362. *The Kinetics of Hydrogen Isotope Exchange Reactions.*
Part XII.* The Behaviour of Primary Alcohols in Acidic Media.

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n-Propyl alcohol rearranges to isopropyl alcohol in 8M-perchloric acid at 100°. The equilibrium constant of the rearrangement is ⩾100. When performed in a tritiated medium, the reaction yields a product containing tritium, the rate of tritium uptake being consistent with the occurrence of exchange after rearrangement. The unrearranged alcohol contains no significant amount of tritium. Comparisons of the rate of rearrangement with rates of related reactions support the view that the rearrangement involves an intramolecular hydride shift in the n-propyl cation and does not go through propene.

Experiments with cyclohexylmethanol in tritiated acidic media likewise indicate that there is no exchange in the primary alcohol but that exchange occurs in either a rearranged alcohol or its decomposition product(s).

THE present work was started with the object of investigating the hitherto undecided question whether exchange of the aliphatic hydrogen atoms in a primary alcohol can be realised in acidic media. It was expected that such exchange might be accompanied by rearrangement since the intermediate formation of a carbonium ion or of an olefin (or both) would have that consequence. Thus n-propyl alcohol, the first compound studied, might rearrange to isopropyl alcohol. We find that this rearrangement as well as the entry of tritium into paraffinic positions occur under our somewhat drastic acid conditions. The connection between exchange and rearrangement is now examined.

In previous work on the n-propyl system[1] it was noted that solvolysis of n-propyl bromide in formic acid containing mercury salts was accompanied by *ca.* 13% of rearrangement to an isopropyl compound, and that at least part of the rearrangement must follow a route not involving propene as an intermediate. On the other hand, hydrogen exchanges of aliphatic substrates in acidic media have been explained in terms of olefinic intermediates.[2-4] Our experiments attempt to clarify the reaction scheme which is applicable to the acid-catalysed rearrangement of n-propyl alcohol and to the hydrogen exchange in a primary alcohol.

EXPERIMENTAL

n-Propyl alcohol (from Messrs. Hopkin and Williams) was treated with bromine according to Kretschmer's method to remove olefins.[5] After fractional distillation the product was either used without further purification (for dilution purposes only) or converted into the propyl hydrogen 3-nitrophthalate by heating it with 3-nitrophthalic anhydride at 76—110° for 15 hr. The product was in turn crystallised from water, 3 : 1 benzene–light petroleum (b. p. 100—120°), and benzene. The ester was hydrolysed under reflux with aqueous 7·5N-sodium hydroxide (45 min.), and the product was distilled off, both operations being carried out in an atmosphere of nitrogen. The first fraction had a strong smell of aldehyde. The second fraction (b. p. 87—92°) was dried (K_2CO_3) and stored under reduced pressure in the dark over 2,4-dinitrophenylhydrazine. For kinetic experiments samples were freshly vacuum-distilled from this stock. Gas-chromatography (columns A and F of ref. 4) indicated 0·2—0·5% of s-butyl alcohol (initially *ca.* 1·5%) and complete absence of t-butyl alcohol (initially *ca.* 1·5%). Both the original and the purified sample were found to be free from allyl alcohol, which is reported to be a

* Part XI, preceding paper.

[1] Coe and Gold, *J.*, 1960, 4940.
[2] Gold and (D. P. N.) Satchell, *Quart. Rev.*, 1955, **9**, 51.
[3] Coe and Gold, *J.*, 1960, 4185.
[4] Gold and (R. S.) Satchell, preceding paper.
[5] Kretschmer, *J. Phys. Colloid. Chem.*, 1951, **55**, 1351.

common impurity of propyl alcohol.[6] Cyclohexylmethanol (from Aldrich Chemical Company) was distilled (b. p. 186—188°/768·5 mm.; $n_D^{19·5}$ 1·4642; closely agreeing with values in the literature). Gas-chromatography with three different column packings (silver nitrate–glycerol on Celite; Apiezon L grease on Celite; and Silicone oil on Celite) failed to reveal impurities.

1-Methylcyclohexanol was prepared from cyclohexanone and methyl iodide by a Grignard reaction.[7] The ether extract of the product was shaken with saturated sodium hydrogen sulphite solution, washed with water, and dried (Na_2CO_3). After filtration and removal of ether, the residue was distilled under reduced pressure. The first fraction (b. p. 45—46·5°/6·5 mm.) gave no evidence of impurity (gas-chromatography) and was used in all experiments.

Formic acid (" AnalaR ") was fractionally distilled and the fraction with b. p. 100—100·5°/753 mm. and f. p. 8·2° was used. Solutions in a reaction medium containing 90% formic acid with water and 0·1M-hydrobromic acid were prepared by adding aqueous solutions of hydrobromic acid and of the reagent alcohol to formic acid.

Other acid media, reagents, and radioactive-counting equipment were the same as before.[4]

Exchange of n-Propyl Alcohol in 90% Formic Acid with 0·1M-Hydrobromic Acid at 100°.—These experiments, carried out under the conditions employed by Coe and Gold,[8] indicated very small amounts of exchange [N(exchange number) = 0·001 after 20 hr. with a 0·15M-solution of the purified specimen]. The exchange numbers were greater with alcohol samples containing s-butyl and t-butyl alcohol, being 0·035 and 0·044 for samples containing 1·5 and 2·9% of these two alcohols in the former case and 2·9 and 0·07% in the latter. The results confirm the previously expressed suspicion that the observed apparent tritium uptake by organic material from the medium under these conditions is not an exchange reaction of n-propyl alcohol.[8]

The reaction was carried out in sealed ampoules which were heated at 100° for 20 hr. After cooling, a tube was broken in a large flask containing water (20 ml.) and inactive propyl alcohol (50 ml.). The liquids were transferred to a separatory funnel, saturated with sodium chloride, and further treated before counting in the same manner as for the isopropyl alcohol samples in previous work.[4] (This treatment removes hydroxylic tritium from the sample.)

Isomerisation of n- to Iso-propyl Alcohol.—The reaction was followed by heating sealed ampoules containing 5 ml. of 7·6 or 8·0M-aqueous perchloric acid and 0·13M-n-propyl alcohol at 100°, and analysing the resultant mixture of alcohols either by the spectrophotometric estimation of isopropyl alcohol (with salicylaldehyde, after oxidation to acetone [1,9]) (" method 1 ") or by gas-chromatography (silver nitrate–glycerol on Celite) (" method 2 "). A correction could be applied for the presence of low concentrations ($\leqslant 10^{-3}$M) of n-propyl alcohol in the spectrophotometric analyses for isopropyl alcohol. Solutions were therefore diluted so as to fall below this concentration. For analysis by gas-chromatography, 40% aqueous sodium hydroxide (7 ml.) was added with cooling (tap water) to a 5 ml. sample of reaction mixture. Extraction with ether (6 × 3 ml. or 6 × 5 ml.) was shown to remove 97—99% of the alcohols and was carried out for each sample. A known weight (15·1 mg.) of pentanol was added to the combined extracts, and the volume of the solution was made up to 50 ml. with ether. The amounts of the propyl alcohols in the solution were found by comparing the areas under their chromatogram traces with the area under the pentanol trace. The method was repeatedly standardised with synthetic mixtures but was of limited reproducibility. Each chromatographic analysis was therefore repeated several times and the standard deviation of the mean value calculated as an indication of reliability. Results obtained by the two methods are given in Tables 1 and 2. (No analytical figure was excluded from the calculation of the mean quoted.)

It was suspected that carbonyl compounds might be formed during the reaction, but colorimetric estimation with 2,4-dinitrophenylhydrazine [10] failed to detect any propanal or acetone. However, no conclusions can be drawn from this negative result since propanal is destroyed under these conditions. A sample left in 8M-perchloric acid for 1 hr. at room temperature and 5·25 hr.

[6] Weissberger, Proskauer, Riddick, and Toops, " Technique of Organic Chemistry," Vol. VII, Interscience Publ. Inc., New York, 1955, p. 343.

[7] Signaigo and Cramer, *J. Amer. Chem. Soc.*, 1933, **55**, 3326.

[8] Coe and Gold, *J.*, 1960, 4571.

[9] Neish, " Analytical Methods for Bacterial Fermentation," National Research Council of Canada, Saskatoon, 1952.

[10] Lappin and Clark, *Analyt. Chem.*, 1951, **23**, 541.

TABLE 1.

Isomerisation of n-propyl alcohol in 8·01M-perchloric acid at 100°.
(Analysis: method 1.)

$[Pr^nOH]_0 = 0.133M$.

Reaction time (hr.)	100[Pr^IOH]/[Pr^nOH]_0		Reaction time (hr.)	100[Pr^IOH]/[Pr^nOH]_0	
	exptl.*	calc.†		exptl.*	calc.†
1·5	11·1 (0·2)	10·8	24	78·4 (2·1)	77·5
4	24·4 (1·8)	26·1	72	79·1 (1·1)	79·8
8	44·3 (0·8)	44·5	168	63·8 (1·4)	63·0
15	64·9 (1·5)	64·7	480	27·9 (0·7)	28·4

* Values in parentheses are standard deviations of mean of n (usually 4—8) analyses, calc. as $[\sum \Delta^2/n(n-1)]^{\frac{1}{2}}$ where Δ is deviation from mean value. † Calc. from eqn. (1) ($\times 100$), with $k_1 = 2.14 \times 10^{-5}$, $k_2 = 0.16 \times 10^{-5}$, and $k_3 = 0.07 \times 10^{-5}$ sec.$^{-1}$.

TABLE 2.

Isomerisation of n-propyl alcohol in *ca.* 7·6M-perchloric acid at 100°.
(Analysis: method 2.)

Reaction time (hr.)	100[Pr^IOH]/[Pr^nOH]_0	100[Pr^nOH]/[Pr^nOH]_0	Reaction time (hr.)	100[Pr^IOH]/[Pr^nOH]_0	100[Pr^nOH]/[Pr^nOH]_0
0·0	—	96·8 (1·9)	17	37·8 (3·1)*	35·7 (1·9)
0·7	2·6 (0·4) *	91·7 (3·4)	24	50·1 (3·9)	27·5 (0·8)
1·5	3·8 (0·2)	74·0 (2·4)	48	55·0 (3·0)	7·2 (0·5)
4·0	11·3 (0·4)	75·5 (2·4)	100	57·2 (0·8)	1·4 (0·1)
8	25·8 (0·6)	58·7 (3·5)			

* See first footnote of Table 1.

at 100° was found finally to contain less than 2% of the original amount of propanal. The product of this reaction is not known but could be propionic acid.

Tritium Uptake with n-Propyl Alcohol in 8M-*Perchloric Acid.*—In the first and main series of experiments (Table 3) the alcohol product, extracted as for the experiments with formic acid, was not distilled before counting. The radioactivity measured therefore includes tightly bound tritium in all organic compounds present except any that are highly soluble in, and are therefore removed by washing with, aqueous sodium hydroxide. In these experiments the alcohol activity was estimated by a variant of the internal standardisation procedure described. In this method, counts were performed on the following three mixtures of identical chemical composition with 20 ml. of the scintillator solution: (1) water, 0·5 ml., and inactive n-propyl alcohol, 2 ml. (background); (2) water, 0·5 ml., and active alcohol, 2 ml. (*i.e.*, the alcohol mixture extracted by n-propyl alcohol); and (3) diluted tritiated water, 0·5 ml., and the active alcohol, 2 ml. (as before). This modification is preferable where there is a change in the chemical

TABLE 3.

Tritium uptake by organic solutes for solutions of n-propyl alcohol in
8·0M-perchloric acid at 100°.

$[Pr^nOH]_0 = 0.131M$; activity of medium = 14·9 mc per g.-atom of exchangeable hydrogen.

Reaction time (hr.)	Activity * (mc)	N (exptl.)	N (calc.†)	N (calc.‡)	Reaction time (hr.)	Activity * (mc)	N (exptl.)	N (calc.†)	N (calc.‡)
1·5	0·0025	0·25	0·30	0·65	24	0·0376	3·85	4·56	4·65
4	0·0103	1·05	1·19	1·57	72	0·0517	5·29	4·79	4·79
8	0·0235	2·41	2·39	2·67	168	0·0493	5·05	3·78	3·78
15	0·0369	3·78	3·72	3·86	480	0·0304	3·11	1·70	1·70

* Activity of organic substrate (not extracted by aqueous sodium hydroxide) in 5·02 ml. of reaction mixture.

† Calc. from equation 2 with $k_4 = 2.7 \times 10^{-4}$ sec.$^{-1}$ (ref. 4) and $\overset{\infty}{N_1} = 6$.

‡ Calc. from equation 3 with $\overset{\infty}{N_1} = 6$.

nature of the exchanging substrate. Exchange numbers (Table 3) were evaluated on the hypothetical basis that the concentration of exchanging solute remained constant during the course of the reaction.

Comparison of Tables 1 and 3 establishes that rearrangement and exchange occur at comparable speeds. Since it is known that exchange of isopropyl alcohol is faster than either of these reactions,[4] it is possible that all the activity found is in fact due to exchange in the rearranged product. To determine the distribution of activity between the two alcohols a mixture of n- (50 ml.) and iso-propyl alcohol (50 ml.) was used as diluent in the extraction of the products from the reaction mixture. After the usual treatment for removal of hydroxylic tritium and drying, the mixture was fractionally distilled and the activities were determined for different fractions of the distillate. (Isopropyl alcohol–water azeotrope containing 87·4% of the alcohol has b. p. 80°; isopropyl alcohol has b. p. 82°; n-propyl alcohol has b. p. 97°.)

Table 4 gives results for an experiment run for 8 hr. Independent product analyses (by

TABLE 4.

Distribution of tritium activity in the alcohol products from the
reactions of n-propyl alcohol in 8·00M-perchloric acid at 100°.

$[Pr^nOH]_0 = 0\cdot131M$; activity of medium: 14·9 mc per g.-atom of exchangeable hydrogen.

Distillate fraction	B. p.	Activity * (μc)	Distillate fraction	B. p.	Activity * (μc)	Distillate fraction	B. p.	Activity * (μc)
1	80·5—83·5°	0·612	4	86·0—87·0°	0·528	7	91·2—92·8°	0·275
2	83·5—85·0	0·557	5	87·0—88·8	0·470	8	92·8—95·0	0·107
3	85·0—86·0	0·565	6	88·8—91·2	0·395	9	95·0	0·025

* Activity per 2·01 ml. of respective fraction.

gas-chromatography, and see also Table 1) have shown that after this time each of the two alcohols should be present in solution to the extent of *ca.* 45% of the initial amount of n-propyl alcohol. On this basis the activity of fraction 9 corresponds to $N = 0\cdot14$ for n-propyl alcohol. It is also evident from the figures that the concentration of tritium in n-propyl alcohol is very much lower than that in its isomer. Later experience with the distillation of mixtures of these isomers labelled with [14]C (Table 5) leads us to think that fraction 9 in Table 4 may have contained a small proportion of (active) isopropyl alcohol, so that $N = 0\cdot14$ must be regarded as a maximum value for the n-alcohol.

The Occurrence of the Isomerisation of Iso- to n-propyl Alcohol.—The results in Tables 1 and 2 indicate that the equilibrium between the two alcohols favours the iso-compound, but that the total concentration of alcohols decreases during the isomerisation under our conditions. For this reason, the exact position of the equilibrium could not be ascertained by letting the reaction proceed for a long time. The equilibrium constant was therefore determined by measuring the extent of conversion of [1,3-^{14}C]propan-2-ol (obtained from the Radiochemical Centre and diluted by us with pure [4] isopropyl alcohol) after various periods in 8·0M-perchloric acid at 100°. The product was diluted with a mixture of the alcohols and fractionally distilled as in the preceding experiment. The fractions from the distillation were assayed for radioactivity and analysed by gas-chromatography (silver nitrate–glycerol on Celite column). The main results are contained in the final line of Table 5.

The low first value in the final line confirms the absence of [^{14}C]propan-1-ol in the sample of [^{14}C]propan-2-ol.

Experiments with Cyclohexylmethanol.—The rate of tritium uptake by the solute (0·14—0·17M) from aqueous perchloric acid and from a mixture of trifluoroacetic acid, perchloric acid, and water was studied along with product analyses for olefin, cyclohexylmethanol, and 1-methylcyclohexanol.

Tritium uptake was detected in several media. The radioactivity assay was performed as for propyl alcohol except that 1-methylcyclohexanol or cyclohexylmethanol (or a mixture of the two) was used in the extraction. Representative results are tabulated (Table 6). Values of N for the first three media are calculated on the hypothetical basis that organic material is not destroyed during the reaction and that the extract and distillate used were representative of the total radioactivity in the substrate.

Olefin estimations were carried out as in experiments with the cyclohexanol–cyclohexene system.[4]

TABLE 5.

Formation of [^{14}C]propan-1-ol from [^{14}C]propan-2-ol in 7·98M-perchloric acid at 100°.

1	2	3	4	5	6
			Composition (%)		Activity of
Fraction	B. p.	Activity *	Pr^{n}OH	Pr^{i}OH	Pr^{i}OH †
(A) *After 0 hr.*					
1	80·2—80·8	87,890			
2	80·8—82·0	87,580	11·4	88·6	99,550
3	82·0—84·8	89,120			
4	84·8—91·5	66,840			
5	91·5—94·4	29,800			
6	94·4—97·0	2972	96·75	3·25	
(B) *After 24 hr.*					
1	79·5—80·1	94,240			
2	80·1—81·3	94,910	0·7	99·3	95,420
3	81·3—82·5	95,120			
4	82·5—84·8	90,580	5·9	94·1	96,260
5	84·8—91·8	65,240			
6	91·8—95·2	26,870			
7	95·2—96·1	8556			
8	96·1—96·6	2828	98·0	2·0	
9	96·6	1968			
(C) *After 48 hr.*					
1	80·1—80·3	94,820	2·0	98·0	96,760
2	80·1—80·3	84,130	2·2	97·8	86,020
3	80·2—81·2	85,730	1·1	98·9	86,680
4	81·2—82·4	90,040	5·6	94·4	95,380
5	82·4—83·3	88,740	5·1	94·9	93,510
6	83·3—87·2	78,760			
7	87·2—93·9	43,320			
8	93·9—95·6	16,740			
9	95·6—96·4	6831			
10	96·4—96·6	3149			
11	96·6—96·8	1805	99·3	0·7	

* Counts per 100 sec. per 2-ml. sample.   † (Result in column 3) × (100/result in column 5)

(D) *Summary of results.*

(1) Time (hr.)	0	24	48
(2) Calc. activity for pure propan-2-ol	99,550	95,630	91,67
(3) Activity of fraction rich in propan-1-ol	2972	2828	1805
(4) No. of that fraction	(A)6	(B)8	(C)11
(5) Pr^{i}OH (%) in that fraction	3·25	2·0	0·7
(6) Activity due to Pr^{i}OH in that fraction	3235	1913	642
(7) Activity due to Pr^{n}OH in that fraction	−263	915	1163
(8) % [^{14}C]propan-2-ol rearranged to [^{14}C]propan-1-ol	−(0·3)	1·0	1·3

Notes: (2, 3, 6, 7) Counts per 100 sec. per 2 ml. sample of distillate.   (2) Mean values in column 6 of sections (A), (B), (C).   (3, 4, 5) See sections (A), (B), (C).   (6) (Result in line 2) × (Result in line 5)/100.   (7) (Result in line 3) − (Result in line 6).   (8) (Result in line 7) × 100/(Result in line 2).

The results (Table 6) indicate incorporation of tritium into an organic solute, but are inconclusive as to whether any of this activity is associated with the original material.   The following experiment was therefore carried out.

Cyclohexylmethanol (0·0389M) was heated in a tritiated medium (35 ml. containing 68·3 mc per g.-atom of exchangeable hydrogen) of perchloric acid (8·15M) in water–dioxan (63 : 37 w/w) for 19·25 hr. at 50°.   The product was extracted with cyclohexylmethanol (18·6 g.) and, after the usual removal of hydroxylic tritium and drying (K$_2$CO$_3$), the alcohol extract was distilled.   The first fraction (b. p. <183°) was discarded.   The activity of the second fraction (b. p. 183—186°) was measured.   Some of this fraction (2·5 ml.) was heated at 100° for 65 min. with phthalic anhydride (2·8 g.) and dry pyridine (1·6 ml.).   After being cooled, the product was dissolved in acetone (4 ml.) and then reprecipitated by addition of ice-cold *ca.* 5M-hydrochloric acid (44 ml.).   It was filtered off, washed with water, and assayed for radioactivity. The product was then divided into two portions, one of which was recrystallised once from hexane and the other twice from 50% aqueous acetic acid.   The activity was found to decrease

TABLE 6.

Exchange experiments with cyclohexylmethanol in various media at 50°.

Expt.	Medium	Time (hr.)	N
1	$CF_3 \cdot CO_2H$–$HClO_4$–H_2O (73 : 7 : 20) *	113	0·67
2	$CF_3 \cdot CO_2H$–$HClO_4$–H_2O (60·6 : 10·9 : 28·6) *	21·5, 86·5, 153	0·89, 1·31, 0·76
3	8·22M-$HClO_4$ in water †	21·25	0·51
4	8·16M-$HClO_4$ in water–dioxan (63 : 37 w/w) ‡§	19·1	1·84, 1·34, 1·51

* Molar percentages. † The solution from a parallel experiment in identical conditions contained 0·5—0·6% of the original amount of cyclohexylmethanol as olefin. Gas-chromatography (silicone high-vacuum grease on Celite) of ethereal extracts (6 × 4 ml.; after neutralisation of the sample with sodium hydroxide) indicated *ca.* 20% loss of the cyclohexylmethanol, with formation of 0·7% of 1-methylcyclohexanol. ‡ Olefin estimation indicated 5% of initial alcohol as olefin. Gas-chromatography of ethereal extracts (see preceding footnote) showed that *ca.* 70% of original alcohol is left as cyclohexylmethanol, and *ca.* 1% converted into 1-methylcyclohexanol. A corresponding experiment with 1-methylcyclohexanol indicated only *ca.* 30% of this alcohol to be present after 1 hr. at 50°. § Extraction with an equimolar mixture of cyclohexylmethanol and 1-methylcyclohexanol. The three values of N correspond to three fractions of the distillation of the extracts (b. p. 145—169°; 169—176°; 176°, respectively) (cf. experiment described in Table 4).

sharply on crystallisation from either solvent. The radioactivity counts of the resulting pure cyclohexylmethyl hydrogen phthalate were indistinguishable from the background values. On the assumption that 70% of the original cyclohexylmethanol is present unchanged at the end of this experiment (see footnote ‡ of Table 6), this indicates that the value of N for cyclohexylmethanol must be below 0·02. The purification was simultaneously performed on a specimen of ester prepared from the original cyclohexylmethanol and the m. p. was found to correspond to that of the sample derived from the run. The parallel effects of crystallisation from acetic acid and hexane dispose of the possibility that exchange might have occurred during recrystallisation from acid. The results are summarised in Table 7.

TABLE 7.

Purification and assay of cyclohexylmethyl hydrogen phthalate from run in tritiated medium.

Sample		M. p.	Activity * (μc)	Activity (%) retained on purification
Alcohol extract	R	—	4·63 †	(100)
Crude ester	I	113—117	—	—
	R	115·5—117·5	1·70	37
Ester recryst. from hexane	I	116	—	—
	R	116—118	0·268	5·8
Ester recryst. once from 50% acetic acid	R	118—119	0·22	4·7
Ester recryst. twice from 50% acetic acid	R	118—120 ‡	<0·07 §	<1·6

R = from reaction. I = from inactive alcohol.

* Activity per g. of cyclohexylmethanol. † Corresponds to $N = 0.94$ (calc. for cyclohexylmethanol). ‡ Lit., m. p. 119—120°. § Corresponds to $N < 0.02$.
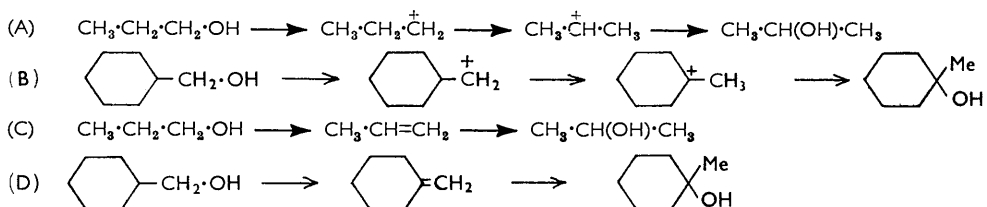
DISCUSSION

The results for both n-propyl alcohol and cyclohexylmethanol indicate tritium uptake by a solute from an acidic medium under conditions of high acidity and high temperature. However, in neither case can radioactivity be detected in the primary alcohol employed.

For n-propyl alcohol, the rate of tritium uptake largely parallels the rate of rearrangement to isopropyl alcohol and the activity is found to be present in the secondary alcohol.

For cyclohexylmethanol the identity of the radioactive compound or compounds has not been established. Because of its greater complexity, this system has been studied less completely. The activity is not due to the presence of 1-methylcyclohexanol since this alcohol has been shown not to be sufficiently stable in the media employed (see footnote ‡ of Table 6). It is, nevertheless, possible that this substance is the first compound formed in the reaction sequence in which cyclohexylmethanol is destroyed, and that the tritium detected in the organic reaction products is present in molecules formed from 1-methylcyclohexanol by further reaction. The formation of 1-methylcyclohexanol is closely
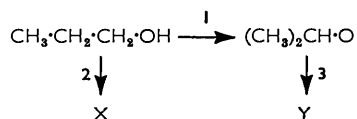
analogous to the rearrangement of n- to iso-propyl alcohol. The two reactions can be visualised either as hydride shifts in an intermediate primary carbonium ion to give, respectively, a tertiary or secondary carbonium ion, or as dehydration followed by rehydration according to Markovnikov's rule:

(A) $CH_3 \cdot CH_2 \cdot CH_2 \cdot OH \longrightarrow CH_3 \cdot CH_2 \cdot \overset{+}{C}H_2 \longrightarrow CH_3 \cdot \overset{+}{C}H \cdot CH_3 \longrightarrow CH_3 \cdot CH(OH) \cdot CH_3$

(B)

(C) $CH_3 \cdot CH_2 \cdot CH_2 \cdot OH \longrightarrow CH_3 \cdot CH=CH_2 \longrightarrow CH_3 \cdot CH(OH) \cdot CH_3$

(D)

It is also possible for the cyclohexylmethyl cation to rearrange with ring enlargement to yield cycloheptanol[11] (cf. the deamination of cyclohexylmethylamine to give 63% of cycloheptanol[12]). In either reaction the primary alcohol—which appears to be inert in acid-catalysed hydrogen exchange—disappears and is replaced by a secondary or a tertiary alcohol.

In the exchange starting from n-propyl alcohol the rearrangement to isopropyl alcohol is the important process. The precise determination of its rate is slightly obscured by the loss of material which occurs under the drastic conditions employed. Because of this loss the concentration of isopropyl alcohol does not reach the initial concentration of n-propyl alcohol but passes through a maximum of 80% of that concentration or less. The proportion of n-propyl alcohol at equilibrium with isopropyl alcohol is certainly much less than 20 : 80. Gas-chromatographic analyses for both alcohols (Table 2) indicate that it is less than 20 : 80. An independent estimate from the rearrangement reaction iso- $\longrightarrow$ n-propyl alcohol studied with ^{14}C-labelled isopropyl alcohol (Table 5) indicates that of the order of 1% of the retro-rearrangement occurs in 24 hours, *i.e.*, after about 3 half-lives of the equilibration. From these relative values of the rate of the two rearrangements it follows that the equilibrium constant for the rearrangement of n- to iso-propyl alcohol is of the order of 100, but this could be an underestimate if, as is not impossible, the [1,3-^{14}C]propan-2-ol was not quite radiochemically pure and contained minor amounts of radioactive substances which, in the course of the reaction, produced radioactive products not separated from n-propyl alcohol in our distillation. For the purposes of the following kinetic analysis the rearrangement to isopropyl alcohol can be treated as a reaction with negligible reversal.

The destruction of material which is responsible for the low maximum concentration of isopropyl alcohol can affect both alcohols. The rate constant for the disappearance of isopropyl alcohol can be deduced from the decreasing concentrations towards the end of the run in experiments such as those in Table 1. These results lead to a first-order constant of *ca.* 7×10^{-7} sec.$^{-1}$. The decreasing experimental value of N towards the end of the run in Table 3 is further evidence that at least some of the loss of material affects a compound in which exchange has occurred, *i.e.*, a compound other than n-propyl alcohol. However, it appears that there is also some destruction of n-propyl alcohol and the observations are best explained in terms of the scheme:

$$CH_3 \cdot CH_2 \cdot CH_2 \cdot OH \xrightarrow{\ 1\ } (CH_3)_2 CH \cdot O$$

$$\overset{2}{\downarrow} \qquad\qquad\qquad \overset{3}{\downarrow}$$

$$X \qquad\qquad\qquad Y$$

where X and Y are unidentified decomposition products.

[11] Rosanov, *Russ. J. Phys. Chem. Soc.*, 1916, **48**, 309.
[12] Baer, Ege, and Smith, *J. Amer. Chem. Soc.*, 1954, **76**, 4564.

The instantaneous concentration of isopropyl alcohol (i) relative to the initial concentration of n-propyl alcohol (n_0) is then given by solution of the equations

$$-dn/dt = (k_1 + k_2)n, \text{ or } n = n_0 \exp\left[-(k_1 + k_2)t\right],$$

and
$$-di/dt = k_3 i - k_1 n,$$

whence
$$di/dt + k_3 i = k_1 n_0 \exp\left[-(k_1 + k_2)t\right],$$

which is integrated to give

$$\frac{i}{n_0} = \frac{k_1}{k_3 - k_1 - k_2}\left\{\exp\left[-(k_1 + k_2)t\right] - \exp\left[-k_3 t\right]\right\}, \tag{1}$$

where (for 8M perchloric acid at 100°) the values $k_1 = 2.14 \times 10^{-5}$, $k_2 = 1.6 \times 10^{-6}$, and $k_3 = 7 \times 10^{-7}$ sec.$^{-1}$ fit our experimental data. It is likely that products X and Y are soluble oxidation products formed by further oxidation of propanol and acetone, respectively. (The importance of reaction 2 seemed to depend somewhat on the batch of perchloric acid used.) Values of i/n_0 calculated from this equation with the above numerical values of the rate constants agree well with the experimental values (Table 1).

The rate of tritium uptake should exactly equal the rate of rearrangement to isopropyl alcohol only if the exchange in isopropyl alcohol is infinitely greater than the velocity of rearrangement. For finite rate differences the tritium enrichment should lag behind the rearrangement. According to the above rate constants and the previously determined value for the exchange velocity of isopropyl alcohol this lag should be just detectable. For a system
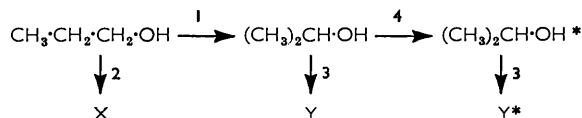
the rate of tritium uptake, expressed in terms of the apparent exchange number N (calculated on the basis of the initial concentration of n-propyl alcohol) is obtained by combining equation (1) with

$$dN/dt = k_4[\overset{\infty}{N_i}(i/n_0) - N] - k_3 N,$$

where k_4 is the first-order rate constant for exchange in isopropyl alcohol [4] and $\overset{\infty}{N_i}$ is the maximum value of N in the absence of destruction of material. We thus obtain

$$\frac{dN}{dt} + (k_3 + k_4)N = \frac{k_1 k_4 \overset{\infty}{N_i}}{k_3 - k_1 - k_2}\left\{\exp\left[-(k_1 + k_2)t\right] - \exp\left[-k_3 t\right]\right\},$$

which gives, on integration,

$$\frac{N}{\overset{\infty}{N_i}} = \frac{k_1}{k_3 - k_1 - k_2}\left(\frac{k_4}{k_3 + k_4 - k_1 - k_2}\left\{\exp\left[-(k_1 + k_2)t\right] - \exp\left[-(k_3 + k_4)t\right]\right\}\right.$$
$$\left. - \exp\left[-k_3 t\right] + \exp\left[-(k_3 + k_4)t\right]\right) \tag{2}$$

It is assumed that the concentration of solute is low so that the abundance of tritium in the solvent remains constant throughout a run.

If k_4 were very much greater than the other rate constants, the right-hand side of expression (2) would reduce to the right-hand side of equation (1), *i.e.*,

$$N/\overset{\infty}{N_i} = i/n_0. \tag{3}$$

The last two columns of Table 3 list values of N calculated on the basis of equations (2) and (3), respectively. It will be seen that the former equation gives a better fit for the values obtained during the early stages of the exchange, confirming the view that exchange occurs after formation of the isopropyl alcohol molecule and not at some intermediate step of the rearrangement (*e.g.*, as the carbonium ion), in which case exchange and rearrangement velocities should be equal.

The agreement between calculated and experimental values of N becomes progressively worse at later stages of the run. The development of this discrepancy becomes intelligible when the experimental procedure of this tritium experiment is recalled. In this particular exchange the tritium assay was performed on the undistilled extract from the reaction mixture. The radioactivity figure therefore included all non-hydroxylic tritium present in combinations included under the species titles X and Y in the above schemes, other than extremely water-soluble species (for example, an oligomer of propanal might be such a tritiated species). For this reason the rise of the experimental value of N/N_1^{∞} above the calculated value, as the concentration of tritiated decomposition products in the system becomes important, is to be expected in these experiments.

The mechanism of the rearrangement can most reasonably be pictured in terms of scheme (A) or (C) given above, but comparison with other aliphatic rearrangements for which olefin formation can be ruled out, renders (A) perhaps the more likely.

The results of the preceding paper show that dehydration of cyclohexanol is *ca.* 35 times faster than that of isopropyl alcohol and this, in turn, *ca.* 75 times faster than the rearrangement of n-propyl alcohol deduced from the present work (at the same acidity of the medium). The rearrangement of the primary alcohol, therefore, has a velocity rather close to the remarkably large range of values for the dehydration of secondary alcohols. In view of the grossly differing ionising tendencies of primary and secondary alkyl derivatives it is improbable that the two reactions would have the same mechanism, *i.e.*, a rate-controlling dehydration. However it is possible for the heterolytic generation of carbonium ion to be rate-controlling if it is assisted by the intramolecular hydride shift, *i.e.*, if the direct reaction

$$CH_3 \cdot CH_2 \cdot CH_2 \cdot OH_2^+ \longrightarrow CH_3 \cdot \overset{+}{C}H \cdot CH_3 + H_2O$$
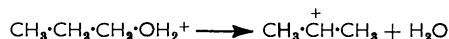
leading to the secondary carbonium ion is subject to synartetic (anchimeric) acceleration. It is generally assumed that hydride shifts do not affect reaction velocities in this manner, but this idea seems largely to be based on rate comparisons which show that other groups are *more* effective than hydrogen but leave unanswered the question whether hydrogen itself exerts an effect of this kind.
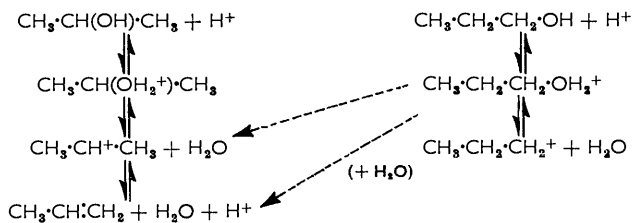
On this basis the acid-catalysed rearrangement of n- to iso-propyl alcohol resembles the rearrangement which accompanies the mercury-salt-catalysed solvolysis of n-propyl bromide[1] in not involving the intermediate formation of olefin and this would conform to the general pattern of similar rearrangements. It may not be permissible to rely on analogies in support of this mechanism and the values of the rate coefficients for primary and secondary alcohols could be reconciled if the formation of olefin were a bimolecular process

$$H_2O + CH_3 \cdot CH_2 \cdot CH_2 \cdot OH_2^+ \longrightarrow H_3O^+ + CH_3CH=CH_2 + H_2O$$
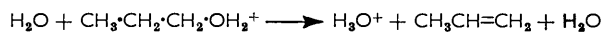
as distinct from the unimolecular formation of olefin from the secondary oxonium ion *via* the secondary carbonium ion. It should, in principle, be possible to test the role of olefin in the mechanism by diversion (*e.g.*, by complex-formation, as in previous work[1]), but we have not succeeded in devising a satisfactory technique for such a study.

The two formulations of the mechanism (which are indicated by broken arrows in the equations below) both avoid the difficulty about relative rates which attend the assumption of free primary carbonium ions. There must be other kinetic schemes which circumvent

this difficulty by assuming the " free-ness " or " primari-ness " of the carbonium ion to be reduced in some different way. Our schemes are represented as follows:

$$CH_3 \cdot CH(OH) \cdot CH_3 + H^+ \qquad\qquad CH_3 \cdot CH_2 \cdot CH_2 \cdot OH + H^+$$

$$CH_3 \cdot CH(OH_2^+) \cdot CH_3 \qquad\qquad CH_3 \cdot CH_2 \cdot CH_2 \cdot OH_2^+$$

$$CH_3 \cdot CH^+ \cdot CH_3 + H_2O \qquad\qquad CH_3 \cdot CH_2 \cdot CH_2^+ + H_2O$$

$$(+ H_2O)$$

$$CH_3 \cdot CH{:}CH_2 + H_2O + H^+$$

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