

## Kinetics and Mechanism of *vic*-Diol Dehydration. II. The *p*-Anisyl Group in Pinacolic Rearrangements<sup>1,2</sup>

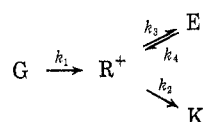
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The kinetics of the sulfuric acid catalyzed rearrangements of 1,2-di-*p*-anisyl-1,2-diphenylethylene glycol (1) and epoxide (3) and tetra-*p*-anisylethylene glycol (2) and epoxide (4) were studied in anhydrous acetic acid. The spectrophotometric rate of rearrangement and the titrimetric rate of dehydration of 1 under the same conditions are identical within experimental error. That no epoxide intermediate does accumulate above a small steady-state concentration was further substantiated by independent spectrokinetic studies of the corresponding epoxide 3 which rearranged about seven times faster than the glycol 1. Activation parameters for 1 and 3 are compared with those from benzopinacol and tetraphenylethylene oxide. Similar studies were carried out for glycol 2 and the corresponding epoxide 4, where the same situation prevails as for 1 and 3. Plots of the rate coefficients for rearrangement,  $k_r$ , vs.  $[H_2SO_4]$  are linear with 2 and 4 showing a stronger dependence than 1 and 3. Added water serves only to reduce the proton-donating capacity of the medium and does not, within the limits of thin layer chromatographic detection, divert the carbonium ion derived from epoxide ring opening to the corresponding glycol. From spectrokinetic, titrimetric, and product analysis, the order of neighboring-group reactivity is *p*-anisyl > -OH  $\geq$  *p*-tolyl > phenyl. The factors determining this order are discussed.

In our previous paper in this series<sup>1</sup> the kinetic and mechanistic aspects of the pinacolic rearrangement associated with benzopinacol, tetraphenylethylene oxide, and the symmetrical di- and tetra-*p*-methyl substituted derivatives of these were explored. We noted that the acid-catalyzed dehydration of the various glycols was characterized by the concurrent and rather substantial accumulation of an intermediate, which decomposed in a subsequent process to the carbonyl function diagnostic of these molecular reorganizations. Identification of this intermediate as the corresponding epoxide was accomplished through the application of titrimetric and spectrokinetic measurements in conjunction with thin layer chromatography. Furthermore, these complementary techniques made it possible to construct time concentration curves for all the components found in these rearrangement processes. Further insight into these pinacolic transformations was gained by analyzing the stereochemical and energetic features pertaining to acid-catalyzed epoxide ring opening. Thus we concluded that a benzhydryl-like carbonium ion was a common intermediate in both the epoxide ring opening and glycol dehydration reactions. The kinetic scheme shown below was proposed, where



G represents glycol, E, epoxide and K, ketone, and where

$$\left(-\frac{d[G]}{dt}\right)_{\text{init}} = \left(\frac{d[E]}{dt}\right)_{\text{init}} + \left(\frac{d[K]}{dt}\right)_{\text{init}}$$

From the above formulation of the dynamics of *vic*-diol dehydration it would be anticipated that the glycols would be distinguished by their kinetic behavior into

(1) Part I: Y. Pocker and B. P. Ronald *J. Amer. Chem. Soc.*, **92**, 3385 (1970), and references cited therein.

(2) Supported in part by the National Science Foundation Grant GP-5103 and in part by the National Institutes of Health Public Health Service Grants AM 09221 and GM-10181. We gratefully acknowledge the donors of these funds.

(3) To whom inquiries should be directed.

(4) Taken in part from the Ph.D. thesis of B. P. Ronald, University of Washington, 1968.

three categories: (a) those following explicitly the above scheme where

$$\left(-\frac{d[G]}{dt}\right) > \left(\frac{d[K]}{dt}\right)$$

and thus

$$\left(\frac{d[E]}{dt}\right)_{\text{init}} > 0$$

(b) those for which

$$\left(-\frac{d[G]}{dt}\right) = \left(\frac{d[K]}{dt}\right)$$

and

$$\left(\frac{d[E]}{dt}\right) = 0$$

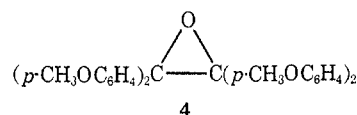
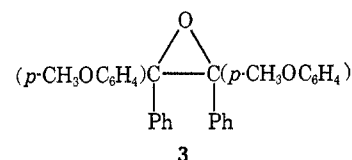
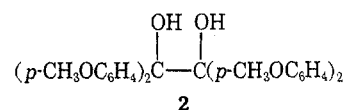
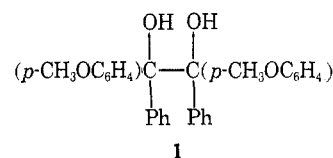
and (c) those for which

$$\left(-\frac{d[G]}{dt}\right) = \left(\frac{d[E]}{dt}\right)$$

and thus

$$\left(\frac{d[K]}{dt}\right) = 0$$

The present paper reports on a kinetic and mechanistic study of the dehydration of 1 and 2 which belong to the



b category and compares these with the rearrangement of the corresponding epoxides 3 and 4.

### Experimental Section

**Materials.**—The glycols, 1 and 2, were synthesized from their respective *para*-substituted benzophenones by photochemical bimolecular reduction in isopropyl alcohol.<sup>5</sup> Purity after repeated recrystallization from benzene-petroleum ether (bp 30–60°) (1:1) was verified by tlc, uv spectral analysis, and melting point. Each glycol was converted to the corresponding ketone or ketones by acid-catalyzed dehydration with sulfuric acid in acetic acid solvent.<sup>6</sup> Ketone mixtures were analyzed by cleaving in *t*-BuO<sup>-</sup>K<sup>+</sup>-DMSO, isolating the resultant benzoic acids,<sup>7</sup> and then esterifying them using a tenfold excess of MeOH. The resultant esters were then submitted to vpc analysis. Examination of standard ester mixtures confirmed that the ratio of the peak areas was proportional to the mole ratio.

The epoxides, 3 and 4, corresponding to the above glycols were synthesized by the controlled<sup>8</sup> perbenzoic acid oxidation of the appropriate tetraarylethylenes in chloroform solution. The purity of each epoxide was assayed by thin layer chromatography, uv spectral analysis, as well as melting point. Further substantiation came from analyzing by the above methods the product(s) derived from acid-catalyzed rearrangement. These tetraarylethylenes in turn were synthesized from the appropriate ketonic product derived from glycol dehydration. The ketone was reduced with LiAlH<sub>4</sub> in ether-benzene solvent (1:1) to the corresponding alcohol,<sup>9</sup> which without purification was dehydrated to the olefin with a catalytic amount of sulfuric acid or acetyl chloride in acetic acid solvent.<sup>10</sup> The purity of these tetraarylethylenes was established by melting point and uv, nmr, and thin layer chromatographic analyses.

Solvent acetic acid for kinetics has been discussed, as has anhydrous 100% sulfuric acid.<sup>1</sup> Other solutions such as 0.100 or 0.05 *N* potassium acid phthalate, KHP, in acetic acid, 0.100 *N* potassium dichromate in water, 0.1 *N* sodium thiosulfate, starch indicator, 0.1 *N* lead tetraacetate in acetic acid, 0.1 *M* potassium iodide in water, and 1.0 *M* sodium acetate in water were all made in accordance with currently accepted procedures.

Since the acidity required to cause the rearrangement of the substrates at a convenient rate was very low, 10<sup>-2</sup> to 10<sup>-5</sup> *M* sulfuric acid in acetic acid, H<sub>2</sub>SO<sub>4</sub>-HOAc, it was not possible to assay independently the amount of acid catalyst in each rate measurement. Rather, a stock solution of 0.1 *M* H<sub>2</sub>SO<sub>4</sub>-HOAc whose acid content was accurately determined by titration against 0.100 *N* KHP to the  $\alpha$ -naphtholbenzein end point was sequentially diluted to give a series of secondary stock solutions. Where possible these secondary stock solutions were restandardized and then used as catalysts for the rate measurements.

**Kinetic Measurements.**—The rate of glycol dehydration was followed by lead tetraacetate oxidation and iodometric titrimetry of aliquots withdrawn from the reaction solutions at various times.<sup>11–13</sup> To ca. 10<sup>-2</sup> *M* solution of the glycol in acetic acid the appropriate amount of acid catalyst was added at time zero. At recorded time intervals aliquots were quenched in acetic acid containing enough sodium acetate to neutralize all the acid

catalyst. A measured amount of lead tetraacetate was added to oxidize the glycol completely and the solution set aside for 2 hr.<sup>14</sup> The excess lead tetraacetate remaining after complete glycol oxidation was determined by iodometric titrimetry. Rate coefficients were determined graphically.

Spectrophotometric rate measurements were made with a Beckman Model D.U. fitted with a specially designed cell compartment containing a liquid bath (water). This bath was thermostated by bucking a Sargent Thermonitor and coil heater against a cold water stream circulating through a copper pipe traversing the bottom of the cell compartment. Later a Forma Temp Jr. circulated a liquid (antifreeze) thermostated to 25.0  $\pm$  0.02° through the copper pipe and eliminated the need for the Thermonitor unit. Stirring the bath precluded any but the minutest temperature fluctuations.

Depending upon the specific compound and the wavelength to be used, enough substrate was weighed into a 50-ml volumetric flask in order to make a 10<sup>-3</sup> to 10<sup>-4</sup> *M* solution in acetic acid. After prior thermostating, the rate measurement was begun by adding a predetermined amount of stock H<sub>2</sub>SO<sub>4</sub>-HOAc at time zero. Infinity values of the absorbance taken well after 10 half-lives were stable for a period of several days to several weeks depending upon the acid concentration. Rate coefficients were determined graphically.

Thin layer chromatography was performed on lantern slides coated with a uniform layer of silica gel G. The samples were dissolved in benzene. The developing solvent was a mixture of benzene-pet ether or heptane-ethyl acetate in varying proportions as found expedient for good separation. The chromatograms were visualized with SnCl<sub>4</sub>-SOCl<sub>2</sub> vapor, I<sub>2</sub> vapor, and uv light. The limit of detection by these methods is about 1%. When thin layer chromatographic analysis was performed on reacting solutions, the procedure was as follows. Aliquots were taken at various times and quenched in aqueous NaOH-NaCl. Enough base was present to render the pH of the quenched solution ca. 4 or higher. The organic material usually precipitated immediately and was filtered, washed with water, dried, and chromatographed as described above.

Uv spectra were measured on a Cary Model 14 recording ultraviolet spectrophotometer. Nmr spectra were measured on either a Varian Model HA-60 or Model A-60 nuclear magnetic resonance spectrometer. The solvent was carbon tetrachloride and the internal standard was TMS. Vapor phase chromatograms were measured on an Aerograph 1520 equipped with a flame ionization detector whose output was connected to a Leeds and Northrup Speedomax H strip chart recorder.

### Results

In pure anhydrous acetic acid solvent the rate of dehydration of 1,2-di-*p*-anisyl-1,2-diphenylethylene glycol,<sup>15</sup> 1, as followed by lead tetraacetate oxidation and iodometric titrimetry shows good linear pseudo-first-order kinetics for 1 to 2 half-lives, Figure 1. The convenient rate range falls in the concentration region of 10<sup>-5</sup> up to 10<sup>-3</sup> *M* H<sub>2</sub>SO<sub>4</sub>-HOAc. Under precisely the same conditions (temperature, catalyst concentration, and solvent) the rate of product formation was observed at its  $\lambda_{\text{max}}$ , 330 m $\mu$ , in the Beckman D. U. spectrophotometer. These spectrophotometric rate measurements showed good linear pseudo-first-order kinetics for 2 to 3 half-lives, Figure 1. Furthermore, the rate coefficients from the titrimetric and spectrophotometric rate measurements were identical within experimental error. Thus the rate of glycol dehydra-

(14) J. P. Cordner, and K. H. Pausacher, *J. Chem. Soc.*, 104 (1953). Two hours was found to be adequate for at least 98% oxidation of the glycol.

(15) This glycol consists of a mixture of *pl* and *meso* forms which were indistinguishable by thin layer chromatography. Although two crystalline forms of dianisylidiphenylethylene glycol were isolated from acetic acid solutions, no stereochemical assignment could be made. A small difference in rate was observed between these two forms (ca. 7%), but neither form appears to give detectable amounts of epoxide. If these crystalline forms correspond to the two diastereomers existing in this system, then they appear to rearrange faster than they equilibrate. Further studies pertaining to this point and other aspects of stereochemistry are in progress.

(5) W. E. Bachman, "Organic Syntheses," Coll. Vol. II, A. H. Blatt, Ed., Wiley, New York, N. Y., 1943, p 71.

(6) See ref 5, p 73. Although acetyl chloride was occasionally used to effect these rearrangements, whenever a product mixture could result, kinetic conditions (solvent, temperature, catalyst concentration and type) were employed.

(7) P. G. Gassman, and F. V. Zaler, *Tetrahedron Lett.*, No. 40, 3031 (1964).

(8) L. S. Silbert, E. Siegel, and D. Swern, *J. Org. Chem.*, **27**, 1336 (1962). Since the epoxides 3 and 4 are very sensitive to acids only small amounts of the peracid were added when necessary. The epoxidation reaction was monitored by thin layer chromatography, uv spectra, and crude iodometric titration. When no olefin could be detected by uv spectra, any excess peracid was destroyed by reaction with cyclohexene and the desired epoxide was quickly removed, washed, and dried.

(9) J. Levy, and R. Lagrave, *Bull. Soc. Chim. Fr.*, **43** [4], 437 (1928).

(10) J. Levy, *ibid.*, **29** [4], 897 (1921). The dehydration of 2,2-di-*p*-anisyl-1,2-diphenylethanol results in the formation of 1,2-di-*p*-anisyl-1,2-diphenylethylene.

(11) R. Criegee, L. Kraft, and B. Rank, *Justus Liebig's Ann. Chem.*, **507**, 157 (1933).

(12) R. Criegee, E. Buchner, and W. Walther, *Ber.*, **73**, 571 (1940).

(13) R. Criegee, E. Hoger, G. Huber, P. Kruck, F. Markscheffel, and H. Schellenberger, *Justus Liebig's Ann. Chem.*, **599**, 81 (1956).

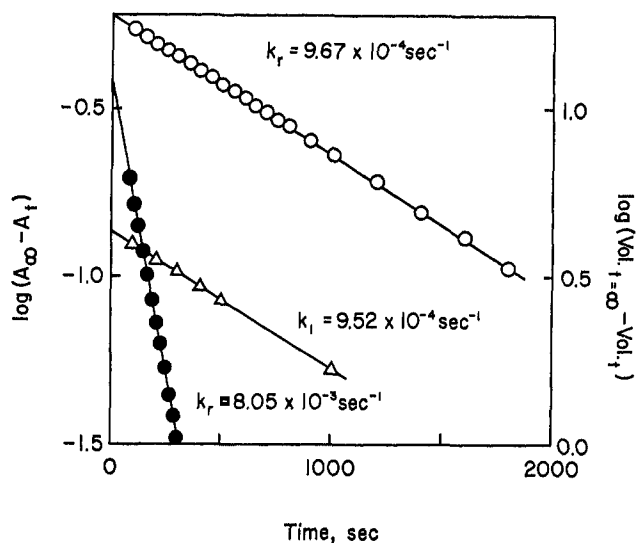
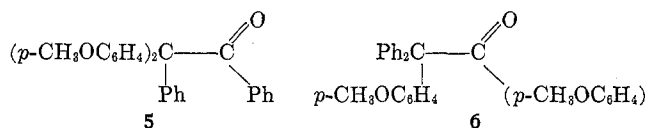


Figure 1.—First-order plots of the spectrophotometric rates of rearrangement of 1 (O) and 3 (●), and the titrimetric rate of dehydration of 1 (Δ). Data given for  $2 \times 10^{-3} M H_2SO_4-HOAc$  at  $25.0^\circ$ .

tion is equal to the rate of ketone formation, and any intermediate, if present, may accumulate only to the extent of its small steady-state concentration. In fact, thin layer chromatographic analysis of samples removed from the reacting solution confirmed that only two components were present, the reacting glycol and its ketonic product; *i.e.*, no epoxide was detected. The ketonic product is actually a mixture of the two ketones, 5, and 6, the composition of which reflects the relative



tendency of the aromatic rings to undergo migration. Analysis of this mixture of ketones by vapor phase chromatography established that the *p*-anisyl group migrates in preference to the phenyl group by a factor of 1000:1.

Since no epoxide could be detected in glycol solutions undergoing dehydration an independent study was undertaken to ascertain the rate of rearrangement of the epoxide, 1,2-di-*p*-anisyl-1,2-diphenylethylene oxide,<sup>16</sup> 3. The spectrophotometric rates of epoxide rearrangement were determined under conditions identical to those prevailing for its corresponding glycol and obeyed good linear pseudo-first-order kinetics for 2 to 3 half-lives, Figure 1. The observed rate coefficient was about 10 times as great as that found for glycol dehydration. It appears that even in these weakly acidic media, epoxide 3 is much more reactive than glycol 1 and furthermore displays a slightly stronger dependence upon the concentration of the acid catalyst. Analysis of solutions resulting from either glycol dehydration or epoxide rearrangement indicated the ketonic products to be formed in quantitative yield. Also, the melting points, uv spectra, and thin layer chromatographic behavior of the products

(16) This epoxide is believed to be a mixture of *DL* and *meso* forms which were indistinguishable by thin layer chromatography.

from the glycol dehydration were identical with those obtained from the epoxide rearrangement.

Tetra-*p*-anisylethylene glycol, 2, was found to be even more sensitive than 1 to acid catalysis. The spectrophotometric rate of glycol rearrangement showed good linear pseudo-first-order kinetics from 2 to 3 half-lives, Figure 2. Thin layer chromatographic analysis of reacting solutions indicated that only two components were present, the unreacted glycol and its corresponding ketone; no epoxide was observed here either. Furthermore, the conversion of the glycol to ketone was shown to be quantitative through uv spectral and thin layer chromatographic analysis. Because glycol 2 possesses limited solubility in the reaction medium, it was not possible to perform titrimetric rate measurements similar to those carried out for glycol 1. However, the totality of the data presented herein established that for glycol 2

$$\frac{-d[G]}{dt} = \frac{d[K]}{dt}$$

The epoxide, tetra-*p*-anisylethylene oxide, 4, corresponding to glycol 2, was independently studied to determine whether it behaved as its dianisyl analog. When 4 was subjected to the identical conditions (temperature and solvent and catalyst concentration) prevailing for glycol rearrangement, good linear pseudo-first-order kinetics were observed from 2 to 3 half-lives, Figure 2. The rate coefficient for epoxide rearrangement was about 3 times larger than that for glycol rearrangement. Thin layer chromatographic and uv spectrophotometric analysis indicated that the conversion to one and the same ketone was quantitative. Furthermore, since no epoxide was detected by the methods in solutions of glycol undergoing dehydration these substrates 2 and 4 mirror the behavior of their dianisyl analogs 1 and 3. The gross kinetic and thin layer chromatographic characteristics exhibited by these systems implies that during glycol dehydration epoxide intermediates do not accumulate to any detectable extent.<sup>17a</sup> This is to be contrasted with the kinetic and thin layer chromatographic behavior for benzopinacol and its corresponding epoxide.<sup>1</sup>

(17) (a) According to our kinetic scheme, the amount of epoxide formed on partitioning  $R^+$  is given by  $k_3[R^+]/(k_2 + k_3)$ . However, the neighboring-group reactivities of *p*-anisyl *vs.*  $-OH$  are such that  $k_2$  is at least 100-fold larger than  $k_3$  so that actually more than 99% of the  $R^+$ 's get converted directly to ketone while epoxide formation must amount to less than 1%. Actually, epoxide accumulation should be further reduced by the operation of the rearrangement term,  $k_4k_2[E]/(k_2 + k_3) \approx k_4[E]$ . Thus when  $k_2 \gg k_3$ , the partitioning of  $R^+$  becomes the dominant factor while the relative rate at which epoxide rearranges is no longer of primary importance in determining the amount of epoxide buildup from its conjugate glycol. (b) It is interesting to note that the free energies of activation for benzopinacol as determined by us and by Gebhard and Adams [*J. Amer. Chem. Soc.*, **76**, 3925 (1954)] are very similar:  $\Delta F^\ddagger_{25^\circ}$  (Pocker and Ronald) = 20.8 kcal/mol;  $\Delta F^\ddagger_{25^\circ}$  (Gebhard and Adams) = 20.4 kcal/mol. Yet, our medium and that of Gebhard and Adams is quite different. They used low concentrations of  $HClO_4$  ( $2 \times 10^{-4}$  to  $5.5 \times 10^{-5} M$ ) in acetic acid which contained as much as  $1.7 \times 10^{-1} M H_2O$ . Since water is more basic than  $HOAc$  the major protonating species in their media was probably  $H_3O^+ ClO_4^-$ . We have employed  $H_2SO_4$  ( $10^{-2}$  to  $1.1 M$ ) in anhydrous acetic acid. The major protonating species in our studies is  $AcOH_2^+ HSO_4^-$ . Since the protonation equilibria of benzopinacol and of tetraphenylethylene oxide are included in the experimental rate coefficients, it is perhaps not surprising that the corresponding Arrhenius activation parameters differ in the two studies. (c) L. L. Schaeleger and F. A. Long, *Advan. Phys. Org. Chem.*, **1**, 1 (1963). (d) Stereochemical and energetic considerations pertaining to epoxide ring opening force us to discard the concerted participation by a neighboring aromatic group as a possible pathway for these reactions. See ref 1.

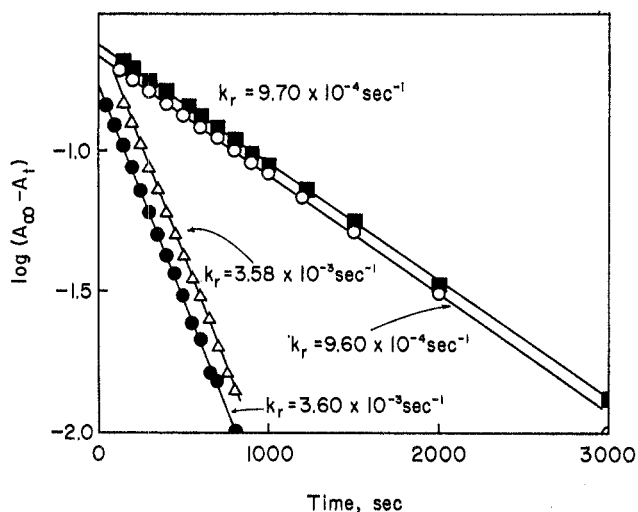
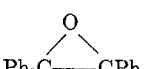
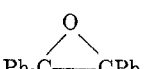


Figure 2.—Duplicate first-order spectrophotometric rate plots for the rearrangement of 2 (■ and ○) and 4 (△ and ●). Values pertaining to 4 (●) plotted as  $(t - 100)$  sec for clarity. Data given for  $6 \times 10^{-5} M$   $H_2SO_4$ -HOAc at  $25.0^\circ$ .

It is conceivable that solvent attack in a ring opening process may occur upon these reactive epoxides, especially 4. One must conclude, however, that the epoxide does not suffer solvent attack to any detectable extent, since thin layer chromatographic analysis of solutions of 4 undergoing rearrangement reveals the presence of only two components, the original epoxide and its corresponding ketone. Even under conditions conducive to attack by added water, the epoxide did not form any glycol. When  $5.55 M$  water was added to the medium and the rates of rearrangement of both the glycol, 2, and the epoxide, 4, were measured under identical conditions, good linear pseudo-first-order kinetics were observed. Both rates were depressed from their normal values in anhydrous solvents, and the epoxide rate coefficient was almost an order of magnitude larger than that of the glycol. It seems unlikely therefore that any significant fraction of the epoxide would be undergoing solvent attack under our kinetic conditions, Table I.

TABLE I  
THE EFFECT OF ADDED WATER ON THE RATE OF REARRANGEMENT AT  $25^\circ$

Substrate	$H_2SO_4$ - HOAc, M	Added $H_2O$ , M	$k_r^a \times 10^4$ , sec $^{-1}$	% re- action $^b$
2 	$6 \times 10^{-5}$	0.0	9.65	81
		5.55	1.54	89
		5.0	17.2	84
4 	$6 \times 10^{-5}$	0.0	35.9	75
		1.0	2.9	93
		2.0	0.93	89
		5.55	10.7	86

<sup>a</sup> Rate coefficients derived from first-order plots of spectrophotometric measurements. Good linearity was observed for the percentage of reaction indicated. <sup>b</sup> Percentage reaction over which spectrophotometric rate data was accumulated.

The rates of rearrangement of all these *p*-methoxy substituted compounds are very strongly dependent upon the acidity of the medium. For both systems, plots of  $k_r$  vs. acid concentration,  $H_2SO_4$ -HOAc, show

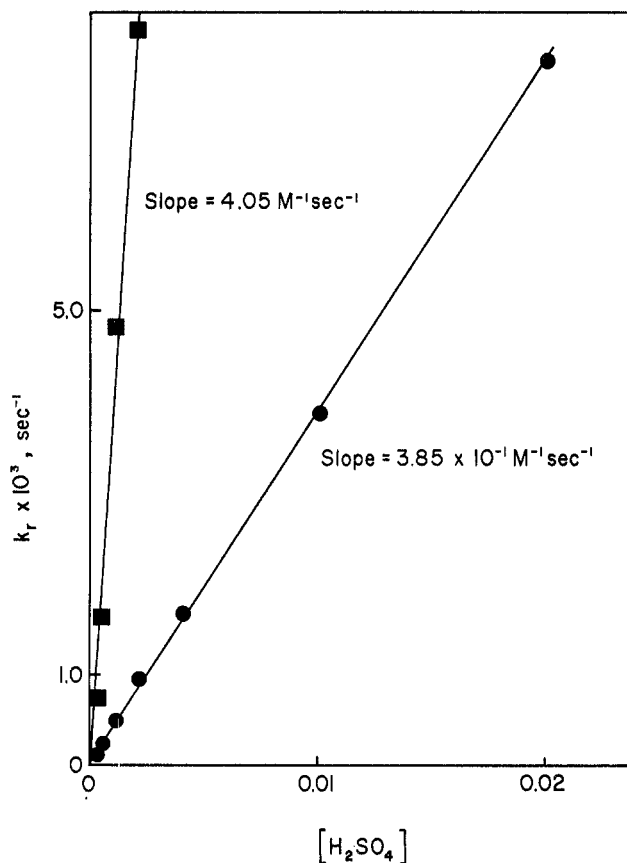


Figure 3.—Acidity plot of  $k_r$  vs.  $[H_2SO_4]$  at  $25.0^\circ$  for the rearrangement of 1 (●) and 3 (■).

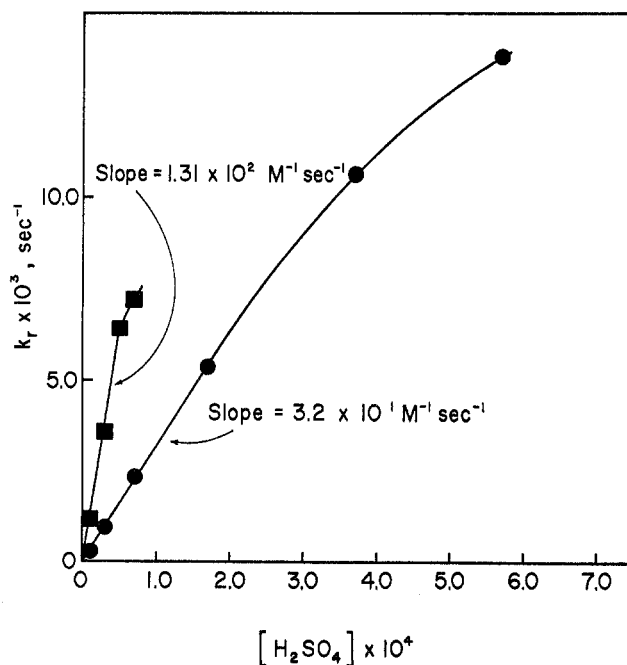


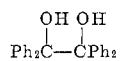
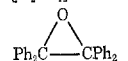
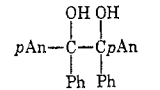
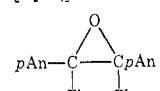
Figure 4.—Acidity plot of  $k_r$  vs.  $[H_2SO_4]$  at  $25.0^\circ$  for the rearrangement of 2 (●) and 4 (■).

linearity with the epoxides being more sensitive to the amount of the acid catalyst than the glycols, Figures 3 and 4. The rate depression observed with added water is due to a reduction in the proton donating capacity of this medium, Table I.

Preliminary Arrhenius activation parameters measured for 1,2-di-*p*-anisyl-1,2-diphenylethylene glycol

and oxide were in accord with expectations,  $E_a^{\text{glycol}} = 20.0 \text{ kcal mol}^{-1}$ ,  $E_a^{\text{epoxide}} = 18.8 \text{ kcal mol}^{-1}$ . For comparison these parameters for benzopinacol and tetraphenylethylene oxide are  $E_a^{\text{glycol}} = 23.5 \text{ kcal mol}^{-1}$ ,  $E_a^{\text{epoxide}} = 20.7 \text{ kcal mol}^{-1}$ .<sup>17b</sup> The entropies of activation for these compounds are also in accord with what is known about these processes.<sup>17c</sup> The values for both the glycols and the epoxides are near zero, Table II. For further comparison, entropies of activation have been calculated for these reactions after the two systems were brought to the same free energy of activation.

TABLE II  
ARRHENIUS ACTIVATION PARAMETERS

Substrate	$t, ^\circ\text{C}$	$k_r \times 10^4, \text{ sec}^{-1}$	$E_a, \text{ kcal mol}^{-1}$	$\Delta S^\ddagger, \text{ eu}$
	25	2.78 <sup>b</sup>		+4 <sup>c</sup>
	35	9.82 <sup>b</sup>	23.5	+7 <sup>d</sup>
	45	32.7 <sup>b</sup>		+5 <sup>e</sup>
	25	9.75		
	33	23.5	20.7	-3
	42	63.2		-5 <sup>f</sup>
	25	1.0		+5
	35	3.0	20.0	+5
	45	8.2		-3 <sup>g</sup>
	25	7.7		
	34	19.9	18.8	+9
	42	42.7		+5 <sup>h</sup>

<sup>a</sup> Calculated from  $\Delta F^\ddagger_{25^\circ} = \Delta H^\ddagger_{25^\circ} - T\Delta S^\ddagger_{25^\circ}$  where  $\Delta F^\ddagger_{25^\circ} = 2.303 RT (\log kT/h - \log k_r/[H_2SO_4])$  and  $\Delta H^\ddagger_{25^\circ} = E_a - RT$ . <sup>b</sup> Initial spectrophotometric rates of ketone formation. <sup>c</sup> Calculated from glycol rearrangement using  $k_r^i = 2.78 \times 10^{-4} \text{ sec}^{-1}$  at  $25.0^\circ$  and  $[H_2SO_4] = 0.40 M$ . <sup>d</sup> Calculated from glycol dehydration using  $k_1 = 1.71 \times 10^{-3} \text{ sec}^{-1}$  at  $25.0^\circ$  and  $[H_2SO_4] = 0.40 M$ . <sup>e</sup> Calculated for glycol dehydration using first-order rate coefficient. <sup>f</sup> Calculated for epoxide rearrangement using first-order rate coefficient. <sup>g</sup> Calculated for glycol dehydration using the first-order rate coefficient,  $k_r = 1.71 \times 10^{-3} \text{ sec}^{-1}$  at  $25^\circ$  and  $[H_2SO_4] = 4.45 \times 10^{-3} M$ . This  $k_r$  value was extrapolated from a plot of  $k_r$  vs.  $[H_2SO_4]$  whose slope was  $3.85 \times 10^{-1} M^{-1} \text{ sec}^{-1}$ . <sup>h</sup> Calculated for epoxide rearrangement using the first-order rate coefficient,  $k_r = 18.0 \times 10^{-3} \text{ sec}^{-1}$  at  $25^\circ$  and  $[H_2SO_4] = 4.45 \times 10^{-3} M$ . This  $k_r$  value was extrapolated from a plot of  $k_r$  vs.  $[H_2SO_4]$  whose slope was  $4.0 M^{-1} \text{ sec}^{-1}$ .

### Discussion

A unique feature characterizing the acid-catalyzed pinacolic rearrangement and dehydration of certain glycols is the accumulation and eventual destruction of an intermediate whose identity was established as the corresponding epoxide. Those glycols then are representatives of category a where initially

$$\frac{-d[G]}{dt} > \frac{d[K]}{dt}$$

and

$$\frac{d[E]}{dt} > 0$$

Another kinetic feature pertaining to this category was curved rate plots for the spectrophotometric rates of glycol rearrangement.<sup>1</sup> These distinctive characteristics are notably absent from the acid-catalyzed dehydration of the *p*-methoxyl bearing substrates **1** and **3**.

Careful scrutiny of the experimental data suggests that the proper category for substrates **1** and **3** is b where

$$\frac{-d[G]}{dt} = \frac{d[K]}{dt}$$

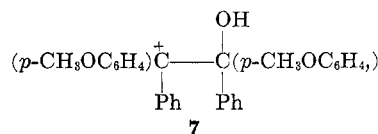
and

$$\frac{d[E]}{dt} = 0$$

Our inability to detect any epoxide intermediates in the dehydration reactions of **1** and **3** after applying titrimetric, spectrokinetic and thin layer chromatographic methods of analysis supports the contention that only steady-state concentrations of intermediates can be present. The previously proposed mechanism<sup>1</sup> uniquely accommodates the experimental observations related to *p*-methoxyl bearing substrates with the single stricture that  $k_4K_{eq}[E][\text{acid}] \gg k_5[R^+]$ .

The carbonium ion,  $R^+$ , is itself interesting because it possesses certain outstanding properties. If  $R^+$  undergoes ring closure with the neighboring hydroxyl group to form the conjugate acid of the epoxide it must by the principle of microscopic reversibility ring open to form the same  $R^+$ .<sup>17d</sup> It is eminently reasonable to suppose that this same carbonium ion is generated from glycol dehydration. Furthermore this process should in principle be reversible. However, energetically more favorable routes for carbonium ion destruction appear to exist, since conditions conducive to collapse with solvent fail to produce solvent adduct products.

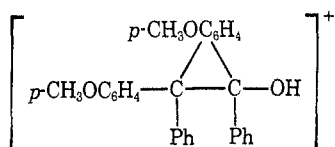
The preferred pathway for carbonium ion destruction is through attack on the neighboring aromatic rings. These reactions then resemble electrophilic aromatic substitution processes and electrophilic aromatic dealkylations. Little is known about the latter process where one alkyl group displaces another from the aromatic ring.<sup>18</sup> Electrophilic aromatic substitution processes have been studied in some detail and have a definite bearing upon aryl migration reactions.<sup>18</sup> The attack of  $R^+$  upon the neighboring aromatic ring leads to a transition state similar to that suggested for electrophilic aromatic substitution reactions. The aromatic ring undergoing attack possesses a certain characteristic susceptibility which reflects its capacity to support and stabilize a positive charge. Those aromatic rings possessing substituents capable of accepting some of the positive charge through resonance interaction have an enhanced probability of undergoing reaction. The susceptibility of aromatic rings to attack by electrophiles is further influenced by their propinquity to the positive center and the stability of this positive center. When both the aromatic rings and the carbonium ion are contained within the same carbon skeleton as in ion **7**, then entropic considerations favor collapse with the



rings as opposed to collapse with the solvent.<sup>19,20</sup> The reaction with solvent is a bimolecular process,

- (18) L. M. Stock, and H. C. Brown, *Advan. Phys. Org. Chem.*, **1**, 35 (1963).  
 (19) T. C. Bruice, and S. Benkovic, "Bioorganic Mechanisms," Vol. I, W. A. Benjamin, New York, N. Y., 1966, pp 119-125.  
 (20) W. P. Jencks, "Catalysis in Chemistry and Enzymology," McGraw-Hill, New York, N. Y., 1969, pp 7-30.

whereas the reaction with the neighboring aromatic ring is a unimolecular process. In the former not only is there a considerable loss in translational entropy accompanying the bringing together of the reactants, but  $R^+$  and the nucleophile in all probability are desolvated as the activated complex is formed. On the other hand, no such translational entropic restriction applies to the unimolecular process, and furthermore only a slight, if any, reorganization of the solvent may be required to attain the transition state configuration. At the same time these effects together with the compensating resonance delocalization must counterbalance any strain energy accumulated in the attack of the carbonium ion on its neighboring groups. Thus a phenonium ion may have transient existence in the migration step involving the aromatic ring.



The stability of  $R^+$  strongly governs its selectivity.<sup>21</sup> When the carbonium ion is very stable, *i.e.*, it has a long life time, it tends to be very discriminating towards approaching nucleophiles. On the other hand only a small or negligible discriminatory capacity is displayed by those carbonium ions possessing a short life time. The carbonium ion generated in these studies either from glycol dehydration or epoxide ring opening is a tertiary ion possessing two aromatic rings which aid in delocalizing the positive charge and thus in enhancing its stability. An adverse inductive effect due to the  $\beta$ -hydroxyl group and the  $\beta$ -aromatic rings reduces the stability somewhat.<sup>22,23</sup> Perhaps the best description of the ion is that it is benzhydryl-like.

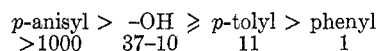
The observation that ion 7 prefers to attack the neighboring *p*-anisyl group to the phenyl group in the

(21) M. Stiles, and R. P. Mayer, *J. Amer. Chem. Soc.*, **81**, 1497 (1959).

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

(23) J. Hine, "Physical Organic Chemistry," McGraw-Hill, New York, N. Y., 1962, p 327.

ratio of 1000:1 suggests some discriminatory ability. That this discriminatory capacity is not large is shown by comparison with the data of Bethel and Gold on the attack of substituted benzhydryl cations on various aromatic rings.<sup>24</sup> Anisole reacts  $10^6$  times as fast as benzene with 4-methoxybenzhydryl cation generated by the sulfuric acid catalyzed dehydration of 4-methoxybenzhydrol in acetic acid solvent. The reactivity of anisole to benzene in other electrophilic aromatic substitution reactions<sup>18</sup> ranges from  $10^3$  to  $10^5$ . Thus ion 7 and those analogous to it do not seem to possess the discriminatory capacity exhibited by the benzhydryl cations in the above bimolecular electrophilic substitutions. However they do effectively discriminate against the solvent. Admittedly though, acetic acid containing sulfuric acid is a solvent possessing a very low order of nucleophilic character. Perhaps the structural feature possessing the dominant influence on the reactions of ion 7 and its analogs is the neighboring group whose observed order of reactivity is



The position of the hydroxyl group in this series is unique, for in most other nucleophilic series it is better than most aromatic groups. This new order and the position of the  $-\text{OH}$  group results from the following factors: (1) the collapse of these carbonium ions is a unimolecular process; (2) all neighboring groups have the same relative concentration within the solvation shell; and (3) strain energy is accumulated when either the  $-\text{OH}$  group or the aromatic rings react with the positive center but resonance stabilization compensates for this strain energy only in the latter case. Further studies concerning the various kinetic categories (a, b, and c), the effect of solvent composition, and the energetics of neighboring-group migration are being actively pursued in these laboratories and will be communicated presently.

**Registry No.**—DL-1, 19235-02-0; *meso*-1, 19235-01-9; 2, 19920-00-4; DL-3, 25124-98-5; *meso*-3, 25124-99-6; 4, 25125-00-2.

(24) D. Bethel, and V. Gold, *J. Chem. Soc.*, 1905, 1930 (1958).