i) heated at 60° for 5 hr. or (ii) left at room temperature for 3 days. Products (isolated as in the experiments with benzene) were found to be identical in composition, which indicates that the reaction had proceeded either to completion or to

---

[1] Bethell and Gold, *J.*, (*a*) 1958, 1905; (*b*) 1958, 1930; (*c*) Bethell, Gold, and Riley, *J.*, 1959, 3134; (*d*) Gold and Riley, *J.*, 1960, 2973.

[2] Deno, Berkheimer, Evans, and Peterson, *J. Amer. Chem. Soc.*, 1959, **81**, 2344.

[3] Boyd, Taft, Wolf, and Christman, *J. Amer. Chem. Soc.*, 1960, **82**, 4729.

[4] Tsukervanik and Nazarova, *J. Gen. Chem.* (*U.S.S.R.*), 1935, **5**, 767; *Chem. Abs.*, 1936, **30**, 443.

[5] Fileti, *Gazzetta*, 1886, **16**, 116.

[6] Paterno and Spica, *Gazzetta*, 1876, **6**, 536.

[7] Tsukervanik and Tambovtseva, *Bull. Univ. Asie centrale*, 1938, **22**, 221; *Chem. Abs.*, 1940, **34**, 4729.

equilibrium in both cases. The more drastic conditions (i) are therefore not necessary. The infrared spectrum of the products consisted of a superposition of the spectra of anisole and *p*-t-butylanisole, with the addition of peaks at 8·8 and 9·1 μ. The reaction was also studied in a slightly different manner with several alcohols in turn, as follows. Anisole (32 ml.) was shaken with 60% perchloric acid (100 ml.) for 30 min. The alcohol (11 ml.) was then added. The heterogeneous mixture was shaken for a few minutes and then left at room temperature for 48 hr. Aromatic substances were isolated from the product mixture as before, and care was taken to avoid distillation of anisole during the distillation of ether. In the attempted reactions with methanol and with isobutyl alcohol, anisole was the only compound detected in the residue. With t-butyl alcohol, the residue weighed 37·1 g. (the expected weight for the complete consumption of t-butyl alcohol with formation of t-butyl derivatives of anisole only being 38·1 g.). This product was found to be a mixture of mainly anisole and *p*-t-butylanisole, but it also showed the infrared peaks at 8·8 and 9·1 μ. Vapour-phase chromatography indicated anisole, *p*-t-butylanisole, and one further product with a slightly shorter retention time (on a Celite–paraffin column) than *p*-t-butylanisole. From the weight of the aromatic residue, this substance must be a t-butylanisole. On the assumption that the thermal conductivity detector has the same response for two isomeric t-butylanisoles, the mole-percentage composition of the product mixture was calculated to be: anisole, 58·6; *p*-t-butylanisole, 33·1; *x*-t-butylanisole, 8·3%. The last product is probably *o*-t-butylanisole. On this assumption, the *o*- and *p*-t-butylanisole are formed in a ratio of 1 : 4. The analogous reaction with isopropyl alcohol was not quantitative. It gave two products which were identified by vapour-phase chromatography to be *o*- and *p*-isopropylanisole, formed in the ratio 1 : 1·2. The retention times of *o*- and *p*-isopropylanisole (10·3 and 11·7 min.) compare with a time of 12·8 min. for the unidentified t-butylanisole and of 15·2 min. for *p*-t-butylanisole. The sequence supports the inference that the unidentified t-butylanisole is the *ortho*-isomer.

Kinetic Experiments.—Reactions (at 25°) were initiated by mixing freshly prepared solutions of anisole and of t-butyl alcohol in perchloric acid. After an appropriate interval the entire contents (10 ml.) of a reaction flask were diluted with an equal volume of water and extracted with five successive 10-ml. portions of carbon tetrachloride. The combined extracts were made up to exactly 50 ml., a little finely powdered barium oxide was added to take up residual moisture and acid, and the mixture was shaken. After 1 hr. the solutions were analysed spectrophotometrically (Beckman DU). In order to simplify the application of the kinetic law, anisole was present in *ca.* ten-fold excess over t-butyl alcohol.

Stock solutions of t-butyl alcohol and of anisole in the batch of perchloric acid used for kinetic experiments were stable at room temperature for considerably longer periods than required for our purposes. The t-butyl alcohol solutions in 60% perchloric acid remained colourless for at least 3 days and analysis [8] indicated less than 1% loss of t-butyl alcohol in this time. The stability of anisole solutions was greatly increased by rigorous purification and storage in the dark. Analyses after 2 days' storage indicated negligible loss of anisole. The same behaviour was noted for a solution of *p*-t-butylanisole in perchloric acid. The reported formation of small amounts of isobutene and di-isobutene during the t-butylation of phenol in perchloric acid [9] may be connected with the use of a higher temperature (60°) and may occur at a smaller speed in our system.

Initial and final optical densities (D_0, D_∞) at 2860 Å were compared with values calculated from the spectra of the starting materials and of *p*-t-butylanisole (on the supposition either that *p*-t-butylanisole is the only product under these mild conditions or that the other product has a similar extinction coefficient at 2860 Å). Comparative values are recorded in Table 1.

TABLE 1.

$HClO_4$ (wt. %)	D_0 (found)	D_0 (calc.)	D_∞ (found)	D_∞ (calc.)	$HClO_4$ (wt. %)	D_0 (found)	D_0 (calc.)	D_∞ (found)	D_∞ (calc.)
52·8	0·703	0·703	0·870	0·872	57·3	0·508	0·507	0·686	0·667
53·9	0·508	0·508	0·686	0·688	58·3	0·770	0·772	1·031	1·008
55·3	0·703	0·702	0·870	0·860	58·7	0·770	0·772	1·031	1·002
55·8	0·713	0·709	0·979	0·971					

---

[8] Duke, *Ind. Eng. Chem., Analyt.*, 1945, **17**, 572.
[9] Sears, *J. Org. Chem.*, 1948, **13**, 120.

The satisfactory stability of solutions of reagents, and the agreement between observed and calculated optical densities, were not found with every batch of perchloric acid. In particular, some experiments indicated a marked discrepancy between observed and calculated values of D_0, which pointed to the occurrence of a rapid concurrent process of unknown nature. The kinetic results now reported relate entirely to the batch of reagents for which the above stability tests were satisfactory. In other acid solutions discrepant rates were observed but the dependence of the reaction velocity on acidity was confirmed. It is our view that the variable complications are associated with minor impurities in the perchloric acid to which, because of the high concentration of acid and low concentrations of other reagents, our kinetic experiments are likely to be sensitive. The consequent lack of reproducibility of these results with different batches of acid detracts from their value but it seems unlikely that our chief conclusions are invalidated thereby.

First-order rate constants (k_1) were calculated from the equation $k_1t = 2{\cdot}303 \log [(D_\infty - D_0)/(D_\infty - D_t)]$ where D_t is the optical density after a time t. The equation yields the rate constant for the disappearance of t-butyl alcohol in the presence of a given excess of anisole and applies irrespectively of whether this reaction results in just one or in several isomeric t-butylanisoles. Second-order constants (k_2) were calculated by dividing k_1 values by the concentration of anisole.

Results are recorded in Table 2.

TABLE 2.

Rate constants for t-butylation of anisole in aqueous perchloric acid.

$HClO_4$ (wt. %)	10^3[Anisole] (M)	10^4[Bu^tOH] (M)	10^4k_2 (sec.$^{-1}$ mole^{-1} l.)	$\log k_2$	$-J_0$	$-(\log k_2 + J_0)$
52·8	8·85	7·30	5·42	$\bar{4}{\cdot}73$	8·68	11·95
53·9	6·40	7·75	12·50	$\bar{3}{\cdot}10$	9·08	11·98
53·9	9·70	7·75	12·68	$\bar{3}{\cdot}10$	9·08	11·98
55·3	8·85	7·30	37·3	$\bar{3}{\cdot}57$	9·46	11·89
55·8	8·98	11·55	42·3	$\bar{3}{\cdot}63$	9·64	12·01
57·3	6·40	7·75	128·6	$\bar{2}{\cdot}11$	10·14	12·03
58·3	9·70	11·20	300	$\bar{2}{\cdot}48$	10·46	11·98
58·8	9·70	11·20	421	$\bar{2}{\cdot}63$	10·68	12·05

DISCUSSION

The present results show, first, that the rate of t-butylation of anisole by t-butyl alcohol in aqueous perchloric acid follows the J_0 acidity function,[10] as established for indicators of the triphenylmethanol type,[2] and, secondly, that secondary and primary aliphatic alcohols are ineffective or less effective in the analogous reactions. The results suggest that the transition state of the reaction is made up from anisole and the t-butyl cation, *i.e.*, that the mechanism of t-butylation is substantially the same as that of diarylmethylation in acetic acid solution containing an acidic catalyst.[1] Structural variation in the alcohol enhances the reactivity according to the known effects of alkyl substitution on the stability of aliphatic carbonium ions.[11] This sequence accords with an earlier finding [1b] that the order of reactivity is determined by the ionising tendency of the alkylating agent and not by the (inverse) sequence of reactivity of the resulting carbonium ions.

The linear dependence of the logarithm of the rate constant on the acidity function J_0 provides the first recorded example of such behaviour for a reaction of an aliphatic alcohol. An isolated case of the dependence of a reaction velocity on a particular measure of solvent acidity ([H$^+$], h_0 or j_0) is no longer, by itself, acceptable evidence for a particular reaction mechanism. A reaction will be proportional to one of these functions in an aqueous solvent mixture if a certain quotient involving activity coefficients is invariant with solvent composition over the range studied. The situation is explained by Table 3 which lists

---

[10] (*a*) Gold and Hawes, *J.*, 1951, 2102; (*b*) Gold, *J.*, 1955, 1263.

[11] Bethell and Gold, *Quart. Rev.*, 1958, **12**, 1058.

the quotients that must be constant for a reaction characterised by a certain transition-state composition, given on the left, to be proportional to the acidity functions listed at the head of the Table. The Table is not comprehensive since the participation of more than one water molecule must in principle be considered.[12] If a further species Y takes part in the reaction and is included in the composition of the transition state, the relevant quotient must be multiplied by the factor f_Y. In this Table, B represents an H_0-indicator (typically an aromatic primary amine) and ROH stands for an indicator used for establishing the J_0 function {typically triarylmethanols with the significant exclusion of those containing acylamino-groups,[13] whose ionisation tendency follows the function [10b] J_0' [$\equiv H_0 + \log (H_2O)$]}. The diagonal elements in the array represent the conditions which follow from the Zucker–Hammett hypothesis and its logical extensions. These are consistent with a composition {Me_3C, anisole}$^+$ for the transition state of our reaction. This conclusion is supported by the fact that a different reaction of t-butyl alcohol, namely, oxygen-isotope exchange, shows a velocity-dependence on H_0 and that this is also consistent with the Zucker–Hammett hypothesis.[3] It is a common feature of different mechanistic interpretations of this reaction [3,14] that the transition state is a strained alkoxonium ion (composition: {Bu, H_2O}$^+$), and the H_0-dependence (the exact slope of the linear graph of log k against H_0 is $-1{\cdot}2$) requires near-constancy of the ratio $f_{BH^+}f_{BuOH}/f_Bf_\ddagger$. Analogously, the dehydration of tertiary alcohols, which also follows H_0 [3,15] but is a slower reaction,[14] can be interpreted in terms of an isomeric transition state of the same composition.

TABLE 3.

	H_3O^+	h_0	j_0
{SH *plus* H_2O}$^+$ …………	$f_{H_3O^+}f_S/f_\ddagger$	$f_{BH^+}f_S(H_2O)/f_Bf_\ddagger$	$f_{R^+}f_S(H_2O)^2/f_{ROH}f_\ddagger$
{SH}$^+$ ……………………	$f_{H_3O^+}f_S/f_\ddagger(H_2O)$	$f_{BH^+}f_S/f_Bf_\ddagger$	$f_{R^+}f_S(H_2O)/f_{ROH}f_\ddagger$
{SH *minus* H_2O}$^+$ ………	$f_{H_3O^+}f_S/f_\ddagger(H_2O)^2$	$f_{BH^+}f_S/f_Bf_\ddagger(H_2O)$	$f_{R^+}f_S/f_{ROH}f_\ddagger$

The most relevant comparison of our results is with a study of the acid-catalysed formation of *N*-t-butylacrylamide from t-butyl alcohol and acrylonitrile.[16] The reaction is thought to be initiated by nucleophilic attack of nitrile upon the central carbon atom in t-butyl alcohol (whereas our reaction entails similar attack by the aromatic species). The reaction with acrylonitrile differs from that with anisole in the manner of its acidity-dependence. At low acidities its velocity is proportional to h_0, but the rate increase gradually levels off. The authors of this work interpret the proportionality to h_0 as indicating a bimolecular reaction between protonated t-butyl alcohol and acrylonitrile and ascribe the levelling off to the attainment of complete protonation of the alcohol at high acidities. They show that the assumption of a pK value of $-3{\cdot}80$ for the conjugate acid of t-butyl alcohol would reconcile the whole range of data,[16] a procedure similar to that previously used in explaining an anomalous acidity-dependence of the velocity of a reaction of isopropyl alcohol.[17] This result contrasts with the steady increase of reaction velocity with acidity found in the present study (which extends well beyond solvent acidities of $H_0 = -3{\cdot}8$). If the two reactions had the analogous mechanisms it would then follow that they could not both conform to the Zucker–Hammett hypothesis. A comparison of the terms which appear in the relevant quotients of activity coefficients (Table 3) does not reveal any factor to explain the difference. Such a difference in the dependence of activity coefficients on composition of the medium could arise from a difference in the " surfaces " which the solute molecules concerned present to the solvent

---

[12] Cf. Leisten, *Chem. and Ind.*, 1959, 397.

[13] Deno and Evans, *J. Amer. Chem. Soc.*, 1957, **79**, 5804.

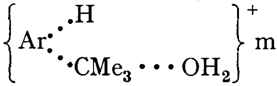
[14] Dostrovsky and Klein, *J.*, 1955, 791.

[15] Roček, *Coll. Czech. Chem. Comm.*, 1960, **25**, 375.

[16] Deno, Edwards, and Perizzolo, *J. Amer. Chem. Soc.*, 1957, **79**, 2108.

[17] Bartlett and McCollum, *J. Amer. Chem. Soc.*, 1956, **78**, 1441.

and thus in the interactions (particularly hydrogen-bonding) that are possible between solutes and solvent.[18]

Indeed, the difference in acidity-dependence between the two reactions is so gross that detailed considerations of acidity functions are hardly required to reach the conclusion that different mechanisms apply to the two reactions. This deduction appears strange at first sight since it seems to imply the postulation of different reactive entities derived from t-butyl alcohol for reactions of a similar character and comparable velocity. This assumption does not, however, appear so arbitrary when the steric requirements of the two transition states are compared. It can then be argued that, whereas a linear transition state $\{\mathrm{R{-}C{\equiv}N}\cdots\mathrm{CMe_3}\cdots\mathrm{OH_2}\}^+$ can accommodate the presence of the water molecule, the corresponding more crowded structure which would apply to aromatic t-butylation  $\left\{\mathrm{Ar}\begin{array}{l}\cdot\cdot\mathrm{H}\\ \cdot\cdot\mathrm{CMe_3}\cdots\mathrm{OH_2}\end{array}\right\}^+$ might be too unstable for the water molecule to remain attached to the t-butyl group as the $\mathrm{Ar}\cdots\mathrm{CMe_3}$ distance shortens to its transition-state value. Inasmuch as kinetic orders yield information only about the composition of a transition state and not about equilibrium processes preceding its formation, the t-butylation of anisole can, with equal validity in the light of present information, be regarded either as a bimolecular reaction between $\mathrm{Me_3C{-}OH_2^+}$ and anisole with loss of a water molecule in the course of the molecular rearrangement leading to the transition state, or as a bimolecular reaction between $\mathrm{Me_3C^+}$ and anisole. The two points of view differ only in kinetic inessentials, *viz.*, the timing of the detachment of water, a situation reminiscent of the different interpretations of H_0-dependent proton-transfer reactions.[19]

Although the postulation of a steric effect in the expected direction seems to explain the difference in reaction mechanism between acrylonitrile and anisole, an unexplained discrepancy remains in that the pK value assumed by Deno *et al.*[16] for t-butyl alcohol would require almost complete protonation of t-butyl alcohol at the higher acidities employed by us. Since the equilibrium (real or hypothetical) between the bulk form of t-butyl alcohol (*i.e.*, $\mathrm{Me_3C{-}OH_2^+}$) and t-butyl cations would then involve only a dehydration, the acidity-dependence of the reaction velocity well beyond $H_0 = -3{\cdot}8$ should follow the function $(J_0 - H_0)$ rather than J_0. At somewhat lower acidities the function $J_0 + \log (K + h_0)$ (where K is the acidity constant of the conjugate acid of t-butyl alcohol) should apply. Our results are not claimed to be very accurate but they do not reflect such a trend. It would therefore be desirable to find independent evidence concerning the basic strength of t-butyl alcohol in aqueous solution.

We thank D.S.I.R. for the award of a Fellowship (to T. R.).

KING'S COLLEGE UNIVERSITY OF LONDON,
STRAND, LONDON, W.C.2.

[*Received, April 27th*, 1962.]

---

[18] Cf. Taft, *J. Amer. Chem. Soc.*, 1960, **82**, 2965.

[19] Gold, Lambert, and Satchell, *J.*, 1960, 2461.