Solvolysis of Optically Active 1-Phenylethyl Chloride. Polarimetric Rates, Deuterium Isotope Effects, Product Configurations, and Mechanisms¹

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For 1-phenylethyl chloride, the rate of change of optical activity is found to exceed the solvolysis rate by factors of 1.72, 1.16, and 1.07, respectively, in solvents 97% 2,2,2-trifluoroethanol-3% water (97 T), 80 vol. % ethanol-water (80 E), and 60 vol. % ethanol-water (60 E). α - and β -deuterium effects on the rates of change of optical activity are observed to be similar to those on the rates of solvolysis. The products in all three solvents show appreciable optical activity, indicating that nucleophilic attack on the carbonium ion fragment occurs before the leaving group has completely diffused away. The importance of internal ion-pair recombination is indicated by the initial formation of 1-phenylethyl chloride in sixfold excess over 1-phenylethyl trifluoroethyl ether in the reaction of undissociated HCl with styrene in pure trifluoroethanol (100 T). These results can be nicely accommodated by the solvolysis scheme involving two ion-pair intermediates. Applying this scheme to the present results one concludes that in these solvolyze (via the solvent separated ion pair), and 7 invert their configuration; in 60 E, of 100 formed, 70 return, 28 solvolyze, and 1.4 invert. α - and β -deuterium effects on the rates of acid-catalyzed racemization of 1-phenylethanol in trifluoroethanol-water mixtures indicate that the rate-determining step is the ionization of the C–O bond of the conjugate acid.

In earlier publications from these laboratories,²⁻⁵ the effects of α - and β -deuterium substitution on the rates of solvolysis of a series of substituted 1-phenylethyl chlorides and bromides were interpreted to indicate that unsubstituted 1-phenylethyl chloride (and bromide) and their more reactive ring-substituted derivatives solvolyze in aqueous ethanol and aqueous trifluoroethanol solvents via a transition state in which there is no partial covalent bond between the reacting carbon and either leaving or incoming group. This is consistent with the rate-determining step in each case being the diffusion apart of an ion pair or the conversion of one type of ion pair to another, but is inconsistent with it being either the formation of an ion pair from the covalent reactant, or nucleophilic attack on the covalent reactant, ion pair, or free carbonium ion.

In these latter reactions, the rate-determining step leads either directly to or directly from a state having at least one of the reactant groups covalently attached to carbon; therefore these transition states must have partial covalent attachment between carbon and incoming or leaving groups, a situation inconsistent with the isotope effect evidence.

If conversion of one ion pair to another is the ratedetermining step, then the first ion pair must undergo dominant recombination to covalent reactant (ion pair return).⁶ Traditionally, racemization of reactant has been associated with ion-pair return even though return can occur predominantly without racemization.⁷

(1) Taken in part from the thesis submitted by P. C. Vogel in September of 1967 to the Graduate School of Indiana University in partial fulfillment of the requirements for the Ph.D. Degree.

(5) V. J. Shiner, Jr., in "Isotope Effects in Chemical Reactions," C. J. Collins and N. S. Bowman, Ed., Van Nostrand-Reinhold, Princeton, N. J., 1970, p 105 ff.

We were, therefore, encouraged to look for racemization of optically active 1-phenylethyl chloride concurrent with solvolysis. The most straightforward way of doing this appeared to be to determine whether or not the rate of change of optical activity of a solvolyzing solution exceeded the solvolysis rate measured by the conductance method. The recent availability of more sensitive commercial polarimeters based on the Faraday magnetooptic effect made it more likely that small rate differences could be conclusively observed and also made the measurement of α - and β -deuterium effects on polarimetric rates appear practical. After this work was undertaken, De La Mare, Hall, and Mauger⁹ reported a polarimetric kinetic study of the solvolysis of 1-phenylethyl chloride and related phenomena in aqueous dioxane. The results of the two investigations are similar in some important aspects but the different solvent systems are known to be sufficiently different in behavior¹⁰ for the results to be complementary rather than redundant.

Experimental Section

A. Materials.—All solvents were carefully purified for conductance work by standard methods reported earlier.^{2,3} Mixed solvents were prepared by weighing the components, although $EtOH-H_2O$ mixtures are reported in accord with tradition in volume per cent.

1-Phenylethyl alcohol and its $\beta \cdot d_s$ analog were prepared from the corresponding ketones by lithium aluminum hydride reduction. The $\beta \cdot d_s$ ketone was prepared from the hydrogen compound by exchange in dioxane-D₂O, triethylamine solutions. The $\alpha \cdot d$ alcohol was prepared from acetophenone by reduction with lithium aluminum deuteride. Chlorides for conductance work were prepared from the alcohols by treatment with the hydrogen chloride. Full experimental details have been reported previously.^{2,3}

The 1-phenylethyl alcohols were resolved via the brucine salts of their hydrogen phthalate esters by the method of Downer and Kenyon.¹¹ The optically active alcohols were obtained by first treating with dilute hydrochloric acid and ether to decompose the brucine salt and then by refluxing the ether layer with 4 NNaOH for several hours to hydrolyze the ester. In typical

⁽²⁾ V. J. Shiner, Jr., W. E. Buddenbaum, B. L. Murr, and G. Lamaty, J. Amer. Chem. Soc., 90, 418 (1968).
(3) V. J. Shiner, Jr., W. Dowd, R. D. Fisher, S. R. Hartshorn, M. A.

⁽³⁾ V. J. Shiner, Jr., W. Dowd, R. D. Fisher, S. R. Hartshorn, M. A. Kessick, L. Milakofsky, and M. W. Rapp, J. Amer. Chem. Soc., **91**, 4838 (1969).

 ⁽⁴⁾ V. J. Shiner, Jr., M. W. Rapp, E. A. Halevi, and M. Wolfsberg, J.
 Amer. Chem. Soc., 90, 7171 (1968).

⁽⁶⁾ S. Winstein, B. Appel, R. Baker, and A. Diaz, Special Publication No. 19, The Chemical Society, London, 1965, p 109.
(7) H. L. Goering and H. Hopf, J. Amer. Chem. Soc., 93, 1224 (1971).

⁽⁷⁾ H. L. Goering and H. Hopf, J. Amer. Chem. Soc., 93, 1224 (1971).
However, it has been argued that racemization could be an entirely different process not associated with solvolysis.⁵
(8) L. P. Hammett, "Physical Organic Chemistry," 2nd ed, McGraw-

⁽⁸⁾ L. P. Hammett, "Physical Organic Chemistry," 2nd ed, McGraw-Hill, New York, N. Y., 1970, p 162.

⁽⁹⁾ P. B. D. De La Mare, D. M. Hall, and E. Mauger, Recl. Trav. Chim. Pays-Bas, **87**, 1394 (1968).

⁽¹⁰⁾ H. Weiner and R. A. Sneen, J. Amer. Chem. Soc., 87, 287 (1965).
(11) E. Downer and J. Kenyon, J. Chem. Soc., 115b (1939).

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preparations the optically active materials were found to have the following specific rotations.

| Alcohol | $[\alpha]_{5481}(neat), deg$ |
|--------------------------------|------------------------------|
| 1-Phenylethyl | -46.8 |
| 1-Phenylethyl- α -d | +30.3 |
| 1-Phenylethyl- β - d_3 | -41.5 |

These materials were stored in glass vials in a freezer until used.

Optically active chlorides for the polarimetric work were prepared from the alcohols by the method of Burwell, Shields, and Hart.¹² In typical preparations, chlorides with the following specific rotations were obtained.

| Chloride | $[\alpha]_{5461}(neat), deg$ |
|--------------------------------|------------------------------|
| 1-Phenylethyl | +123 |
| 1-Phenylethyl- α -d | -39.4 |
| 1-Phenylethyl- β - d_3 | +113.4 |

The nmr spectra of all materials were in accord with the assigned structures and revealed no absorptions due to impurities.

B. Conductance Measurements.—The conductometric method of Murr and Shiner¹³ was used. Details of this, the conductance parameters, and the statistical method used to treat the kinetic data have all been reported before.^{2,8,13}

C. Polarimetric Measurements.-The polarimetric measurements were made using a Bendix Model 965 automatic balancing polarimeter system. A modified Vidar 500 integrating digital voltmeter was used to convert the cutput from the Bendix into digital display and to BCD form for automatic recording. The digital voltmeter and a Computer Measurements Corp. time interval meter were connected via control electronics to a Tally paper tape punch, so that, at preset time intervals, readings from the time interval meter and the digital voltmeter could be punched onto paper tape, thus allowing completely automatic collection of data. The intervals between readings could be adjusted to any value, down to three readings per second. In routine kinetic runs about 200 readings were taken over a period of about two half-lives. The data were transferred from paper tape to computer cards, by an IBM 47 tape-to-card converter, in a format suitable for direct entry into a least-squares program used to treat the results.14

The digital voltmeter was calibrated against standard sucrose solutions and found to give a linear response over the range of operation used in this work. It was adjusted so that the display registers (in millivolts) corresponded directly to rotations (in millidegrees) of a sample in the polarimeter. Rotations of optically active samples were measured to the nearest 1/10 of a millidegree, although the uncertainty claimed by the manufacturer is 3/10 of a millidegree. Reading errors were thus estimated to be of the order of 0.3-1% of the overall rotation changes which were in the range from 50 to 150 millidegrees.

At the beginning of this work we experienced difficulty in reproducing rate constants, and traced this to inadequate temperature control of the polarimeter cell. We finally used a 5-cm jacketed fused quartz cell supplied by Opticell. This was modified to allow a calibrated thermistor probe to be inserted through the side arm of the cell to record the temperature of the sample in the cell. The cell was cooled by circulating a mixture of ethylene glycol-water from a thermostat through the jacket. The thermostat was adjusted to control the cell temperature to $25.00 \pm 0.01^\circ$.

The solutions for kinetic runs with the chlorides were prepared by adding enough of the chloride to the solvent in a small flask to produce a concentration of 0.02-0.03~M in substrate. After mixing well, the solution was placed in the polarimeter cell and allowed to come to thermal equilibrium before taking readings; usually about 3-5 min were required. At this concentration the initial rotations of the solutions were about 100-150 millidegrees.

The same method was used for reactions of the 1-phenylethyl alcohols and HCl in various TFE solutions. The standard solutions of HCl in TFE were prepared by bubbling dry HCl into the TFE solution and determining the concentration by titration with standardized NaOH solutions. The alcohol was then added to a solution of HCl in TFE and placed in the polarimeter cell.

Nmr Rate Measurements.-All spectra were recorded D with a Varian HA-100 instrument equipped with an internal lock. Reactions were carried out using approximately 0.5 ml of 0.05 Msolution in 5-mm nmr tubes. Rates were determined by com-paring the recorded peak heights of the methyl proton doublet of 1-phenylethyl chloride, 1-phenylethyl trifluoroethyl ether, or 1-phenylethyl alcohol with that of an added internal standard, acetonitrile, at various intervals over approximately two half-In trifluoroethanol solvent, the center of the methyl lives. doublet (J = 6 Hz) of 1-phenylethyl chloride is 11 Hz upfield from acetonitrile; the center of the methyl doublet of 1-phenylethyl trifluoroethyl ether is 43 Hz upfield from acetonitrile, not resolved from the similar doublet of 1-phenylethyl alcohol. In pure trifluoroethanol the solvolysis (at $\sim 0.05 M$) proceeds only to the extent of about 30%, reaching apparent equilibrium in about 1000 sec. In the presence of a slight excess of potassium hydroxide, a twofold excess of potassium hydroxide, or a twofold excess of pyridine the appearance of ether product followed the first-order rate law smoothly for more than two half-lives; the first-order rate constants at 29° (the probe temperature) under these conditions were 1.19, 1.17, and 1.12 \times 10⁻³ sec⁻¹, respectively. In 97% trifluoroethanol-3% water at the same probe temperature the solvolysis of 1-phenylethyl chloride proceeds to apparent completion via a first-order process in the absence of a base $(k = 1.26 \times 10^{-3} \text{ sec}^{-1})$ or in the presence of 2 equiv of pyridine $(k = 1.17 \times 10^{-3} \text{ sec}^{-1})$.

The rate of conversion of 1-phenylethanol to the chloride in solution in pure trifluoroethanol with HCl was also determined by nmr. These processes were only roughly first order as expected; for $0.05 \ M$ alcohol the rough pseudo-first-order rate coefficient was $10 \times 10^{-3} \sec^{-1}$ for $0.10 \ M$ HCl and $5 \times 10^{-3} \sec^{-1}$ for $0.033 \ M$ HCl.

The formation of 1-phenylethyl chloride from 0.106 M HCl and 0.05 M styrene in trifluorcethanol was observed to follow with reasonable accuracy the first-order rate law, $k = 5.2 \times$ 10^{-8} sec⁻¹. During the first 10 min of reaction the ratio of the initial peak height for 1-phenylethyl chloride to that for 1-phenylethyl trifluoroethyl ether was 6.0-6.5. This ratio decreased to 4.5 after 0.5 hr and was again observed at that value after 18 Since the rate constant for solvolysis of 1-phenylethyl hr. chloride in pure TFE was about 1.19×10^{-5} sec⁻¹, the initial addition of $\hat{0}.1 \ M$ HCl to $0.05 \ M$ styrene occurs much faster than the reverse solvolysis. From the ratio of peak heights after 18 hr, the equilibrium constant for the conversion of 1-phenylethyl chloride to 1-phenylethyl trifluoroethyl ether plus HCl can be calculated, as can the second-order rate constant for the reaction of the ether with HCl. This showed that the initial formation of 1-phenylethyl chloride was faster than could be accounted for in terms of intermediate formation of the trifluoroethyl ether. Thus, the initial ratio of products observed by nmr must be the ratio characteristic of the addition reaction itself.

E. Product Studies.—The products from the solvolysis of optically active 1-phenylethyl chloride at 25° in 60 and 80% ethanol-water solvents were isolated and separated by the procedure of Okamoto and coworkers.¹⁵ In 60% ethanol-water, 1-phenylethyl alcohol was obtained with 32.6% net inversion and in 80% ethanol it was formed with 34.2% net inversion (the balance in each case being racemic). For reactions in TFE solvents the products were identified by their retention times on vpc analysis. A Varian series 1200 gas chromatograph fitted with a flame ionization detector was used. Good separations were obtained with a 12 ft \times $^{1}/_{16}$ in. column packed with 10% Carbowax 20M on Carbosorb P operating at 130° with nitrogen at 60 psi as the carrier gas. The observed retention times in minutes follow: 2,2,2-trifluoroethanol, 3.6; styrene, 6.0; 1-phenylethyl trifluoroethyl ether, 7.2; 1-phenylethyl chloride, 14.2; 1-phenylethyl alcohol, 39.0. It was found from control experiments that both 1-phenylethyl chloride and alcohol gave rise to a small styrene peak owing to elimination in the gas chromato-In 97 T, 0.05 M 1-phenylethyl chloride in the presence graph. of 0.08 M potassium hydroxide gave 79% trifluorcethyl ether, 21% 1-phenylethanol, and less than 1% styrene. With other bases the yields of ether and alcohol, respectively were as follows:

⁽¹²⁾ R. L. Burwell, A. D. Shields, and H. Hart, J. Amer. Chem. Soc., 76, 908 (1954).

⁽¹³⁾ B. L. Murr, Jr., and V. J. Shiner, Jr., J. Amer. Chem. Soc., 84, 4672 (1962).

⁽¹⁴⁾ Details of this least-squares program are available in the thesis of P. C. Vogel.¹

⁽¹⁵⁾ K. Okamoto, N. Uchida, S. Saito, and H. Shingu, Bull. Chem. Soc. Jap., 39, 307 (1966).

excess CaCO₃, 82 and 18%; excess lutidine, 81 and 19%; 0.2 M KOH, 84 and 16%.

Results

The results of solvolysis of 1-phenylethyl chloride and its α -d and β -d₃ analogs in different solvents are given in Tables I and II. For the conductance work

TABLE I Reaction Rate Constant for 1-Phenylethyl Chloride at 25°

| a a a | | | | Optical |
|------------------|--------------------------|--------------|--------------|---------------------------|
| Solvent" | Added reagent | $Method^{o}$ | $10^4 k_1^c$ | result^d |
| $60~{ m E}$ | None | \mathbf{C} | 1.0865* | |
| $60~{ m E}$ | None | Р | 1.136 | 28.5% |
| | | | | inversion |
| $80~{ m E}$ | None | \mathbf{C} | 0.10019¢ | |
| 80 E | None | Р | 0.116 | 25.1% |
| | | | | inversion |
| $97 \ T$ | None | \mathbf{C} | 6.70 | |
| $97 \ T$ | None | Р | 11.53 | 5.7% |
| | | | | retention |
| $97 \ T$ | 0.03 M pyridine | Р | 10.81 | 5.4% |
| | | | | retention |
| 100 T | None | Р | 12.50 | Racemic |
| $100 \mathrm{T}$ | 0.03 M pyridine | Р | 12.20 | 8.0% |
| | | | | retention |
| $100 \ T$ | $0.012 \ M \ \text{KOH}$ | Р | 12.43 | 7.5% |
| | | | | retention |
| 100 T | 0.014~M KOH | Р | 12.48 | 7.0% |
| | | | | retention |
| $100 \ T$ | $0.080 \ M \ \text{KOH}$ | Р | 13.68 | 8.1% |
| | | | | retention |
| | | | | |

^a 60 E refers to 60 vol. % ethanol-40 vol. % water, 97 T refers to 97 wt % 2,2,2-trifluoroethanol-3 wt % water, etc. ^b P, polarimetric; C, conductometric. ^e First-order rate constants; error in polarimetric rate constants is estimated as $\pm 2\%$ and in conductometric rate constants as $\pm 0.1\%$. ^d Figures refer to the optical rotation at the end of the kinetic run as a percentage of the initial rotation. This does not refer to the change in configuration, although this is known for the ethanol-water solvents. ^e From ref 2.

TABLE II

Reaction Rate Constants for Deuterated 1-Phenylethyl Chlorides at $25^{\circ_{a-e}}$

| | Deu- | | | |
|--|-------------|---------------------|----------------|-----------------------------|
| $Solvent^a$ | terium | Method^b | $10^4 k_1^{c}$ | Optical result ^d |
| $60 ~ { m E}$ | 1-d | \mathbf{C} | 0.944° | |
| $60~{ m E}$ | 1-d | Р | 0.970 | 29% inversion |
| $97 \ T$ | 1-d | С | 5.79 | |
| $97 \mathrm{T}$ | 1-d | \mathbf{P} | 9.64 | 5.5% retention |
| $97 \mathrm{T} + \mathrm{Py}^{\prime}$ | 1-d | Р | 9.44 | 5.7% retention |
| 100 T | 1-d | Р | 10.52 | Inactive |
| 100 T + Py' | 1-d | Р | 10.41 | 8.0% retention |
| 60 E | $2,2,2-d_3$ | С | 0.8867 | |
| $60 ~ \mathrm{E}$ | $2,2,2-d_3$ | Р | 0.893 | 26.8% inversion |
| 97 T | $2,2,2-d_3$ | \mathbf{C} | 5.50 | |
| $97 \mathrm{T}$ | $2,2,2-d_3$ | Р | 9.26 | 6.0% retention |
| 97 T + Py' | $2,2,2-d_3$ | \mathbf{P} | 8.91 | |
| 100 T | $2,2,2-d_3$ | Р | 10.18 | Inactive |
| 100 T + Py' | $2,2,2-d_3$ | Р | 9.54 | 8.3% retention |
| | | | | 10.00 |

 a^{-e} See footnotes of Table I. ' Py indicates presence of 0.03 M pyridine.

the reproducibility of the rate constant between different runs was usually $\pm 0.1\%$ or better and for the polarimetric runs it was usually $\pm 1-2\%$ but in some cases better than $\pm 1\%$. All kinetic runs were observed to be accurately first order as indicated from an analysis of the error plots printed out by the computer program and a comparison of observed and calculated initial and infinity readings. For example, in an experiment with 1-phenylethyl-1-d chloride solvolyzing in 97% TFE at 25° the initial reading was -0.0589° observed and -0.0589° calculated; the infinity reading was -0.0040° observed and -0.0038° calculated. The calculated readings were parameters which gave the best fit of the data to the first-order rate law according to the least-squares criterion.¹⁴

The results for the reactions of the 1-phenylethyl alcohols with HCl in 70, 97, and 100% TFE are given in Table III. The reactions in 70 and 97% TFE were

| TABLE I | п |
|---------|---|
|---------|---|

| RATE CONSTANTS FOR RACEMIZATION OF ACTIVE 1-Phenylethyl Alcohol (and Its α -d and β -d ₃ Analogs) with HCl in Trifluoroethanol Solutions at 25° | | | | |
|---|-------------------|--------|---------------------|-----------------------|
| | | [HC1], | | |
| Deuterium | $Solvent^a$ | mol 11 | $10^4 k_p^b$ | $k_{\rm H}/k_{\rm D}$ |
| None | $100 \ T$ | 0.0001 | ${\sim}7^{\circ}$ | |
| None | $100 \mathrm{~T}$ | 0.0013 | ${\sim}40^{\circ}$ | |
| None | $100 \ T$ | 0.0033 | ${\sim}200^{\circ}$ | |
| None | $97 \ T$ | 0.0087 | 0.264 | |
| None | $97 \ T$ | 0.130 | 8.70 | |
| None | $97 \ T$ | 0.153 | 12.27 | |
| None | $70~\mathrm{T}$ | 2.20 | 6.23 | |
| 1-d | $97 \ T$ | 0.153 | 10.33 | 1.187 |
| 1-d | $70 \mathrm{T}$ | 2.20 | 5.41 | 1.152 |
| $2, 2, 2-d_3$ | $97 \ \mathrm{T}$ | 0.153 | 11.03 | 1.112 |
| $2, 2, 2 - d_3$ | $70 \ T$ | 2.20 | 5.70 | 1.094 |

 a 70 T represents 70 wt % trifluoroethanol-water, etc. b Errors. c Errors are ${\sim}20\%$.

accurately first order but in 100% TFE only approximately first order.

Discussion

As indicated in Table IV, the polarimetrically measured rates exceed the conductometrically measured

| TABLE | IV |
|-------|----|
|-------|----|

| Comparison of Rate Constants for Solvolysis of | |
|---|----|
| 1-Phenylethyl Chloride Measured Conductometricali | ĹΥ |
| (k_{e}) and Polarimetrically $(k_{m{lpha}})$ | |

| $k \alpha / k_0^a$ |
|--------------------|
| 1.05 |
| 1.16 |
| 1.72 |
| |

^a The error in the ratio is estimated to be ± 0.02 .

rates in each of the three solvents used, although the difference is small in the ethanol-water solvents. In 97 T internal racemization becomes almost as fast as solvolysis, suggesting a considerable amount of ionpair return. The occurrence of ion-pair return in 100 T is also indicated by the initial formation of a sixfold excess of 1-phenylethyl chloride over 1-phenylethyl trifluoroethyl ether in the addition of undissociated HCl to styrene; the most straightforward interpretation of this result is to conclude that the 1-phenylethyl cation-chloride ion pair formed after proton transfer from covalent HCl to styrene combines six times faster than it solvolyzes. We have proposed in earlier publications¹⁶ that the generalized solvolysis scheme below¹⁷ (Scheme I) can



be used to explain the presently known details of a wide variety of nucleophilic solvolytic substitution reactions. We shall, therefore, discuss the present results, as well as those obtained earlier on these specific reactions, directly in terms of this scheme. In particular, we will attempt to determine for each reaction which step in the scheme represents the rate-determining step and in which step the covalent bond that characterizes the product is formed ("product-forming step"). Particularly important in the present discussion is the designation of racemization as occurring via a reaction (with rate constant k_8 or k_9) whereby an ion-pair is converted to its enantiomer, rather than as a static property of a particular kind of ion pair.

First, the nature of the solvolysis products is only consistent with their being formed predominantly before the free carbonium-ion stage but after the tight ion-pair stage. Nucleophilic attack on the substrate or on the tight ion pair^{18,19} is expected to lead to product of completely inverted configuration, while product formed from the free carbonium ion should be completely racemic. It has long been known that the products of solvolysis of optically active 1-phenylethyl chloride show significant amounts of racemization and significant amounts of optical activity generally of inverted configuration. These results, recalculated to more recently determined values for the rotations of the pure enantiomers, are summarized in Table V.

In none of the solvents in which it has been determined is the racemization of reactant rapid enough to account alone for the large extent of racemization of product. It would seem reasonable to infer that, with the possible exception of acetic acid, this would be true of all solvents listed in Table V. Thus the solvolysis itself must lead to significant but unequal yields of each of the two enantiomers.

These results rule out either the substrate, the tight ion pair, or the free carbonium ion as *sole* product forming electrophile. The fact that the extent of racemization of product is not markedly changed by changing solvent from 80% aqueous ethanol to pure water¹⁵ suggests that in these solvents the free carbonium ion is not a precursor to a significant fraction of the product. If the second ion pair were partitioned between nucleophilic attack and dissociation to the free carbonium ion, the extent of this partitioning and the extent of racemization should depend on solvent composition. Thus it appears that most of the product in ethanol-water solvents is derived from nucelophilic attack at the second ion-pair stage. In 100 T (in the presence of base) the overall result is $\sim 8\%$ retention of optical rotation in the kinetic reaction mixture. Since the starting material is racemizing almost as fast as it solvolyzes, the substitution on the ion pair intermediate directly formed from optically pure starting material must involve about 15% retention of optical rotation. In 97 T the rotation is retained to the extent of $\sim 6\%$, indicating that the *alcohol* product is probably formed predominantly by inversion as it is in ethanolwater solutions. However, because of the lack of precise data on the extent of inversion of substitution over a range of composition of trifluoroethanol-water mixtures it is not possible to conclude that an insignificant amount of reaction in these solvents goes via the free carbonium ion.

Second, we have argued earlier from the fact that the α -d isotope effect on the rate is at or near the maximum that the steps with rate constants k_2 or k_3 must be rate determining (see introduction). This and the conclusion that the product is formed predominantly by the step with rate constant k_6 require that the scheme will fit only if the step with rate constant k_2 is the rate-determining step in the solvolysis. This is the conclusion that we had reached earlier^{2,3} and can only be strictly true if the racemization of starting material observed in the present work occurs via k_8 , the inter-conversion of enantiomeric tight ion pairs; e.g., if race-mization involved k_9 , some return via k_{-2} would also be required and the step with rate constant k_2 could not be rate determining.

Thus, the more detailed scheme reduces for the present reactions to the following, as the simplest explanation of all of the results.²⁰

$$RX \xrightarrow{k_{1}} R^{+}X^{-} \xrightarrow{k_{2}} R^{+} | |X^{-} \xrightarrow{k_{6}} \delta RS + (1-8)SR$$

$$k_{8} | \downarrow$$

$$XR \xrightarrow{k_{1}} X^{-}R^{+} \xrightarrow{k_{2}} X^{-} | |R^{+} \xrightarrow{k_{6}} \delta SR + (1-8)RS$$

In this simplified scheme the key intermediate is the tight ion pair and several of the reaction variables are simply determined by ratios of the three constants which define its partitioning among return (via k_{-1}), solvolysis (via k_2), and inversion (via k_3). Thus the ratio k_2/k_{-1} determines whether k_1 or k_2 is rate controlling and whether or not the α -d isotope effect is at its maximum.²¹ k_2/k_{-1} also determines the ratio of

⁽¹⁶⁾ V. J. Shiner, Jr., and R. D. Fisher, J. Amer. Chem. Soc., 93, 2553 (1971).

⁽¹⁷⁾ RX and XR refer to different enantiomeric configurations about the asymmetric reaction center and SH is solvent. See ref 16 for additional comments interpreting some of the details of the reaction scheme.

ments interpreting some of the details of the reaction scheme. (18) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill, New York, N. Y., 1940, p 172.

⁽¹⁹⁾ R. A. Sneen and J. W. Larsen, J. Amer. Chem. Soc., 91, 362 (1969).

⁽²⁰⁾ The generalized scheme has many branches. In principle reaction via all paths is possible and, of course, each process occurs with some finite rate constant; however, for each specific reaction, most paths will not be stoichiometrically important. In the present case it is not possible to put a significant, low, upper limit on the amount of the reaction that could be going via the free carbonium ion or by attack on the tight ion pair; there is no evidence that requires any of either. On the other hand, evidence already cited requires that significant proportions of the reaction go via nucleophilic attack on the solvent-separated ion pair. As the argument develops we will explain all the results in these terms and do not need to postulate any reaction via the other pathways; it is a more difficult matter to put quantitative upper limits on their importance.

⁽²¹⁾ B. L. Murr and M. F. Donnelly, J. Amer. Chem. Soc., 92, 6686 (1970).

TABLE V Stereochemical Course of Solvolysis in the α -Phenethyl System

| Compd | Reaction conditions | Inversion, % | Ref |
|---------------------|------------------------------------|--------------|-----|
| α -Phenethyl | Acetolysis, room temp | 12 | a |
| tosylate | | | |
| α -Phenethyl | Acetolysis, 50° | 17 | b |
| chloride | | | |
| | EtOH, 70° | 28 | c |
| | MeOH, 70° | 28 | c |
| | $80\% {\rm Me_2CO-H_2O}, 70^\circ$ | 4 | c |
| | $H_{2}O, 40^{\circ}$ | 24 | d |
| | 60% EtOH−H₂O, 40° | 26.5 (alc) | d |
| | 80% EtOH–H ₂ O, 40° | 31.5 (alc) | d |
| | 60% EtOH–H ₂ O, 25° | 32.6 (alc) | e |
| | 80% EtOH−H₂O, 25° | 34.2 (alc) | e |
| | 70% aq dioxane, 40° | 6.0 | f |
| | 50% aq dioxane, 40° | 10.3 | f |
| a T TZ | | | ~ |

^a J. Kenyon, H. Phillips, and F. M. H. Taylor, J. Chem. Soc., 173 (1933). ^b L. P. Hammett and J. Steigman, J. Amer. Chem. Soc., **59**, 2536 (1937). ^c E. D. Hughes, C. K. Ingold, and A. D. Scott, J. Chem. Soc., 1201 (1937). ^d Reference 15. ^e This work. ^f Reference 9.

alkyl halide to solvolysis product that would be expected in the addition of HCl to styrene if the tight ion pair is produced as an intermediate. A steady-state treatment shows how the ratio k_p/k_c is determined by the ion pair partitioning rate constant ratios.²²

In pure TFE the polarimetric rate (Table I) is about 10% faster than it is in 97 T. Although the precise measurement of solvolysis rates in pure TFE is not possible using our current conductance techniques, approximate rate determinations using nmr indicate that the solvolysis rates in 97 T and 100 T do not differ by more than about 10%. Thus, the added water in 97 T does not change the rate of solvolysis appreciably but does divert about 20% of the reaction to the formation of alcohol. This indicates that the product-forming step (rate constant k_6 in the above scheme) comes after the rate-determining step (rate constant, k_2). Since the reaction rates in 97 T and 100 T are nearly the same, the data from both of these solvents can be discussed in terms of the same relative rate constants for ion-pair partitioning. This is particularly useful because in pure TFE, important mechanistic information can be obtained from a study of the addition of HCl to styrene.

Since HCl is not appreciably dissociated in pure trifluoroethanol, the reactants involved are the olefin and molecular hydrogen chloride. Since solvolysis of 1phenylethyl chloride does not yield appreciable amounts of styrene, any carbonium ion like intermediates in the solvolytic scheme that might also be formed in the acid addition reaction would not be expected to undergo return to olefin and acid reactants. In pure TFE the solvolysis of 1-phenylethyl chloride is reversible so that it and 1-phenylethyl trifluoroethyl ether are in equilibrium in the presence of HCl. However, at reasonable concentrations of HCl, the addition reaction is substantially faster than solvolysis and it is possible to observe from initial yields, determined by nmr, that

the ratio of rates of formation of chloride and ether in the addition reaction itself is $\sim 6:1$. This indicates that the 1-phenylethyl cation-chloride ion pairs produced on transfer of H⁺ from HCl to styrene covalently combine faster than they solvolyze by this same factor of $\sim 6:1^{23}$ and that, if this intermediate is the tight ion pair, k_2/k_{-1} is 1/6 or 0.17. The observed value of k_p/k_c of 1.72 is consistent with this, a value of k_{8}/k_{-1} of 0.085 and a value of k_2/k_8 of about 2. Thus, we can conclude that in 97-100 T, for every 100 tight ion pairs formed, about 80 return, 13 solvolyze, and 7 invert configuration. The value of k_2/k_{-1} of 0.17 requires that k_2 is not completely rate determining and that the observed isotope effect is not precisely at the maximum that would be exhibited if $k_2 \ll k_{-1}$. If we make the assumption that the isotope effect in k_1 is 1.120 (this is a reasonable but probably not a precisely correct value),⁵ then the observed value of $k_{\rm H}/$ $k_{\alpha-d}$ of 1.158 and the k_2/k_{-1} value of 0.17 requires that the limiting isotope effect when $k_2 \ll k_{-1}$ be 1.164. The small variations we have observed for the "maximum" α -d effect for different solvents and different reactants^{2,5} may well be due to the fact that the ratios of k_2/k_{-1} are not sufficiently small to make the step labeled k_2 strictly "rate determining" in all cases. For example, the value of $k_{\rm H}/k_{\alpha \cdot d}$ in 60 E is only 1.151; this is consistent with the limits mentioned above and a k_2/k_{-1} for this solvent of 0.40. Further, the k_p/k_c value of 1.05 requires (for almost any reasonable value of k_2/k_{-1} ; *i.e.*, between 1 and 0.1) that k_2/k_8 be about 20. Having these estimates of the change in the ratios of rate constants for ion pair partitioning on changing solvent from 97 T to 60 E it is of interest to speculate on how the individual rate constants are affected by this change in solvent. It appears to us that the most straightforward conclusion is that the higher dielectric constant of 60 E over 97 T causes about a tenfold increase in k_2 ; this reaction involves simply the further diffusion apart of ion pairs and should not be strongly influenced by nucleophilicity or hydrogen bonding; consistent with this conclusion is the intermediate value of $k_{\rm p}/k_{\rm c}$ of 1.16 observed for 80 E. We would expect higher values of $k_{\rm p}/k_{\rm c}$ for less aqueous ethanol solvents, as their dielectric constants would be near that for 97 T (ethanol and trifluoroethanol have nearly the same dielectric constant). However, in these solvents the reaction appears to be diverted owing to the lower solvent polarity and higher nucleophilicity to nucleophilic attack on the tight ion pair as indicated by lower α -d effects and larger yields of product of inverted configuration.^{2,15} If we assume that the change of solvent from 97 T to 60 E causes about a tenfold increase in k_2 , we must conclude, since k_2/k_{-1} only increases from 0.17 to 0.4, that k_{-1} must increase about fourfold. This seems unusual, since the dielectric constant effect would be expected to operate in the opposite sense. However, it is important to remember that, despite its dielectric constant, 97 T is an excellent solvolytic medium in which 1-phenylethyl chloride reacts about ten times faster than it does in 60 E. This is almost certainly due to the fact that TFE is about a 10^{3} - 10^{4} times stronger acid than ethanol, which allows it to hydrogen bond strongly to the departing chloride

⁽²²⁾ k_0 (the first-order rate constant for solvolysis) = $k_1k_2/(k_{-1} + k_2)$. k_p (the first-order rate constant for change in optical activity) = $k_1(2k_8 + k_2)/(k_{-1} + 2k_8 + k_2)$.

 $k_{\rm p}/k_{\rm c} = \frac{(2k_8/k_{-1} + k_2/k_{-1})(1 + k_2/k_{-1})}{(1 + 2k_8/k_{-1} + k_2/k_{-1})k_2/k_{-1}} = \frac{(1 + 2k_8/k_2)(1 + k_{-1}/k_2)}{(k_{-1}/k_2 + 2k_8/k_2 + 1)}$

⁽²³⁾ V. J. Shiner, Jr. and W. Dowd, J. Amer. Chem. Soc., 91, 6528 (1969).

ion making it effectively a better leaving group and a poorer nucleophile. It is probably this higher effective nucelophilicity of chloride ion in 60 E that causes internal return (k_{-1}) to be faster in this solvent than in 97 T. The tenfold higher value for k_2 and the fourfold higher value for k_{-1} of themselves would tend to make the solvolysis rate in 60 E about 2-5 times faster than in 97 T; the fact that the reaction is actually about ten times faster in 97 T would have to be explained by k_1 being faster in 97 T by a factor of about 25. In effect the above arguments are based on an implicit assumption that the inversion rate constant, k_8 , for tight ion pairs is about the same in 97 T and 60 E. This may be approximately right, since such a reaction would not depend on solvent or counterion nucelophilicity and would probably involve only a small increase in dipole moment and therefore a small dependence on solvent dielectric constant.

The α -d and β -d₃ effect on the polarimetric rates (Table VI) are in general accord with this mechanistic

TABLE VI DEUTERIUM EFFECTS ON RATES OF REACTION OF 1-PHENVLETHYL, CHLORIDE AT 25°

| 1-1 1161 | | ONDE AL 20 | |
|-------------------------------|---------------------|---|-----------------------------------|
| $Solvent^a$ | Method^b | $k_{\mathbf{H}}/k_{\boldsymbol{lpha}\cdot d}$ | $k_{\mathbf{H}}/km{eta}_{-d_{3}}$ |
| 60 E | С | 1.151 | 1.225 |
| 60 E | Р | 1.17 | 1.27 |
| $97 \ T$ | С | 1.157 | 1.218 |
| 97~T | Р | 1.20 | 1.24 |
| $97 \mathrm{T} + \mathrm{Py}$ | Р | 1.145 | 1.213 |
| 100 T | Р | 1.188 | 1.228 |
| 100 T + Py | Р | 1.171 | 1.279 |
| N | | | |

 a,b See footnotes for Table II.

picture but, unfortunately, are not sufficiently accurate to be as conclusive as hoped. Thus, the isotope effects on k_p are a mixture of those that would be expected if the steps with constants k_1, k_2 , or k_3 were rate determining. If $k_p \gg k_c$, then $k_3 \gg k_2$; if also $k_{-1} \gg k_8$ then the isotope effects on k_p should be those that apply if the step with rate constant k_8 , the inversion of the tight ion pairs, is rate determining.

The transition state for this process should involve a structure with the chloride ion in the plane of the carbonium ion (the nodal plane of the vacant p orbital) and no covalent bonding between the carbonium and chloride ions. Thus, the isotope effects should be at their maximum in this situation; we have suggested above that such a maximum ought also apply if k_2 is strictly rate determining and that the α effect would be near 1.164 under these conditions. In the solvents we have used, internal return and internal racemization are most dominant in 97-100 T. The polarimetric isotope effects for these reactions are in the range of $17 \pm 2\%$ for the α -d and $25 \pm 4\%$ for the β -d₃ compound. Within the experimental error involved these are the same as the corresponding effects observed in solvolvsis.

The isotope effects in the acid-catalyzed racemization of 1-phenylethyl alcohol in TFE and TFE-water solvents provide interesting additional mechanistic information. In pure TFE the racemization rate is first order in active 1-phenylethyl alcohol concentration at a given stoichiometric HCl concentration. Although the rates were measured at only three HCl concentrations between 1×10^{-4} and $3 \times 10^{-2} M$, the plot of the logarithm of the first-order racemization rate constants vs. the logarithm of the HCl concentration has a slope in this region of about 0.5–0.6, indicating that the reaction is approximately 0.5 order in HCl. This is consistent with the rate-determining step in the racemization involving *dissociated* 1-phenylethyloxonium ions formed from HCl and 1-phenylethyl alcohol (ROH) via the following equation.

$$ROH + HCl \rightleftharpoons R\ddot{O}H_2\ddot{C}l \rightleftharpoons R\ddot{O}H_2 + Cl \dashv$$

This behavior is expected only if the dominant molecular form of hydrogen chloride in the solution is undissociated (either as HCl or as ion pairs $+ROH_2Cl^-$) and the reactive form of the alcohol is free ROH_2^+ . It is probable that the proton-transfer equilibrium is largely in the un-ionized reactants (ROH is not a very strong base with respect to HCl) and the ionized acid is largely dissociated, since TFE is a reasonably good dissociating solvent. The nmr studies of product formation under conditions similar to these show that initially the alcohol is converted exclusively to the trifluoroethyl ether at a rate, within the rather large experimental error, equal to the rate of racemization and that 1-phenylethyl chloride is only subsequently produced by reverse reaction of the ether with HCl which ends in the establishment of appreciable concentrations of both chloride and ether at equilibrium. These results show that the free carbonium ion produced by heterolylic cleavage of the C-O bond in the free oxonium ion does not undergo a *kinetically* significant fraction of reaction with chloride ion to form alkyl chloride. This is consistent with all of the kinetic results in TFE-water and ethanol-water mixtures, which indicate no mass law effect in 1-phenylethyl chloride solvolysis. The racemizations of 1-phenylethyl alcohol in 97% TFE and 70% TFE as indicated in Table III require significantly higher concentrations of HCl. This is expected, since the water in the solvent partly neutralizes the acidity of HCl by converting it to hydronium and chloride ions. The racemizations in these solvents are first order in active alcohol. In 97% TFE the reaction is also first order in HCl, consistent with the reaction being a rate-determining conversion of the free protonated alkoxonium ion formed in small proportions in equilibrium with H_3O^+ . In 70% TFE the reaction is not quite first order in HCl, probably because the concentrations of HCl required are sufficiently large that the value of the h_0 function is not equal to the stoichiometric concentration of HCl. Although h_0 was not measured in 70% TFE, the rates do correlate reasonably well with the h_0 functions for HCl in the same concentration in water $(70\% \text{ TFE}-30\% \text{ H}_2\text{O} \text{ is about } 70 \text{ mol } \% \text{ water})$. Thus, in all three TFE-containing solvents the racemization seems to be a reaction of the free conjugate acid of the alcohol. It is interesting that the α -d effects in these reactions $[k_{\rm H}/k_{\alpha-d} = 1.15 \ (70\% \ {\rm TFE}), \ 1.19 \ (97\% \ {\rm TFE})$ TFE)] are smaller than those expected for a limiting reaction with oxygen as the leaving group. Consider first the 15% effect in 70% TFE, a solvent in which most of the molecules are water. The rate-determining

step must generally be the breaking of the C–O bond to give a symetrically solvated carbonium ion.

$$\mathrm{H}_{2}\mathrm{O} + \mathrm{ROH}_{2}^{+} \underbrace{\stackrel{k_{1}}{\underset{k_{-1}}{\longrightarrow}}}_{\underset{k_{-1}}{\longrightarrow}} \mathrm{H}_{2}\mathrm{O} \stackrel{+}{\mathrm{R}}\mathrm{OH}_{2} \underbrace{\stackrel{k_{1}}{\underset{k_{-1}}{\longrightarrow}}}_{\underset{k_{-1}}{\longrightarrow}} \mathrm{H}_{2}\overset{+}{\mathrm{OR}} + \mathrm{H}_{2}\mathrm{O}$$

The C-O bond cleavage step *itself* must involve racemization. Therefore, the isotope effect refers to the transition state of the heterolytic step (rate constant k_1 in the general scheme) and is smaller than the maximum of ~ 1.23 characteristic of solvolvtic reactions with oxygen leaving groups, found for processes which involve rate-determining formation of a second ion pair from the first product of ionization.¹⁶ The 15% isotope effect is the same as that found for solvolysis of pinacolyl p-bromobenzenesulfonate in which formation of the tight ion pair is rate determining because of rapid Wagner-Meerwein rearrangement of the 3,3-dimethyl-2-butyl cation.²⁴ The α -d effect in 97% TFE is larger than in 70% TFE, probably because, in at least a significant proportion of the reaction, the molecule at the rear, after initial heterolysis of the C-O bond, is not a water molecule but trifluoroethanol. Thus, a

$$CF_{3}CH_{2}OH + R\ddot{O}H_{2} \xrightarrow{k_{1}} CF_{3}CH_{2}O \overset{H}{R} OH_{2} \xrightarrow{k_{2}} H_{2}O \overset{R}{R} OH_{2} \xrightarrow{k_{2}} H_{2}O \overset{H}{R} O$$

significant fraction of the carbonium ions initially formed would be expected to return to unracemized alcohol via k_{-1} ; the further dissociation of the unsymmetrically solvated, initially formed carbonium ion would contribute to the rate-determining step and give a larger α -d effect, since this transition state involves

(24) V. J. Shiner, Jr., R. D. Fisher, and W. Dowd, J. Amer. Chem. Soc., 91, 7748 (1969).

no partial covalent bond between carbon and oxygen. In this way, it is similar to the rate-determining step in limiting solvolyses which show α -d effects in oxygen leaving groups around 1.23.

The 9.4% β -d₃ effect in racemization of the alcohol is small compared to the 22% effect characteristic of the solvolysis of the chloride. However, the latter process involves rate-determining interconversion of ion pairs (see above) in which it is believed that there is no covalent bond between oxygen and carbon. The partial covalent bond in the transition state for the C-O heterolysis step causes both β and α effects to be smaller when this step is rate determining than they are when the step is labeled k_2 is rate determining. The comparison of β -d₃ effects on the solvolysis of isopropyl brosylate in trifluoroacetic acid $(k_{\rm H}/k_{\beta-d_z} = 1.46)$ and in 70% TFE $(k_{\rm H}/k_{\beta-d_s} = 1.24)$ gives the best example of the change in a β -d₃ effect on changing rate-determining step from ion-pair interconversion to ion-pair formation. Since for the former case the β -d₃ effect for the 1-phenylethylcarbonium ion is 1.22, the above observed effect on the heterolysis step (1.10) is in line with previous results.

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Registry No.—1-Phenylethyl alcohol, 98-85-1; 1-phenylethyl-1-d alcohol, 3101-96-0; 1-phenylethyl-2,2,2-d₃ alcohol, 17537-32-5; 1-phenylethyl chloride, 672-65-1; 1-phenylethyl-1-d chloride, 41203-27-4; 1-phenylethyl-2,2,2-d₃ chloride, 40662-53-1.

The Nature of Solvent Participation in the Restriction of Rotation about Single Bonds. II

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The activation enthalpy for the racemization of 2,2'-dimethoxy-6,6'-diphenamide decreases by 4.2 kcal/molwhen the solvent is changed from acetone to acetic acid. It is shown that this is entirely due to a lowering of the transition state energy. Activation parameters have been determined for the racemization of N-benzenesulfonyl-N-carboxymethyl-2,4-dimethyl-6-nitroaniline in 26 solvents and heats of solution have been measured in nine of these solvents.

When one considers the fact that reaction rates and equilibrium constants may be altered by several powers of ten through changes in the reaction medium, it becomes obvious that the role of the medium must be understood if one is to arrive at a useful understanding of organic reactions as they take place in solution. A change in the solvent may increase the rate of a reaction either by decreasing the free energy of the transition state or by increasing the free energy of the ground state. It is, therefore, important in the understanding of solvent effects that one be able to tell just how much of the variation in the activation parameters is due to changes in ground-state solvation and how much is due to changes in transition-state solvation. This is conveniently done in the case of the activation enthalpy by measuring the heats of solution of the reactant in the solvent systems under investigation.¹⁻³ The difference in the heats of solution is the enthalpy difference between the two solvated ground states, $\delta_M \Delta \vec{H}^g$. The

 E. M. Arnett, P. M. Duggleby, and J. J. Burke, J. Amer. Chem. Soc., 85, 1350 (1963).
 E. M. Arnett, W. G. Bentrude, J. J. Burke, and P. M. Duggleby, J.

(a) E. M. Arner, Chem. Soc., 87, 1541 (1965).
 (3) E. M. Arnett and D. R. McKelvey, Rec. Chem. Progr., 26, 185 (1965).