

**Cyclopropane-*trans*-1,2-dicarboxylic Acid.**—Recrystallization from water gave colorless crystals (m.p. 176–178°) tabular on (100). These are monoclinic with cell dimensions,  $a = 12.71$ ,  $b = 5.07$ ,  $c = 9.44$  Å.,  $\beta = 98^\circ$ ; density measured 1.46 g./ml., density calculated 1.45 g./ml. with 4 molecules per unit cell. The space group is  $A2/a$  with molecular symmetry 1.

**Anhydride of Cyclopropane-*cis*-1,2-dicarboxylic Acid.**—Recrystallization from ethyl ether gave colorless needles (m.p. 59–60°), elongated about the  $c$ -axis with a tendency

to lath formation. The solid had a high vapor pressure and the crystals had to be sealed in gelatin capsules or thin-walled glass capillaries for X-ray examination. The crystals are monoclinic with  $a = 6.13$ ,  $b = 8.43$ ,  $c = 5.35$  Å.,  $\beta = 116^\circ$ ; density measured 1.50 g./ml., density calculated 1.49 g./ml. with two molecules per unit cell. The space group is  $P2_1/m$  with molecular symmetry  $m$ , or  $P2_1$  with molecular symmetry 1.

PITTSBURGH, PENNA.

[CONTRIBUTION OF THE CHEMISTRY DEPARTMENT OF OHIO UNIVERSITY]

## The Role of Hydrogen in the Pinacol Rearrangement of 2-Methyl-2,3-butanediol

BY WILLIAM B. SMITH, RICHARD E. BOWMAN<sup>1</sup> AND THOMAS J. KMET<sup>1</sup>

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The rates of rearrangement of 2-methyl-2,3-butanediol and 2-methyl-2,3-butanediol-3-*d* in aqueous perchloric acid at various temperatures and acidities have been measured. Isotope effects of 1.5–1.8 have been observed. The internal migration of deuterium during the course of the rearrangement was determined through an infrared spectral analysis of the reaction product, methyl isopropyl ketone. The synthesis and rearrangement of 2-methyl-2,3-butanediol-4-<sup>14</sup>C has been carried out. The iodoform degradation of the reaction product indicated that no reversible methyl migration or secondary hydroxyl removal had occurred during the formation of the ketone. Consideration of the kinetic expression supports the belief that the isotope effect arises due to differences in hydrogen participation during the rate-determining step.

In recent years much evidence has been amassed to support the view that atoms or groups of atoms located adjacent to the reaction site may directly participate in organic solvolysis and rearrangement reactions.<sup>2</sup> The question of whether or not hydrogen is capable of such participation has not been completely answered.

Winstein and co-workers have studied several systems which shed some light on this problem.<sup>3</sup> Thus, neomenthyl *p*-toluenesulfonate undergoes acetolysis about one hundred and seventy times more rapidly than the corresponding menthyl compound. While the rate increase here may be due to the contribution which the favorably located hydrogen makes to the rate-determining ionization, the situation is complicated by the fact that steric strain relief is greater for the departure of the axial tosyl group from the neomenthyl compound than for the equatorial tosyl group from the menthyl tosylate.

Winstein and Marshall<sup>4</sup> found that the acetolysis of 3-methyl-2-butyl *p*-bromobenzenesulfonate was about twice as fast as that of 3,3-dimethyl-2-butyl *p*-bromobenzenesulfonate. Again proper assessment of the role of the hydrogen is difficult due to the possible operation of such diverse factors as steric inhibition to solvation of the transition state, hyperconjugation and the inductive effect of the methyl groups at  $C_\beta$ .

A particularly useful approach to this problem is suggested by the effect which the substitution of deuterium for hydrogen may have on the reaction rates and products of organic reactions. Melander<sup>5</sup> has shown that when an isotopic bond is broken in the rate-determining step a significant kinetic isotope effect will be observed. This principle

was first applied to reaction mechanism studies by Melander<sup>6</sup> and Westheimer.<sup>7</sup>

When the deuterium for hydrogen substitution is made at some point more remote from the reaction site, secondary kinetic isotope effects may be observed. Such effects as have been observed are smaller in magnitude than those which actually involve the breaking of isotopic bonds. Shiner<sup>8</sup> has carried out an extensive study of  $SN_1$ ,  $SN_2$ ,  $E_1$  and  $E_2$  reactions by observing the effect of replacing hydrogen by deuterium at a position near the reaction site in a number of different molecules. Lewis and co-workers<sup>9</sup> have also carried out a similar series of experiments. Recently, Streitwieser, *et al.*,<sup>10</sup> have discussed in detail the source of the secondary isotope effects found in the solvolysis reactions of the deuterated cyclopentyl tosylates. In each of the studies carried out by these workers the isotope effects observed were small (1.1–1.3). However, none of these reactions provide any additional information regarding the possibility of hydrogen participation as no examples of an internal 1,2-shift of hydrogen were observed in any of the above.

Of a more pertinent nature is the recent report by Winstein and Takahashi<sup>11</sup> that the formolysis and acetolysis of 3-methyl-2-butyl *p*-toluenesulfonate and 3-methyl-2-butyl *p*-toluenesulfonate-3-*d* proceed with isotope effects of 1.7–2.1. Evidence from the reaction products and rate effects was interpreted as indicating appreciable hydrogen participation (anchimeric assistance) during the course of the rearrangement.

(6) L. Melander, *Acta Chem. Scand.*, **3**, 95 (1949).

(7) F. H. Westheimer and N. Nicolaides, *THIS JOURNAL*, **71**, 25 (1949); M. Cohen and F. H. Westheimer, *ibid.*, **74**, 4387 (1952).

(8) V. J. Shiner, (a) *ibid.*, **74**, 5285 (1952); (b) **75**, 2925 (1953); (c) **76**, 1603 (1954); (d) **78**, 2653 (1956).

(9) E. S. Lewis and C. E. Boozer, (a) *ibid.*, **74**, 6307 (1952); (b) **76**, 791 (1954); (c) **76**, 794 (1954).

(10) A. Streitwieser, R. H. Jagow, R. C. Fahey and S. Suzuki, *ibid.*, **80**, 2326 (1958).

(11) S. Winstein and J. Takahashi, *Tetrahedron*, **2**, 316 (1958).

(1) Taken in part from the M.S. dissertations of Richard E. Bowman and Thomas J. Kmet, Ohio University, 1958.

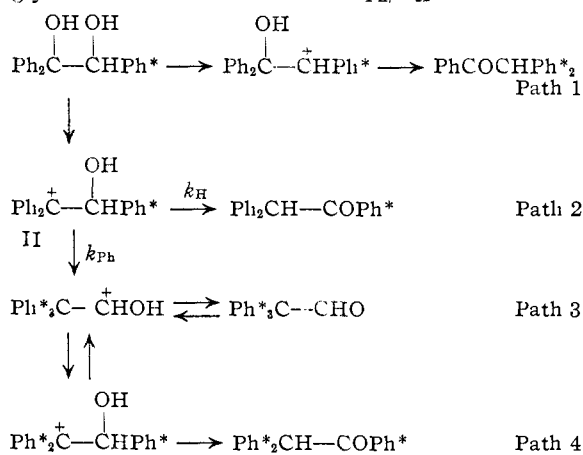
(2) S. Winstein and L. L. Ingraham, *THIS JOURNAL*, **77**, 1738 (1955), and references therein.

(3) S. Winstein, *et al.*, *ibid.*, **74**, 1131 (1952).

(4) S. Winstein and H. Marshall, *ibid.*, **74**, 1120 (1952).

(5) L. Melander *Arkiv Kemi*, **2**, 211 (1950).

As part of a comprehensive study of the mechanism of the pinacol rearrangement Collins, Rainey, Smith and Kaye<sup>12</sup> have carried out a radiochemical and kinetic study of the rearrangement of 1,2,2-triphenylethylene glycol and its C-1 deuterated analog. This system is complicated by the fact that the major product benzhydryl phenyl ketone, shows appreciable phenyl scrambling when glycol uniquely labeled in one phenyl group is used as the starting material. Earlier Collins<sup>13</sup> had demonstrated the following over-all scheme to be applicable to the rearrangement of the triphenylethylene glycol. While the ratio of  $k_{Ph}/k_H$  was found to



vary over several orders of magnitude with different acid catalysts, the values of  $k_H/k_D$  were found to be approximately 3. This independence of the isotope effect coupled with the observation that the interconversion of *threo*- and *erythro*-1,2-diphenyl-1-*p*-tolylethylene glycol is more rapid than their rearrangement has been interpreted as meaning that the tertiary carbonium ion II is a discrete intermediate in the rearrangement. Thus, isotope effects of 2-3 may now be ascribed to reactions which proceed *via* hydride shifts.

In order to elucidate further the role which hydrogen can play as a migrating group, we have studied the kinetics of the rearrangement of 2-methyl-2,3-butanediol and 2-methyl-2,3-butanediol-3-*d* in aqueous perchloric acid and in 1:1 sulfuric acid. The choice of this system was dictated by the following considerations. The only product reported for the rearrangement of this glycol is methyl isopropyl ketone.<sup>14</sup> Thus, the reaction promised to be clean cut. In actual fact an examination of the reaction products did reveal evidence for a small amount of trimethylacetaldehyde (4-5%). Furthermore, the glycols and the ketonic product are water soluble throughout the range of concentrations convenient for the kinetic study. The reactions were carried out in various concentrations of perchloric acid with the assurance that later correlations, if possible, could be made with the known values of the Hammett acidity function,  $H_0$ .<sup>15</sup> The rate constants for the kinetic runs along with the reaction conditions are given in Table I.

(12) C. J. Collins, W. T. Rainey, W. B. Smith and L. A. Kaye, *THIS JOURNAL*, **81**, 460 (1959).

(13) C. J. Collins, *ibid.*, **77**, 5517 (1955).

(14) I. N. Nazarov, *Bull. Acad. U.S.S.R.*, 195 (1940).

(15) M. A. Paul and F. A. Long, *Chem. Revs.*, **57**, 1 (1957).

TABLE I  
RATE CONSTANTS FOR THE PINACOL REARRANGEMENT OF  
2-METHYL-2,3-BUTANEDIOL (I) AND 2-METHYL-2,3-BUTANEDIOL-3-*d* (II) IN DILUTE PERCHLORIC ACID

[H]	T, °C.	(I) $k \times 10^6, \text{sec.}^{-1}$	(II) $k \times 10^6, \text{sec.}^{-1}$
0.301	59.82	0.633	0.398
	59.82	0.602	0.392
	91.11	57.50	35.83
	91.14	52.50	35.00
.599	59.83	1.53	0.93
	59.83	1.68	0.91
	90.75	125	80.6
	90.75	135	83.1
.997	59.83	3.59	2.02
	59.83	3.43	2.08
	75.25	30.3	.....
	75.24	31.5	.....
	75.40	.....	22.2
	75.53	.....	22.2
	90.71	.....	173
	90.77	.....	161
	90.83	.....	178
	90.72	248	.....
1.20	59.83	4.12	2.53
	59.83	4.77	2.88
	90.75	344	220
	90.08	392	242

The rates were determined by following the development of the carbonyl band of the ketone at 274  $\mu$ . It is evident that any correlations which might be drawn from kinetic data with regard to the rearrangement must depend on an intimate knowledge of the contributions made by the various paths which the reaction can take as proposed in Collins' scheme. We have, therefore, synthesized and studied the radiochemical consequences of the rearrangement of 2-methyl-2,3-butanediol-4-C<sup>14</sup>. Finally, the system offered the possibility of the establishment in an unambiguous manner of the internal nature of the hydrogen migration through a spectroscopic study of the ketone produced from the rearrangement of the deuterated glycol.

### Experimental

**Synthesis of 2-Methyl-2,3-butanediol and 2-Methyl-2,3-butanediol-3-*d*.**—Commercial 3-hydroxy-3-methyl-2-butanone<sup>16</sup> was redistilled; b.p. 135-137°,  $n_D^{20}$  1.4132 (reported<sup>17</sup> b.p. 139-141°,  $n_D^{20}$  1.4155). The protonated and deuterated forms of the glycol were prepared by reduction of the hydroxyketone with lithium aluminum hydride and deuteride, respectively.<sup>18</sup>

Ten grams of 3-hydroxy-3-methyl-2-butanone was dropped slowly through a water-cooled condenser into a stirred flask containing *ca.* 2 g. of the appropriate hydride dissolved in 200 ml. of anhydrous ether. The mixture was refluxed overnight, and the excess hydride was decomposed by the addition of 5 ml. of ethyl acetate. The addition complex was decomposed by the addition of 15-20 ml. of 20% sodium potassium tartrate. Sodium chloride was added to decrease the solubility of the glycol, and the two layers were separated. The aqueous layer was extracted with ether, and

(16) The material used in this study was generously furnished by the Air Reduction Chemical Co., Bound Brook, N. J.

(17) J. G. Aston and R. B. Greenburg, *THIS JOURNAL*, **62**, 2590 (1940).

(18) Metal Hydrides, Inc., Beverly, Mass.

the combined extracts were dried over anhydrous sodium sulfate. The ether was then distilled off at atmospheric pressure, and the residue vacuum distilled to obtain the glycol, b.p. 85–86° (18 mm.) (reported<sup>19</sup> b.p. 80–82° (13 mm.)). The refractive indices for the protonated and deuterated glycols were  $n_D^{20}$  1.4362 and  $n_D^{20}$  1.4340, respectively. Yields ranged from 76–84%.

The purity of the glycols, especially freedom from the original starting material, was determined by comparing the absorbance ( $A$ ) of the above materials at 274  $m\mu$  with a sample of glycol which had been carefully distilled through a spinning band column. The  $A$  of a 0.03  $M$  solution of the redistilled glycol in 1  $M$  perchloric acid was 0.016. The singly distilled products used in the kinetic study gave values of 0.018–0.043 under the same conditions.

The infrared spectra of carefully distilled samples of the protonated and deuterated glycols showed no absorption in the carbonyl region. The spectra were run on thin samples (0.025 mm.) in a Perkin-Elmer model 21 infrared spectrophotometer.<sup>20</sup> The spectra of the protonated and the deuterated glycols were identical except for two bands of medium intensity at 2090 and 2135  $cm^{-1}$ , attributable to C–D absorptions, in the latter. The usual bands for hydroxyl groups and methyl groups were found in both cases.

**The Kinetic Runs.**—J. T. Baker analyzed 60% perchloric acid was determined to be 58.47%  $HClO_4$  by means of the standard titration technique utilizing  $HgO-KI$ . Stock solutions of 1.200, 0.9966, 0.9985, 0.5992 and 0.3007  $M$   $HClO_4$  were made up and standardized with  $HgO-KI$ .

The sealed ampoule technique was used throughout. A solution of approximately 0.03  $M$  trimethylethylene glycol in standardized perchloric acid was prepared and divided among ten ampoules. The sealed ampoules were placed in a constant temperature bath and allowed to come to temperature equilibrium. As soon as equilibrium was regained (1–5 min.) the first ampoule was taken from the bath and the reaction quenched immediately by shaking vigorously in an ice-water-bath. Simultaneously, the time was recorded as  $t_0$ . At appropriate times other ampoules were removed and treated accordingly. All of the ampoules for a given run were stored in an ice-bath until the entire batch could be analyzed at one time. Experiments showed that there was no noticeable reaction at 0° even after one month. The ampoule for the infinity point was taken after approximately 8–10 half-lives had elapsed.

The contents of the ampoules were analyzed by following the development of the carbonyl band of methyl isopropyl ketone at 274  $m\mu$ ,  $\epsilon_{274}^{25}$  30.5 in 1  $M$   $HClO_4$ . The analyses were performed on a Beckman DU spectrophotometer using silica cells as the containers.

The reactions were followed from about 5 to 95% completion on the average. The absorbance at infinite time was usually found to be slightly below that calculated from the known amount of starting glycol. The product analysis, carried out below, indicated that about 4–5% of trimethylacetaldehyde was formed in the reaction product. Since the aldehyde was found to have an extinction coefficient slightly greater than 50% of that of the ketone at 274  $m\mu$ , its presence in the reaction mixture would introduce an insignificant error considering that the reproducibility of the kinetic runs was of the order of 5–10%.

First-order plots of the data were linear. The rate constants and reaction conditions are recorded in Table I. The rate constants were calculated using a weighed form of the least squares equation which expresses the fact that those points taken early in the run cannot be determined as accurately as those taken later on. The equation is

$$k_{exp} = \frac{2.303 \sum \log (A_{\infty}) / (A_{\infty} - A_t)}{\sum t}$$

**Rate Determinations in 1:1 Sulfuric Acid.**—Several kinetic runs were made using a 1:1 mixture of concentrated sulfuric acid and water as the solvent. These runs were made directly in the silica cells of the spectrophotometer at the ambient temperature of the room.

The rate constants were calculated as described above with the exception that the theoretical value was taken for the

infinite value of the reaction. In 1:1 sulfuric acid-water, methyl isopropyl ketone gave;  $\epsilon_{274}^{25}$  39.7. The theoretical value was taken for the optical density at infinite time because it was found that a slight yellow color formed in the solution on standing. This coloration was more marked in higher concentrations of sulfuric acid and prevented runs from being carried out under these conditions. The rate constants given in Table II reflect the experimental difficulties encountered. The isotope effect calculated from the averages of the above data was 1.2.

TABLE II  
RATE CONSTANTS FOR RUNS IN 1:1 SULFURIC ACID

Av. temp., °C.	Protonated glycol, $k \times 10^4 \text{ sec.}^{-1}$	Deuterated glycol, $k \times 10^4 \text{ sec.}^{-1}$
26.5	2.67	..
28	..	2.20
26	2.20	..
26	..	1.75

**Rearrangement Product Analysis.**—A homogeneous solution of 2-methyl-2,3-butandiol was prepared by dissolving 0.8 g. of the glycol in 5 ml. of 1  $M$  perchloric acid. The reaction was carried out in a sealed ampoule fitted with a side arm which projected away from the bulk of the ampoule and then downward. The bulb was submerged in a 90° oil-bath, and the side arm was chilled in a Dry Ice-acetone-bath. The ampoule was heated for three hours, the side arm was broken off, and the material collected there was drawn off and dried over anhydrous sodium sulfate. The yield of dry reaction product was 0.37 g.

A sample of reaction product prepared in a similar fashion gave a 2,4-dinitrophenylhydrazone, m.p. 116.5–117.5°; reported<sup>21</sup> for methyl isopropyl ketone 2,4-dinitrophenylhydrazone, m.p. 117°.

The rearrangement of the deuterated glycol was carried out in the same manner. A solution of 0.72 g. of 2-methyl-2,3-butanediol-3- $d$  in 5 ml. of 1  $M$  perchloric acid gave 0.51 g. of product after 7 hours of heating at 90°.

The composition of each of the above reaction products was determined by means of vapor phase chromatography using a Fisher-Gulf partitioner. The standard column furnished with the instrument (tracesyl phosphate on firebrick) was used at a temperature of 81° and a flow rate of ca. 140 ml./min. of helium. The separation was clean cut under these conditions. Two peaks, identified as trimethylacetaldehyde and methyl isopropyl ketone by running a known mixture of these two, were found in each case. The areas under the peaks were taken as a measure of the amount of each component. The product from the protonated glycol gave 4.1% trimethylacetaldehyde and 95.9% methyl isopropyl ketone, while the product from the deuterated glycol gave 4.7% of the aldehyde and 95.3% of the ketone.

The infrared spectra of methyl isopropyl ketone, trimethylacetaldehyde and a 9% mixture of the aldehyde in the ketone were run on thin liquid films (0.025 mm.). The spectrum of the reaction product from the protonated glycol was determined under the same conditions. It was found to be identical with that of the aldehyde-ketone mixture except that the aldehyde bands were less evident.

The product from the deuterated glycol gave a spectrum which contained all of the major bands of the aldehyde-ketone mixture. The weak aldehyde band at 883  $cm^{-1}$  was absent from the spectrum of the reaction product. In addition, there were several small bands in the finger print region of the spectrum which were altered. Of greater significance was the presence of a broad band characteristic of C–D absorption at 2060  $cm^{-1}$  (90% transmission).

The method of Lipkin and co-workers<sup>22</sup> was used to determine that the densities of authentic trimethylacetaldehyde and methyl isopropyl ketone were 0.7887 and 0.8076, respectively, at 25.1°. The reaction product from the deuterated glycol gave  $d_{25.1}^{20}$  0.8130.

**The Synthesis of 2-Methyl-2,3-butanediol-4- $C^{14}$ .**—A solution of methylmagnesium iodide- $C^{14}$  was prepared from 52 g. of methyl iodide- $C^{14}$  and 9.6 g. of magnesium in 160

(19) "Beilstein," E. I., Vol. 1, p. 251.

(20) The authors acknowledge with gratitude the financial aid provided by the National Science Foundation for the purchase of the Perkin-Elmer model 21 infrared spectrophotometer used in this study (NSF-G 3912).

(21) R. L. Shriner, R. C. Fuson and D. Y. Curtin, "The Systematic Identification of Organic Compounds," John Wiley and Sons, Inc., New York, N. Y., 1956, p. 316.

(22) M. R. Lipkin, J. A. Davidson, W. T. Harvey and S. S. Kurtz *Ind. Eng. Chem., Anal. Ed.*, **16**, 55 (1944).

ml of ether. The solution of the Grignard reagent was stirred and cooled in an ice-bath. Freshly distilled isobutyraldehyde (27 g.) in 100 ml. of ether was added dropwise. The reaction was allowed to stand at room temperature overnight. The addition complex was decomposed by adding a slurry of iced, dilute ammonium chloride. The ether was separated and dried over anhydrous magnesium sulfate. Distillation gave 26.2 g. (81%) of 3-methyl-2-butanol, b.p. 108–110°.

A solution of the above alcohol (26.2 g.) in 75 ml. of acetone was cooled to  $-5$  to  $0^{\circ}$  by stirring in an ice-salt-bath. To this solution was slowly added over a 4-hour period a mixture consisting of 27 g. of chromium trioxide, 23 ml. of concentrated sulfuric acid and 78 ml. of water. The reaction was stirred and cooled for an additional hour, then saturated with potassium carbonate. A large amount of precipitate formed at this point. Several portions of methylene dichloride were added, stirred, and decanted from the entire reaction mixture. The combined extracts were dried over anhydrous magnesium sulfate. After filtration, the methylene chloride and a portion of the acetone were removed by distillation through a Widmer column. The remaining acetone and the reaction product were fractionated through a Todd column. All material boiling over the range of 60–94° was collected, yield 17 g. Redistillation indicated that this material was nearly pure methyl isopropyl ketone.

A solution of 16 g. of the crude methyl isopropyl ketone from the above preparation in 100 ml. of low boiling petroleum ether was chilled in an ice-bath in a 3-necked flask fitted with a condenser, dropping funnel and a Trubore stirrer. To the chilled solution was slowly added 31 g. of bromine. The reaction was stirred in the cold for 2 hours and then for 1 hour at room temperature. A water aspirator was attached to the system through the condenser, and the petroleum ether was distilled off at room temperature under reduced pressure. The brown oily residue was then stirred overnight with 250 ml. of 10% potassium carbonate. The reaction was completed by heating for one hour at 100°. After cooling, the mixture was saturated with potassium carbonate and extracted with 3 100-ml. portions of ether. The ether extract was dried and distilled as usual. Distillation of the higher boiling material through a semi-micro column gave 11.3 g. of 3-methyl-3-hydroxy-2-butanone-1-C<sup>14</sup>, b.p. 45–50° (20–22 mm.).

The hydroxyketone prepared in this fashion was reduced with lithium aluminate hydride in the manner previously indicated.

**The Radiocarbon Analysis.**—All samples of labeled material were assayed by first converting to carbon dioxide and then counting by the ion chamber method using a Cary vibrating reed electrometer model 31. The samples were converted to carbon dioxide by means of a standard Pregl combustion tube followed by passage of the gas through a tube of stannous chloride and a heated tube of lead dioxide. Medical grade oxygen containing 5% carbon dioxide was used for burning the sample and flushing it into the ion chamber.<sup>23</sup>

**The Rearrangement of 2-Methyl-2,3-butanediol-4-C<sup>14</sup>.**—The conditions for the rearrangement of the labeled glycol were chosen so as to duplicate those of the kinetic runs, *i.e.*, ca. 300 mg. of the glycol was dissolved in 100 ml. of the appropriately diluted perchloric acid. The reaction was carried at 90.5° for approximately ten kinetic half-lives. The acidities chosen for this study were 0.3 *M* perchloric acid (36 hours) and 1.2 *M* perchloric acid (5.5 hours). After cooling, the reaction mixture was saturated with potassium carbonate, and then steam distilled until the distillate failed to give a test with 2,4-dinitrophenylhydrazine reagent. It was found that all volatile products were contained in the first 15 ml. of distillate.

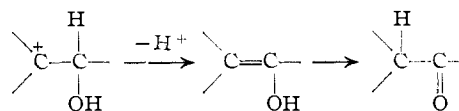
The distillate was cooled, and 4 g. of sodium hydroxide was added. Potassium iodide-iodine reagent<sup>24</sup> was added in portions until the color of iodine persisted. The color was then discharged by the addition of a small amount of dilute sodium hydroxide. The crude iodoform (35–40%)

was collected and recrystallized two or three times from methanol-water; m.p. 118–119°.

In one experiment a portion of the distillate was allowed to react with 2,4-dinitrophenylhydrazine reagent. The product was recrystallized twice from ethanol; m.p. 118–119°. The results of the radioactivity determinations were: 2-methyl-2,3-butanediol-4-C<sup>14</sup>, 1.694 ± 0.023 mc./mole; iodoform from the rearrangement in 0.3 *M* perchloric acid, 1.713 ± 0.010 mc./mole; methyl isopropyl ketone 2,4-dinitrophenylhydrazone from the rearrangement in 1.2 *M* perchloric acid, 1.709 ± 0.006 mc./mole; iodoform from rearrangement in 1.2 *M* perchloric acid, 1.701 ± 0.007 mc./mole.

## Discussion

Ingold<sup>25a</sup> has pointed out that the migration of hydrogen during the pinacol rearrangement may be pictured as taking place *via* an enolization process.



Evidence against this suggestion has been obtained by Ley and Vernon<sup>25</sup> for a system which is very like the pinacol rearrangement in behavior. They observed that when 1,2-dimethoxy-2-methylpropane was allowed to react in deuterated methanolic HCl, the reaction product, 1,1-dimethoxy-2-methylpropane, contained less than the statistical amount of deuterium.

Collins, Rainey, Smith and Kaye<sup>12</sup> have established that the migration of deuterium in the rearrangement of 1,2,2-triphenylethylene glycol-1-*d* was intramolecular in cold concentrated sulfuric acid and at least partially so in refluxing dilute sulfuric acid.

The infrared spectra of 2-methyl-2,3-butanediol and its C-3 deuterated analog were the same except for the C-D bands at 2090 and 2135 cm.<sup>-1</sup> in the latter. Both glycols were rearranged in such a fashion that the products distilled from the reaction mixture soon after they were formed. By carrying out the reaction in this fashion, the possibility of an *ex post facto* exchange of hydrogen for deuterium *via* enolization was greatly reduced. Product analysis revealed that both the protonated and the deuterated form of the glycols lead to about 4–5% of trimethylacetaldehyde, produced through methyl migration, and 95–96% of methyl isopropyl ketone, produced by hydrogen migration. The infrared spectrum of the reaction product from the rearrangement of the deuterated glycol was similar in its gross aspects to that produced by the product from the protonated glycol. A band attributable to C-D absorption was found at 2060 cm.<sup>-1</sup>. This band was fairly broad and produced 90% transmission from a sample 0.025 mm. thick. Thus, it could not be described as a strong band; however, it seems unreasonable to ascribe its presence to the 4–5% of deuteriotrimethylacetaldehyde in the product.

The amount of deuterium in the reaction product was determined by the density method of McLean and Adams.<sup>26</sup> The assumption was made that the density of the mixture of aldehyde and ketone was

(23) The apparatus used here is based on one currently in use by C. J. Collins at the Oak Ridge National Laboratory. Dr. Collins attributed the original concept of adopting the Pregl microcombustion technique for radiocarbon determinations to B. M. Tolbert of the University of California to whom acknowledgment is here extended.

(24) See reference 21, p. 156.

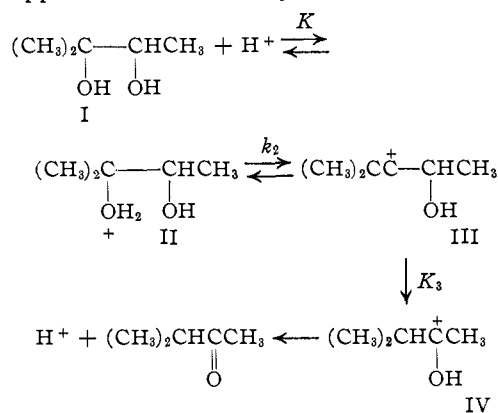
(25a) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., p. 476.

(25) J. B. Ley and C. A. Vernon, *J. Chem. Soc.*, 2987 (1957).

(26) A. McLean and R. Adams, *This Journal*, **58**, 804 (1936).

proportional to the mole fraction of each component in the mixture. Furthermore, it was assumed that all of the aldehyde produced from the deuterated glycol contained deuterium. On this basis of calculation, the density of the reaction product from the deuterated glycol indicated that 65% of the methyl isopropyl ketone formed had retained its deuterium. If the contribution made by the aldehyde was ignored, the amount of deuterium-containing ketone was 56%. Thus, the combination of the above data firmly establishes that the migration of hydrogen during the pinacol rearrangement of the trimethylethylene glycol is internal in nature.

The general mechanistic scheme to be applied to the pinacol rearrangement has now been well established through the research of Bunton and co-workers,<sup>27</sup> Ley and Vernon,<sup>23,28</sup> Duncan and Lynn,<sup>29</sup> and Deno and Perizzolo.<sup>30</sup> The scheme may be applied to the 2-methyl-2,3-butanediol system as



The first step is the establishment of a rapid reversible equilibrium between the glycol I and hydrogen ion with the conjugate acid II. This then decomposes in the rate-determining step to give the carbonium ion III. The carbonium ion partitions itself between two processes; the reversible addition of water to regenerate the ion II and rearrangement to give IV.

As can be seen, the above scheme does not include possible contributions made to the rearrangement by paths 1 and 4 in Collins scheme for triphenylethylene glycol. The justification in omitting these paths from the above scheme is to be found in a consideration of the data obtained from the rearrangement of 2-methyl-2,3-butanediol-4-C<sup>14</sup> in 0.3 and 1.2 M perchloric acid at 90°. The activity of the iodoform produced in each case on degrading the ketonic reaction product was, within experimental error, the same as that of the starting glycol. This result can only be obtained if paths 1 and 4 make no contribution to the over-all rearrangement.

The kinetic data which we have obtained fit well with the above scheme. In keeping with the observations of Duncan and Lynn,<sup>29</sup> plots of  $\log k_{\text{exp}}$  versus  $H_0$  (Fig. 1) and  $\log k_{\text{exp}}/(H^+)$  versus

(27) C. A. Bunton, T. Hadwick, D. R. Llewellyn and Y. Pocker, *J. Chem. Soc.*, 403 (1958).

(28) J. B. Ley and C. A. Vernon, *ibid.*, 3556 (1957).

(29) J. F. Duncan and K. R. Lynn, *ibid.*, 3512 (1956).

(30) N. C. Deno and D. J. Perizzolo, *J. Org. Chem.*, **22**, 836 (1957).

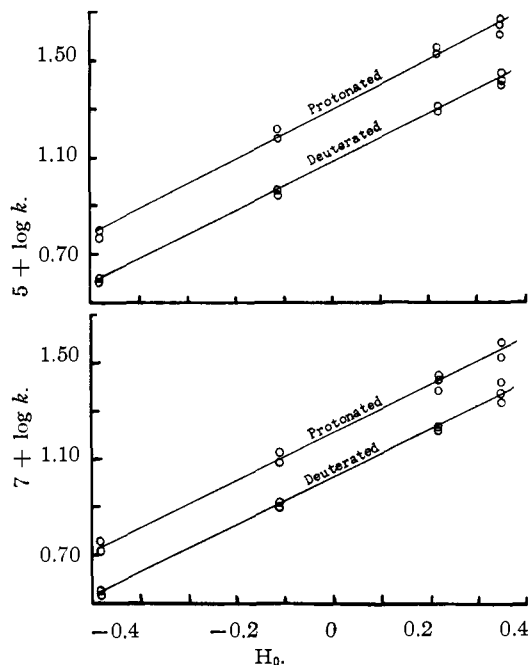


Fig. 1.— $\log k_{\text{exp}}$  plotted as a function of the acidity function  $H_0$  for the rearrangement of 2-methyl-2,3-butanediol (protonated) and 2-methyl-2,3-butanediol-3-d (deuterated) in aqueous perchloric acid: top, 60°; bottom, 90°.

( $H^+$ ) (Fig. 2) were found to be linear. The values of  $H_0$  were taken from smooth line plots of the data of Long and Paul.<sup>15</sup> A least-squares treatment of the data for the plot of  $\log k_{\text{exp}}/(H^+)$  versus ( $H^+$ ) was made. The values of the slopes are given, along with probable errors, in Table III. The isotope effects were calculated from the values of the rate constants determined from the least-squares plot at the appropriate acidities and are given in Table IV.

TABLE III  
LEAST-SQUARE SLOPES OF  $\log k/(H^+)$  vs. ( $H^+$ ) PROTONATED AND DEUTERATED GLYCOLS AT 60 AND 90°

Temp., °C.	Protonated or deuterated	Slope
60	D	0.26 ± 0.01
60	P	.28 ± .02
90	D	.23 ± .01
90	P	.25 ± .02

TABLE IV  
ISOTOPE EFFECTS AT GIVEN TEMPERATURES AND ACIDITIES FOR THE 2-METHYL-2,3-BUTANEDIOLS

(H)	$k_H/k_D$	
	60°	90°
0.3	1.58	1.54
0.6	1.78	1.58
1.0	1.68	1.58
1.2	1.68	1.58

The kinetic expression for the reaction sequence given above has been derived by Bunton and co-workers<sup>27</sup> as

$$\text{rate} = \frac{Kk_2k_3h_0(\text{glycol})}{(k_{-2} + k_3)}$$

Integration followed by equation to the experi-

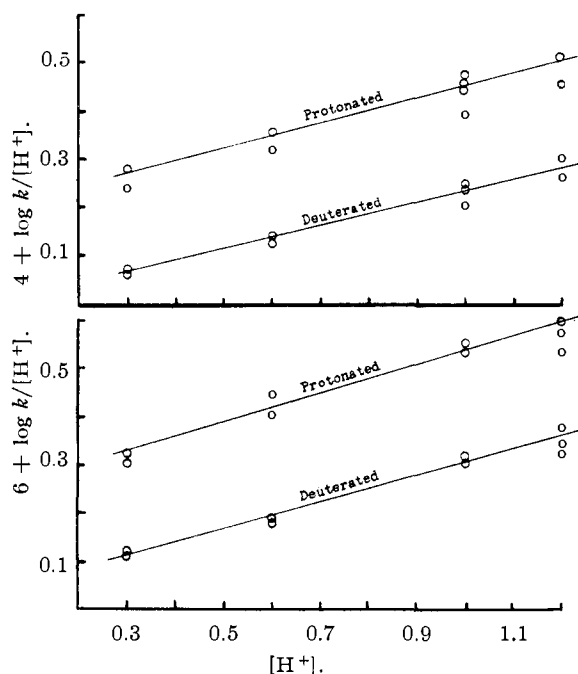


Fig. 2.—Log  $k_{\text{exp}}/[\text{H}^+]$  plotted as a function of  $[\text{H}^+]$  for the rearrangement of 2-methyl-2,3-butanediol (protonated) and 2-methyl-2,3-butanediol-3-*d* (deuterated) in aqueous perchloric acid: top, 90°; bottom, 60°.

mental first-order expression then allows us to write

$$k_{\text{exp}} = \frac{Kk_2k_3h_0}{(k_{-2} + k_3)}$$

The terms here are as given in the above reaction scheme;  $h_0$  is the antilog of the Hammett acidity function  $H_0$ .

As seen here, the experimental rate constant is not a simple function of the rate-determining step. In order to answer the question originally posed as to whether or not hydrogen participation in this step occurs, it is necessary to know the isotope effect given by  $k_2^{\text{H}}/k_2^{\text{D}}$ .

It is evident from the data given in Tables III and IV that the isotope effect is not a function of the acidity of the medium. Thus, the isotope effect must arise at some point after the formation of the conjugate acid of the glycol. This means that the value for  $K^{\text{H}}$  and  $K^{\text{D}}$ , as well as for  $h_0^{\text{H}}$  and  $h_0^{\text{D}}$ , must be the same.

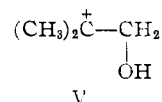
The term  $k_3/(k_{-2} + k_3)$  cannot be determined from our kinetic data. However, a consideration of the literature allows us to arrive at a reasonable estimation of this term. Bunton and co-workers<sup>27</sup> have measured the ratio of  $k_{-2}/k_3$  for the rearrangement of pinacol by measuring the rate of  $\text{O}^{18}$  exchange in enriched water. The value of  $k_{-2}/k_3$  was found to be fairly constant throughout the range of acidities used in the present study. Values of  $k_{-2}/k_3$  from Bunton's data are given in Table V.

A further assessment of the  $k_3/(k_{-2} + k_3)$  term is available from the data of Ley and Vernon,<sup>28</sup> who have measured the amount of 2-methyl-1,2-propanediol and isobutyraldehyde formed during the acid-catalyzed hydration of 2-methylallyl alcohol and the hydrolysis of 2-chloro-2-methyl-1-

TABLE V  
VALUES FOR THE TERM  $k_3/(k_{-2} + k_3)$  AS DERIVED FROM DIFFERENT SYSTEMS

	Aldehyde, %	Glycol, %	$k_{-2}/k_3$	$k_3/(k_{-2} + k_3)$
Pinacol <sup>27</sup>	..	..	2.72	0.27
2 Methylallyl alcohol <sup>28</sup>	23.2	76.8	3.51	.22
2-Chloro-2-methyl-1-propanol <sup>28</sup>	21	75	3.31	.23

propanol. Both of these reactions are postulated as proceeding through the same carbonium ion V. Thus, the product distribution may be taken



as indicative of how this ion partitions itself between the process of hydration ( $k_{-2}$ ) and rearrangement ( $k_3$ ). The values derived from the data of Ley and Vernon are also given in Table V.

As may be seen, the values of  $k_3/(k_{-2} + k_3)$  are remarkably alike in spite of the rather large change in structure on going from two hydrogens at C $\beta$  to two methyl groups. In order to evaluate  $k_2^{\text{H}}/k_2^{\text{D}}$  from our kinetic data, the assumption will be made that the term  $k_3/(k_{-2} + k_3)$  is the same, or very nearly so, for 2-methyl-2,3-butanediol and its C-3 deuterated analog. That this assumption is a reasonable one is amply borne out by the above data. Thus, consideration of the kinetic expression above shows that the experimental isotope effect arises primarily, if not solely, through differences in the rate-determining loss of water ( $k_2$ ).

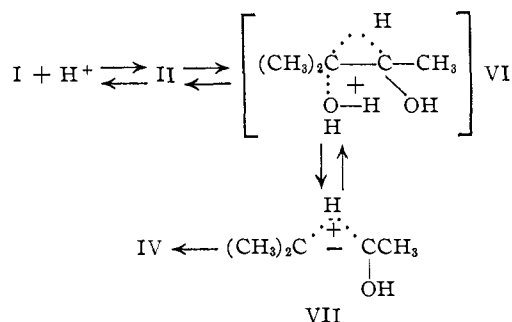
Having arrived at this conclusion, we may now consider in more detail the cause of the observed effects. Two explanations suggest themselves. First, the isotope effect may arise due to differences in the ability of hydrogen versus deuterium to stabilize the ion III through hyperconjugation. Numerous examples are now available which demonstrate the differences in the hyperconjugative abilities of hydrogen and deuterium.<sup>31</sup> The isotope effects vary somewhat with the systems under consideration. However, for systems where the carbonium ion is stabilized by a tertiary hydrogen, values of 1.1–1.2 have been observed.<sup>32</sup> In view of the larger isotope effects found in this study, it is reasonable to reject hyperconjugation as a likely explanation.

A second source for the isotope effect is offered by the possibility of hydrogen participation in the rate-determining step. As cited earlier, Winstein<sup>11</sup> has reported one such case and found that the isotope effect for a hydride ion shift was around two. Combining the observed isotope effects with the known internal migration of hydrogen during the rearrangement, it is now possible to write a reaction scheme which best fits the data.

The transition state (VI) for the formation of the ionic intermediate VII has been pictured here as an unsymmetrically bridged system. This follows from two considerations; namely, the magnitude of the isotope effect, and the fact that the ionic interme-

(31) K. B. Wiberg, *Chem. Revs.*, **55**, 713 (1955).

(32) V. J. Shiner, *This Journal*, **76**, 1603 (1954); V. J. Shiner and Sally Cross, *ibid.*, **79**, 3599 (1957).



diolate VII reacts preferentially with water rather than through rearrangement. Thus, the isotope effect can be rationalized as being larger than that found for hyperconjugation but somewhat smaller than that for a hydride shift.

Bunton and co-workers<sup>27</sup> have calculated from their data that in 1:1 sulfuric acid the partitioning of the ion derived from pinacol strongly favors rearrangement rather than the reversible addition of water. A value of  $k_{-2}/k_3ca.$  1/9 was estimated.

In order to test the hypothesis that the isotope effect was characteristic only of the rate-determining ionization step, several runs were made in 1:1 sulfuric acid. The rate constants are recorded in Table II. Experimental difficulties with the kinetic determinations under these conditions were encountered. However, the data do show a marked decrease in the isotope effect to around 1.2. This decrease may be understood also on the basis of the above mechanistic scheme. As the solvating power of the medium increases, the need for stabilization of the ionic intermediate through hydrogen participation decreases. It is to be expected that 1:1 sulfuric acid is a considerably better solvating medium than dilute solutions of aqueous perchloric acid. The decreased need for hydrogen participation in 1:1 sulfuric acid reflects itself in a lowering of the value of the isotope effect.

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ATHENS, OHIO

[CONTRIBUTION FROM THE INSTITUTE FOR CHEMICAL RESEARCH, KYOTO UNIVERSITY]

## Isotopic Tracer Studies of the Ketonic Pyrolysis of Sodium Carboxylates

BY RISABURO NAKAI, MICHIVASU SUGII AND HIDEO NAKAO<sup>1</sup>

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The isotopic tracer technique has been applied to a study of the formation of ketones by the pyrolysis of a mixture of sodium acetate and sodium phenylacetate or sodium propionate. The specific radioactivity of the symmetrical ketones produced and that of the recovered carboxylic acids shows an exchange reaction between labeled and non-labeled carboxyl groups.

Bell and Reed<sup>2</sup> have pyrolyzed a mixture of barium acetate-carboxyl- $\text{C}^{13}$  and barium formate and suggest a free radical mechanism to account for the exclusive cleavage of the carbon-carbon bond in acetate. By using  $\text{C}^{14}$  tracer techniques, Lee and Spinks<sup>3</sup> have examined the unsymmetrical ketones produced by the dry distillation of several mixtures of calcium carboxylate and explained the observed facts by an ionic mechanism. They, however, have proposed a concerted process for the decarboxylation, in which the reaction may involve either heterolytic or hemolytic cleavage of the bond concerned.

We have carried out similar studies using a mixture of sodium phenylacetate-1- $\text{C}^{14}$  and sodium acetate and a mixture of sodium acetate-1- $\text{C}^{14}$  and sodium propionate, respectively. Since an appreciable difference between the fusion temperature and the decomposition temperature was desired, the sodium carboxylates which possess a distinct fusing point were used. The calcium or barium salts decompose without fusing. Pyrolyses were carried out at reduced pressure to avoid decomposition of the ketones. The ketones produced were converted to the corresponding 2,4-dinitrophenylhydrazones. The crude mixture of hydrazones was separated into its

components by means of column chromatography and the radioactivity of each was determined. The specific radioactivity of the unsymmetrical ketone, the main product, would indicate the ratio of ease with which the carboxyl group is lost in forming ketone, if the specific activity of the symmetrical ketones is equal to that of the corresponding original acids. Contrary to expectation, the results in experiment A, Table I, indicate that the specific ac-

TABLE I  
RADIOACTIVITY OF 2,4-DINITROPHENYLHYDRAZONES

Reactants	2,4-Dinitrophenylhydrazone, ketone	Specific activity, $\mu\text{c./mmole}$	% of original activity
(A) $\text{C}_6\text{H}_5\text{CH}_2\text{C}^{14}\text{OONa}$ $\text{CH}_3\text{COONa}$		$12.60 \pm 0.21$	100
	Methyl	.....	0
	benzyl	$7.04 \pm .15$	55.8
	Dibenzyl	$7.95 \pm .17$	63.1
	Acetone	$4.67 \pm .14$	37.1
	$\text{Na}_2\text{CO}_3$	$6.74 \pm .15$	53.5
(B) $\text{CH}_3\text{C}^{14}\text{OONa}$ $\text{C}_6\text{H}_5\text{COONa}$		$7.68 \pm .18$	100
	Methyl		
	ethyl	$3.56 \pm .12$	46.4
	Acetone	$4.83 \pm .15$	62.9
	Diethyl	$3.42 \pm .10$	44.5
	$\text{Na}_2\text{CO}_3$	$4.15 \pm .12$	54.0

(1) Takamine Research Laboratory, Sankyo Co., Ltd., Shingawa-ku, Tokyo, Japan.

(2) J. Bell and R. I. Reed, *J. Chem. Soc.*, 1383 (1952); 4423 (1955).

(3) C. C. Lee and J. W. T. Spinks, *J. Org. Chem.*, **18**, 1079 (1953).