[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY OF THE UNIVERSITY OF CALIFORNIA AT LOS ANGELES]

Studies in Stereochemistry. XVII. The Course of the Solvolytic-Substitution Reactions in the 1,2-Diphenyl-1-propyl System

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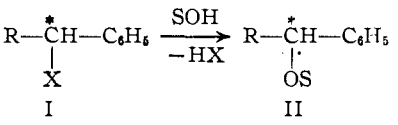
The optically active *erythro* and *threo* isomers of the *p*-bromobenzenesulfonates, chlorides and bromides of the 1,2-diphenyl-1-propyl system have all been solvolyzed in formic acid, and the two active sulfonates in acetic acid, and the products have been examined. No molecular rearrangement occurred, and from the balance between the *threo* and *erythro* esters formed and from the results of control experiments, the following conclusions are drawn. In formic acid the reaction times for the solvolyses of the halides were long enough to allow the diastereomeric formate products to equilibrate, and the equilibrium constant was determined. As expected from steric considerations, the *erythro* isomer predominated in these mixtures. In formic acid the sulfonate esters (shorter reaction time) gave balances of diastereomers which indicate that the reaction occurred largely with retention of configuration with *threo*, and slightly with retention of configuration in the case of *erythro* starting material. In acetic acid with the same sulfonate esters as starting materials the product ratios were closer together and decidedly favored the *threo*-acetate. The *erythro* and *threo* isomers of 1,2-diphenyl-1-propanol were treated with thionyl chloride, phosphorus pentachloride, phosphorus tribromide and hydrogen bromide plus sulfuric acid. In every case the *threo*-halide predominated in the product, but to a far greater extent when the starting material was of the *threo* configuration. The stereochemistry of these reactions is interpreted in terms of the effects that the characters of the departing group and solvent have upon the relative stabilities of the bridged (phenonium) and open ion-pairs that probably occur as intermediates in these reactions.

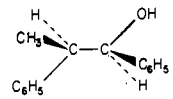
The changes in configuration at an asymmetric carbon atom undergoing a solvolytic substitution reaction have been utilized in studies of the reaction mechanism in acyclic systems such as I in two cases, where R = CH_3 and X = Cl,[3] and where R = $(CH_3)_3C$ and X = Br,[4a] Cl[4b] or *p*-$CH^3C_6H_4SO_3$.[4b] In both of these systems when I was optically active, to the extent that optically active product



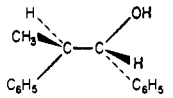
I II

(II) was produced from the reaction (5–15%), the substitution of OS for X occurred with inversion of configuration. No evidence for a bridged cation existing as an intermediate in the reaction was found.[4b]

As an extension of our investigations of bridged ions (*e.g.*, phenonium ions) as intermediates in solvolytic reactions of acyclic systems,[5] the results of the solvolyses of the diastereomeric alcohols, *p*-bromobenzenesulfonates (brosylates), chlorides and bromides of the 1,2-diphenyl-1-propyl system are now reported. Since no detectable molecular rearrangement occurs in these solvolysis reactions, a



L-*erythro*-1,2-diphenyl-1-propanol (III A)



L-*threo*-1,2-diphenyl-1-propanol (III B)

study of the distribution of *products* between the two diastereomeric configurations as a function of the configuration of the starting material provides information regarding the mechanisms of the substitution reactions involved. Examples of solvolyses in which the product distributions are thermodynamically controlled (equilibria) as well as examples in which they are kinetically controlled have been studied.

Results

The preparation and determination of all the stereochemical relationships between the alcohols, the brosylates, the chlorides and bromides of all four of the stereoisomers of III have been previously reported.[6] The solvolyses of the optically active brosylates, chlorides and bromides were all carried out in formic acid (25°) whereas only the brosylates were solvolyzed in acetic acid. In each case an equivalent amount of sodium salt of the solvent was present to neutralize the acid produced by the reaction. The products were first isolated as the carboxylate esters, and these were converted to the free alcohols through the agency of lithium aluminum hydride. These alcoholic mixtures were freed from accompanying traces of olefin through the use of fractional chromatographic elution techniques (alumina) and were analyzed as follows.

The infrared spectra of homogeneous films of *threo*- and *erythro*-1,2-diphenyl-1-propanol (III), 1,1-diphenyl-2-propanol (V) and 1,2-diphenyl-2-propanol (VI) are recorded in Fig. 1. The esters from which V and VI are derived are possible rearrangement products of system IV, and the large differences in extinction coefficients at various wave lengths in the infrared (see Table I) of the four alcohols allow unknown mixtures containing these components to be analyzed. The absence of V and VI in detectable amounts in the unknown mixtures was demonstrated as follows. The infrared spectra of each unknown was taken from 5 to 14 μ, and in every case and at every point, the curves of the unknowns lay between the curves of the two diastereomers of III. The sensitivity of this method is demonstrated by the fact that at the two wave lengths where the greatest differences between III,

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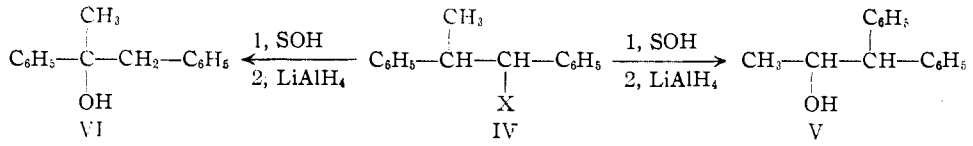
(2) Requests for reprints should be addressed to this author.

(3) J. Steigman and L. P. Hammett, THIS JOURNAL, **59**, 2536 (1937).

(4) (a) P. Skell and C. R. Hauser, *ibid.*, **64**, 2633 (1942); (b) S. Winstein and B. K. Morse, *ibid.*, **74**, 1135 (1952).

(5) (a) D. J. Cram, *ibid.*, **71**, 3863, 3875 (1949); (b) D. J. Cram, *ibid.*, **74**, 2129, 2137, 2159 (1952); (c) D. J. Cram and J. D. Knight, *ibid.*, **74**, 5839 (1952).

(6) (a) D. J. Cram and F. A. Abd Elhafez, *ibid.*, **74**, 5828 (1952); (b) **74**, 5846 (1952); (c) **74**, 5851 (1952).



V and VI are found (see Table I), the optical densities of the unknown mixtures lie between 0.12 and 0.13 at λ 10.55 μ and between 0.13 and 0.14 at λ 11.39 μ (see Table I for corresponding optical densities of V and VI). The unknown mixtures were therefore analyzed as a two-component system consisting of *erythro*- and *threo*-III. Figure 2 is a plot of optical density *vs.* per cent. composition of known mixtures of L-*erythro*- and L-*threo*-III at λ 10.22 μ and λ 12.73 μ.

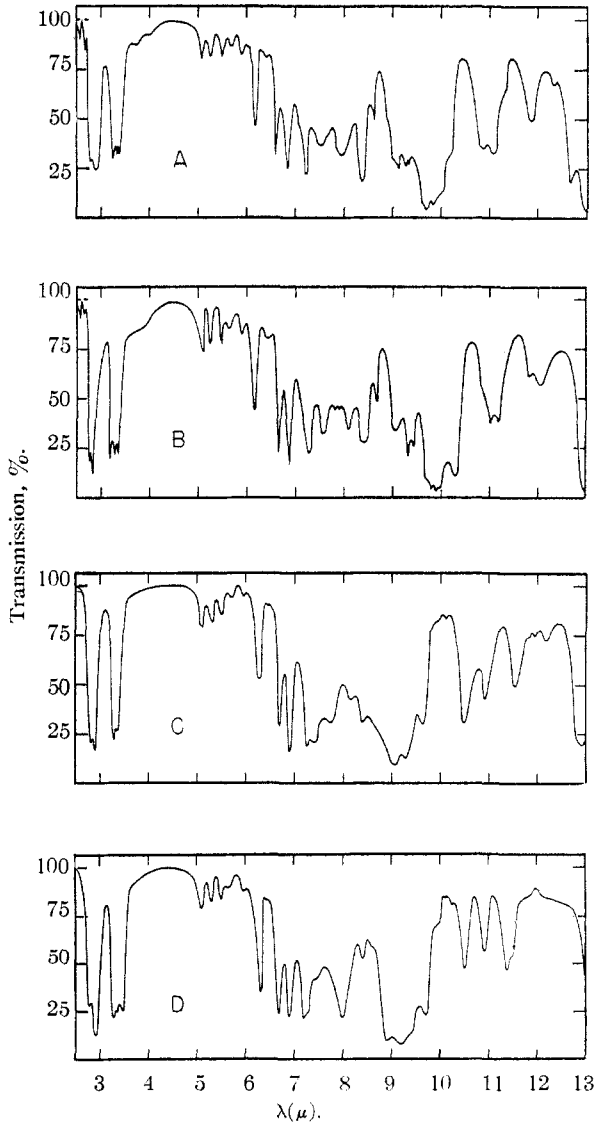


Fig. 1.—Infrared spectra of homogeneous films (0.03 mm. thick) of isomeric alcohols taken with a Beckman IR2T spectrophotometer (NaCl prism): A, L-*erythro*-1,2-diphenyl-1-propanol; B, L-*threo*-1,2-diphenyl-1-propanol; C, 1,2-diphenyl-2-propanol; D, 1,1-diphenyl-2-propanol.

Since in the solvolysis runs optically pure starting materials were always used, the final alcoholic

TABLE I

EXTINCTION COEFFICIENTS OF THE FOUR ISOMERIC DIPHENYLPROPANOLS IN THE INFRARED AT THOSE WAVE LENGTHS USED FOR ANALYSES[a]

Compounds[b]	Slit width (mm.) =	Optical densities, μ[c] λ 10.22 0.568	λ 12.73 1.055	λ 10.55 0.605	λ 11.39 0.740
L-*erythro*-1,2-Diphenyl-1-propanol (III A)		0.482	0.729	0.121	0.141
L-*threo*-1,2-Diphenyl-1-propanol (III B)		.891	.321	.130	.136
1,1-Diphenyl-2-propanol (V)		.157	.147	.712	.501
1,2-Diphenyl-2-propanol (VI)		.141	.275	.796	.187

[a] Beckman spectrophotometer, Model IR2T, NaCl prism and cells. [b] Although these compounds are solids, they can be kept at room temperature as supercooled liquids for short periods of time. [c] Liquid films, 0.03 mm. thick were employed.

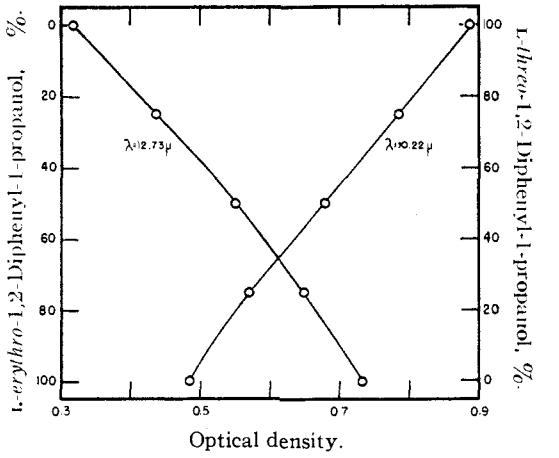


Fig. 2.—Plot of optical densities *vs.* composition of homogeneous films (0.03 mm. thickness) of known mixtures of L-*erythro*- and L-*threo*-1,2-diphenyl-1-propanol (Beckman infrared spectrophotometer, Model IR2T.

mixtures were also analyzed polarimetrically. Figure 3 is a plot of optical rotation *vs.* per cent. composition of known mixtures of L-*erythro*- and L-*threo*-III. Table II reports the results of the solvolysis runs in formic and acetic acids. In control run 9 (Table II) the pure formate of the *erythro* diastereomer and in run 10 a mixture of 80% *threo*-20% *erythro*-formate were allowed to stand in the solvolysis mixtures under the conditions that simulated the solvolyses. The isomers equilibrated to give the same product composition as was found in the solvolysis of the halides in formic acid. In another control run the more labile *threo* isomer of 1,2-diphenyl-1-propyl acetate was shown to persist under the reaction conditions of runs 7 and 8.

Table III reports the results of the treatment of the two diastereomers of III with thionyl chloride, phosphorus pentachloride, phosphorus tribromide and hydrogen bromide plus sulfuric acid. The di-

TABLE II

DISTRIBUTION OF DIASTEREOMERIC PRODUCTS FROM SOLVOLYSES AT 25°, P = CH_3—CH(—C_6H_5)—CH(—C_6H_5)—C_6H_5

Run no.	Starting material[a]	Solv.	Time, hr.	*erythro*-Halide recov., %	Yield olefin, %	POH from solvolysis product[b]: Yield, %	$[\alpha]^{23}D$[c]	*erythro*, % By α	*erythro*, % By I. R. 1st.	*erythro*, % By I. R. 2nd.	*threo*, % By α	*threo*, % By I. R. 1st.	*threo*, % By I. R. 2nd.
1	L-*erythro*-P-Cl	HCO_2H	1344	50	2	43	58.0°	55	56	55	45	44	45
2	L-*threo*-P-Cl	HCO_2H	264	3	5	80	57.9	55	57	56	45	43	44
3	L-*erythro*-P-Br	HCO_2H	1344	46	3	44	58.0	55	55	55	45	45	45
4	L-*threo*-P-Br	HCO_2H	96	5	3	82	57.8	55	55	55	45	45	45
5	L-*erythro*-P-OBros.	HCO_2H	5.5	..	6	85	58.8	59	62	62	41	38	38
6	D-*threo*-P-OBros.	HCO_2H	1.0	..	2	90	−49.7	27	31	30	73	69	70
7	L-*erythro*-P-OBros.	AcOH	45	..	4	88	54.1	40	37	33	60	63	67
8	D-*threo*-P-OBros.	AcOH	4	..	3	86	−51.0	30	31	29	70	69	71
9	D-*erythro*-P-OCHO[d]	HCO_2H	96	..	..	91	−57.9	55	55	55	45	45	45
10	80%-D-*threo*-20%-D-*erythro*-P-OCHO[e]	HCO_2H	24	..	..	87	−57.7	54	55	55	46	45	45

[a] Physical properties of these starting materials (except the formates) have been previously reported (ref. 6c). [b] See Experimental for procedure of obtaining alcohol from the esters. [c] *c*, 5% $CHCl_3$. [d] See Table IV for properties. [e] Composition demonstrated by rotation of alcoholic mixtures obtained upon reduction of this ester (see Experimental).

TABLE III

DISTRIBUTION OF DIASTEREOMERIC PRODUCTS FROM THE SUBSTITUTION OF HALOGEN FOR HYDROXYL GROUP

CH_3—CH(—C_6H_5)—CH(—C_6H_5)—C_6H_5 = P

Run no.	Config.[a] starting POH	Reagent	Molar ratio reagent to POH	Proced.[b]	Total yield, %	Product-ratio *threo*-P-X to *erythro*-P-X
11	DL-*erythro*	$SOCl_2$	2:1	A	95	2.6:1
12	DL-*erythro*	$SOCl_2$	8:1	A	92	2.0:1
13	L-*erythro*	$SOCl_2$	29:1	A	93	1.5:1
14	DL-*threo*	$SOCl_2$	2:1	A	94	4.3:1
15	DL-*threo*	$SOCl_2$	8:1	A	94	Only *threo*
16	L-*threo*	$SOCl_2$	10:1	A	88	Only *threo*[c]
17	DL-*erythro*	PCl_5	2.4-1	B	95	4.3:1
18	DL-*threo*	PCl_5	2.4-1	B	95	5.4:1
19	DL-*erythro*	PBr_3	3:1	C	88	3:1
20	L-*erythro*	PBr_3	3:1	C	92	2.8:1
21	DL-*threo*	PBr_3	3:1	C	90	5:1
22	L-*threo*	PBr_3	3:1	C	94	5.8:1
23	DL-*erythro*	HBr–H_2SO_4	....	D	92	1.2:1
24	DL-*threo*	HBr–H_2SO_4	....	D	90	8:1

[a] See Table I, paper XIII (ref. 6b) of this series for the physical properties of the starting materials. [b] The melting points and rotations of the products are recorded in the experimental part. [c] From the rotation of the crude material isolated (see Experimental part) it appears that this material contained about 4% of L-*erythro*-chloride.

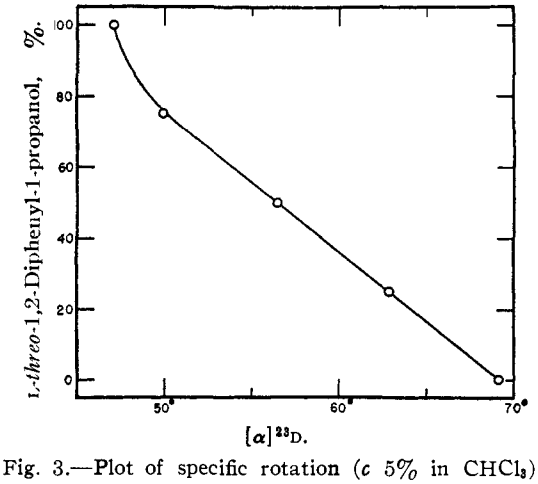
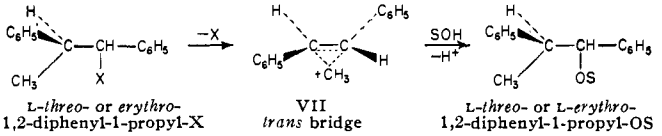


Fig. 3.—Plot of specific rotation (*c* 5% in $CHCl_3$) *vs.* composition of known mixtures of optically pure L-*threo*- and L-*erythro*-1,2-diphenyl-1-propanol.

astereomeric halides were in each case separated by fractional crystallization. The *erythro* isomers of both active and racemic chlorides and bromides are virtually insoluble in ethanol (40°) whereas the *threo* isomers are highly soluble. In control runs (see Experimental) the more labile *threo*-chlorides were demonstrated to be completely preserved whereas the *threo*-bromides were shown to isomerize to *erythro*-bromides only to a minor extent under the conditions of their formation.

Discussion

Solvolyses of the Halides and Esters of the 1,2-Diphenyl-1-propyl System.—In all of the solvolyses of the 1,2-diphenyl-1-propyl system, no molecular rearrangements were detected, and the only structural changes observed involved the modification of the stereochemistry of only one of the two asymmetric centers of the starting material. Evidence against either hydrogen or phenyl migrations occurring is found in the absence of V and VI among the final alcoholic reaction products. Evidence against a methyl migration is less substantial. Should an intermediate such as VII (a *trans* bridged ion is more probable than its *cis* counterpart)[7] be involved in a methyl migration reaction, an identical product could be obtained whether or not a molecular rearrangement had occurred. If an



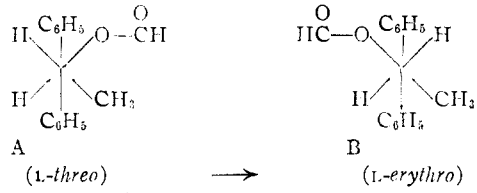
L-*threo*- or *erythro*-1,2-diphenyl-1-propyl-X — VII *trans* bridge — L-*threo*- or L-*erythro*-1,2-diphenyl-1-propyl-OS

analogous process produced the corresponding *cis* bridged ion, then rearrangement could be detected since racemized products would result. The close correspondence between the infrared and polarimetric analyses of the alcohols ultimately obtained (see Table II) indicate that no racemizing stage was involved in the solvolyses. Although no methyl migration was detected in the solvolyses of the 3-

(7) (a) D. Y. Curtin and P. I. Pollak, THIS JOURNAL, **73**, 961 (1950); (b) **73**, 992 (1951).

phenyl-2-butyl system,[5b] extensive methyl migration was found in the solvolysis of the 3,4-dimethyl-4-phenyl-3-hexanol system,[5c] particularly in formic acid where the products themselves underwent continued reaction. Since the formates initially produced in runs 1–4 were demonstrated to be capable of undergoing further extensive transformations (runs 9 and 10), and since the formates stood for a long time in runs 1–4, the possibility does exist that methyl migration did occur which went undetected because the sequence involved VII as an intermediate.

Of the solvolyses reported in Table II, the product balances in runs 1–4, 9 and 10 would appear to be thermodynamically controlled, whereas in runs 5 and 6 in the same solvent (formic acid), the diastereomeric esters must have only partially equilibrated. Since identical product distributions were obtained from six different materials in runs 1–4, 9 and 10, equilibrium must have been reached, and the equilibrium constant between *erythro*- and *threo*-1,2-diphenyl-1-propyl formates in formic acid at 25° amounts to 1.23, and $\Delta F^0 = -120$ cal. It is likely that A and B represent the most stable of the rotational conformations of the two diastereomeric formates (two large groups *trans*), and that the small difference between the stability of A and B is



A (L-*threo*) ⟶ B (L-*erythro*)

$\Delta F^0 = -120$ cal./mole
(solution in formic acid at 25°)

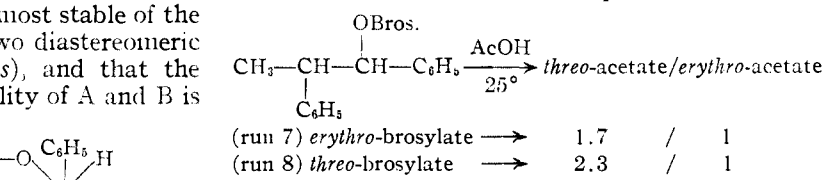
C *d,l*-α,α′-dibromostilbene ⟶ D *meso*-α,α′-dibromostilbene

$\Delta F^0 = > -800$ cal./mole
(solution in carbon tetrachloride at room temperature)

due to the differences in the steric situations in A and B. The differences are that A has one $CH_3 \asymp O-\overset{\|}{C}-H$ and one $H \asymp H$ steric repulsion and B has one $CH_3 \asymp H$ and one $H \asymp O-\overset{\|}{C}-H$ steric repulsion.

Since equilibrium constants between diastereomers in *acyclic* systems have never been measured before, about the only data that provide any kind of comparison are those of Buckles, *et al.*,[8] who found that *d,l*-α,α′-dibromostilbene was transformed into the *meso*-isomer when subjected to the action of either bromine or iodine and light. When the reaction was carried out in carbon tetrachloride at room temperature, an 80% yield of *meso*-dibromide was isolated. Although equilibrium may or may not have been established in this experiment, the results indicate that ΔF° for the transformation amounts to at least 800 cal./mole. The difference in stability between the isomeric dibromostilbenes appears to be greater than the difference in stability between the diastereomeric 1,2-diphenyl-1-propyl formates, although the steric situations in the two sets of molecules are probably nearly comparable. The greater difference in dipole moment[9] in passing from the *d,l*- to the *meso*-dibromide as compared to the corresponding differences in the isomeric formates provides a probable explanation for this phenomenon.[10]

In the solvolyses carried out in acetic acid (runs 7 and 8), the product balances were kinetically controlled (the acetates once formed persisted), and the differences in the distribution of products from the two diastereomeric starting materials indicate that the reactions were partially stereospecific, partially non-stereospecific in character. As in the case of the solvolysis reactions of other but similar systems,[5b,11] solvent molecules and the phenyl on the adjacent carbon atom both become involved in the departure of the brosylate group from the molecule. Chart I outlines both the stereochemical relationships in question as well as a mechanistic rationalization of the data. In this scheme, the formation of bridged and open ion pairs compete with one another as primary processes (processes A and B in the *erythro* and A′ and B′ in the *threo* systems, respectively). Processes A and A′ represent substitution reactions[12] occurring with retention of configuration whereas the stereochemistry of processes B and B′ are governed partially by the secondary processes C, C′, D and D′ and partially by the tertiary processes E, F and F′.



(run 7) *erythro*-brosylate ⟶ 1.7 / 1
(run 8) *threo*-brosylate ⟶ 2.3 / 1

Although the distribution ratios of products in runs 7 and 8 are quite close together and decidedly favor *threo* material, to the extent that the over-all steric results are specific in nature, substitution with retention of configuration appears to apply. These facts provide evidence that processes A and A′ do consume part of the respective starting materials, and they suggest that process A′ is more important in disposing of *threo*-brosylate than process A is in disposing of *erythro*-brosylate. Since process A′ involves *trans*-phenonium ions and process A, *cis*-phenonium ions, and since the former are more sterically favorable,[7b,6c] the observed disposition of products is not unexpected.

With *threo* starting materials (run 8) only 30% of the acetate produced possessed an inverted configuration, and therefore process B′–C′ could at the

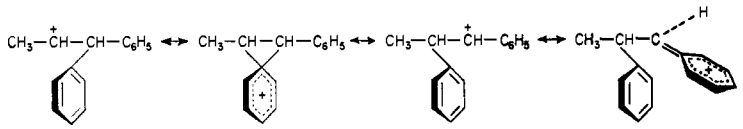
(8) R. E. Buckles, W. E. Steinmetz and N. G. Wheeler, THIS JOURNAL, **72**, 2496 (1950).

(9) A. Weissberger, *ibid.*, **67**, 778 (1945).

(10) S. Mizushima, Y. Morino and T. Shimanouchi, *J. Phys. Chem.*, **56**, 324 (1952).

(11) S. Winstein and K. S. Schreiber, THIS JOURNAL, **74**, 2171 (1952).

(12) The mechanism of the simple solvolytic substitution reaction has been recently discussed both by S. Winstein, E. Grunwald and H. Jones [*ibid.*, **73**, 2700 (1951)] and by C. G. Swain and W. P. Langsdorf [*ibid.*, **73**, 2813 (1951)].



most account for 30% of the total acetate. Furthermore, if one judges from the relative rates at which the two diastereomeric brosylates enter into bimolecular substitution reactions,[6c] process B′–C′ should be more important in run 8 (*threo*-brosylate) than process B–C is in run 7 (*erythro*-brosylate). It seems probable on the basis of work done on the acetolyses of other benzyl-type systems[13] that not more than 10% of the acetate produced by processes B and B′ (runs 7 and 8, respectively) also involved secondary processes C and C′. Therefore, the great preponderance of the 63% of inverted acetate produced in run 7 probably arose by a path other than A or B–C, yet by a path which provides largely *threo*-acetate. If route B–D–E is important, then the disolvated open ion must collapse predominantly to *threo* product. A more likely route is B–D–F′ in which the disolvated open ion collapses to *trans*-phenonium ion, which in turn goes to *threo*-acetate. Process B–D–F′ should predominate over B–D–F because of the enhanced stability associated with a *trans* bridged ion (methyl and phenyl *trans*) as compared to a *cis* bridged ion.

The results of runs 5 and 6 in which *erythro*- and *threo*-brosylates were submitted to formolysis are significant in spite of the fact that the formate products underwent further reaction after their initial formation. In neither run were the products equilibrated, and the data clearly indicate that the initial solvolysis reaction must have produced formate largely with retention of configuration. Therefore in formic acid, processes A and A′ must have played a predominant role, a fact which is consistent with the poor nucleophilic character and strong ionizing power of this solvent. The observation that phenyl participation in solvolytic substitution reactions is enhanced in formic as compared to acetic acid has been previously made.[14,5b]

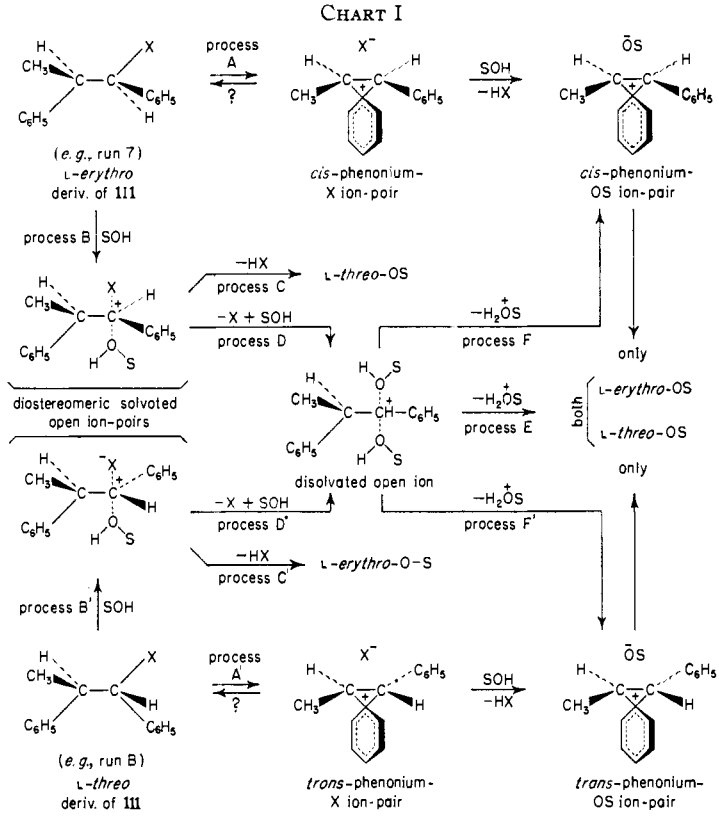
		threo-formate/*erythro*-formate
(run 5) *erythro*-brosylate	HCO_2H, 5.5 hr.	1/1.6
(run 6) *threo*-brosylate	HCO_2H, 1.0 hr.	2.5/1
(runs 1–4, 9 and 10) various starting materials	HCO_2H, time enough for equilibration	1/1.2

(13) In the acetolysis of α-phenylneopentyl tosylate, 10% predominant inversion was observed (ref. 4b), whereas in the acetolysis of α-phenylethyl chloride, 16% predominant inversion was found [ref. 3 and S. Winstein and D. Trifan, THIS JOURNAL, **74**, 1151 (1952)].

(14) S. Winstein, M. Brown, K. C. Schreiber and A. H. Schlesinger, *ibid.*, **74**, 1140 (1952).

The phenonium ions involved in these processes appear to collapse exclusively in one direction, the three-membered ring always being opened at the carbon atom carrying the phenyl (rather than the methyl) group. This phenomenon is associated with the relatively greater contributions of resonance forms c and d to the phenonium ion hybrid as compared to form a. It is interesting to note that the geometry of the hybrid must represent a compromise between that which allows the maximum distribution of charge in the bridging phenyl and that which allows the maximum distribution of charge in the second phenyl group. As has been pointed out by Curtin,[7a] the contribution of forms represented by d would be considerably diminished for steric reasons in the *cis*- as compared to the *trans*-phenonium ion.

CHART I



Reactions of the Diastereomeric 1,2-Diphenyl-1-propanols with Various Halogenating Agents.—The most striking thing about the data of Table III is that the distributions of products between the two diastereomers in these halogenation reactions roughly parallel those distributions found for the products of the acetolysis reactions. With all four halogenating reagents, *threo* products predominated markedly when the starting material possessed the *threo* configuration, and slightly when the starting material was of the *erythro* configuration. These results suggest that the general mechanistic features of the acetolysis and halogenation reactions are similar, and that the balances between the processes of Chart I do not vary widely in these two reactions, providing the configurations of the starting materials are the same.

A number of observations have been made in which systems of the general type $C_6H_5—\overset{*}{C}H—R$ (OH) react with thionyl chloride or other halogenating reagents to give products of the same configuration as that of the starting material,[15] and this type of steric result has been attributed to an S_Ni mechanism in which the bond making and breaking processes at the asymmetric carbon atom occur simultaneously.[16] The current results would tend to support the hypothesis set forth earlier[17] that at least some of these halogenating reactions occur by way of ion-pair intermediates, the anion of which can in some cases decompose to give a new ion pair which in turn can collapse internally to give halide products with retention of configuration, and in other cases the cation of the ion-pair can become involved at the back with either dissolved nucleophiles or with unsaturated groups on adjacent carbon atoms.

The halogenating reagents of Table III can be arranged in the order, $HBr + H_2SO_4 > SOCl_2 > PBr_3 > PCl_5$ in their ability to give halide with retention of configuration when the unfavorable *erythro*-1,2-diphenyl-1-propanol is the starting material. An inverted order is obtained if one considers the ability of these reagents to give the same mixture of products from either starting material. As in the case of the solvolysis reactions, the importance of processes A and A′ of Chart I would appear to increase with increasing ionizing power of the reaction medium. It is of interest to note that in runs 11–13, the larger the molar ratio of thionyl chloride to *erythro*-alcohol, the greater was the proportion of *erythro*-halide formed. These changes are probably due to the differences in the concentrations of the HCl produced during the initial formation of the chlorosulfite. This strong acid could possibly enter into reaction with either the starting alcohol or with the chlorosulfite to promote those processes that give the same balance of products from starting material of either configuration.

Experimental Part

Solvolyses of the Brosylate Esters of the *erythro* and *threo*-1,2-Diphenyl-1-propanol.—The method will be illustrated with the procedure employed in run 7 of Table II. A mixture of 1000 ml. of pure dry glacial acetic acid, 22.3 g. of anhydrous potassium carbonate (0.16 mole) and 36.2 ml. of pure acetic anhydride was allowed to stand for several hours. A mixture of 100 ml. of this solution (0.32 *N* in potassium acetate) and 8.63 g. of the brosylate of L-*erythro*-1,2-diphenyl-1-propanol[6c] was allowed to stand at 25° for 45 hours (the ester went into solution over a period of the first few hours). At the end of this time the solution was poured into ice-water, and the mixture was extracted with pure pentane. The organic layer was washed with water, cold dilute sodium hydroxide solution, again with water, and was dried and concentrated under 18 mm. pressure to a small volume (30 ml.). This solution was slowly dripped into a mixture of excess lithium aluminum hydride and ether. After standing for ten minutes the mixture was cautiously treated with ice-water, the organic layer was washed with dilute hydrochloric acid, and dilute sodium carbonate solution and dried. The solvent was evaporated through a short column, and the resulting oil (non-acidic) was put on a column of activated alumina (2.5 × 34 cm.) made up in pure pentane. After eluting the olefin in the mixture with pure pentane (the progress of the olefin down the column was followed with an ultraviolet lamp), the alcohol was eluted with pure methanol. The methanol eluate was concentrated (a short column was used) to 10 ml., and the residue was shaken with a 1 to 1 mixture of pure pentane and ether and a large amount of water. The organic layer was washed twice with water, dried and the solvent was removed through a short column. The residual oil was flash distilled at 3 mm. pressure to give 4.23 g. of oil which was submitted to infrared spectral and polarimetric analyses.

The pentane eluates from the chromatograph were evaporated through a short column, and the residual oil amounted to 0.09 g. of olefinic mixture.

The procedure for the solvolysis runs conducted in formic acid was similar in every way except that the solvolyzing mixture was prepared as follows. Formic acid (100.02% pure by titration with Karl Fischer reagent) was mixed with freshly fused sodium formate in such a way as to produce a 0.21 molar solution. The runs in both cases were made with 100 ml. of solution and 8.62 g. (0.020 mole) of brosylate ester. In runs 5, 6 and 8, homogeneous solutions formed immediately.

Solvolyses of the *erythro*- and *threo*-1,2-Diphenyl-1-propyl Halides.—The physical properties of the halides used are reported in Table I of paper XIV of this series.[6c] The procedure is identical to that used for the brosylate esters except in the following respects. In each case 0.010 mole of halide and 50 ml. of solvolyzing solution (see above) was employed. In the cases of runs 2 and 4 the halides almost completely dissolved within the first few minutes, but a solid of different character started to crystallize very soon. This material never did completely solvolyze, and after the times shown in Table I this solid was collected and characterized: run 2, wt. 0.09 g., m.p. 141–142°, m.m.p. with L-*erythro*-1,2-diphenyl-1-propyl chloride, m.p. 141–142°, $[\alpha]^{22}D$ +96.3° (*c* 1.5 in $CHCl_3$); run 4, 0.14 g., m.p. 157–160°, $[\alpha]^{21}D$ +137° (*c* 2.2 in $CHCl_3$). In runs 1 and 3 only part of the starting material was consumed. The starting material recovered had the following properties: run 1, 1.15 g., m.p. 141–142°, $[\alpha]^{23}D$ +96.7° (*c* 2.1 in $CHCl_3$); run 3, 1.28 g., $[\alpha]^{23}D$ +137° (*c* 2.5 in $CHCl_3$). The rotation of the starting materials were: run 1, $[\alpha]^{23}D$ +97.0° (*c* 2.2 in $CHCl_3$); run 3, $[\alpha]^{23}D$ +137° (*c* 2.1 in $CHCl_3$). The melting points depend largely on the rate of heating, especially in the case of the *erythro*-bromides, and therefore the rotations are much more definitive physical constants.

The filtrates from the alkyl chloride recoveries were treated in the same way as were the solvolysis mixtures from runs 5–8.

Preparation of Acetates of the 1,2-Diphenyl-1-propanol System.—The acetates of all of the isomers and racemates of the 1,2-diphenyl-1-propanol system were prepared by the ordinary acetic anhydride–pyridine method, and during their isolation, pentane solutions of these esters were passed through short alumina columns to remove traces of unreacted alcohol. The physical properties of these acetates are recorded in Table IV. In each case in which crystalline materials were obtained, they were recrystallized from alcohol; the liquids were flash distilled. The physical properties of the starting materials are recorded in Table I of paper XIII of this series.[6a]

Preparation of the *erythro*-1,2-Diphenyl-1-propyl Formates.—A solution of 5.0 g. of (−)-D-*threo*-1,2-diphenyl-1-propanol[8a] in 8 ml. of pure chloroform was added to 250 ml. of pure, dry, formic acid, and the resulting solution was allowed to stand at 25° for 24 hours. The solution was then poured into a mixture of ice and water, and the product was extracted with pentane. The organic layer was washed with water and with sodium carbonate solution, dried and evaporated to a small volume (5 ml.). When the solution was cooled, hard crystals separated which when crystallized from boiling pentane gave 2.7 g. of D-*erythro*-1,2-diphenyl-1-propyl formate (see Table IV). The filtrates were combined, the solvent was evaporated and the residual oil was dissolved and allowed to stand in 200 ml. of pure formic acid for 24 hours. When worked up, another 1.4 g. of *erythro*-

(15) P. H. Levene and L. A. Mikeska, *J. Biol. Chem.*, **75**, 587 (1927); J. Kenyon, A. G. Lypscomb and H. Phillips, *J. Chem. Soc.*, 415 (1930); J. Kenyon, H. Phillips and F. Taylor, *ibid.*, 382 (1932); E. D. Hughes, C. K. Ingold and I. C. Whitfiebl, *Nature*, **147**, 206 (1941); P. A. Levene and A. Rothen, *J. Biol. Chem.*, **127**, 237 (1939); ref. 2b.

(16) W. A. Condrey, E. D. Hughes, C. K. Ingold, S. Masterman and A. D. Scott, *J. Chem. Soc.*, 1267 (1937).

(17) D. J. Cram, THIS JOURNAL, **75**, 332 (1953).

TABLE IV

ACETATES AND FORMATES OF THE 1,2-DIPHENYL-1-PROPYL SYSTEM

Compound	M.p., °C.	Yield, %	$[\alpha]^{22-25}D$	Formula	Carbon, % Calcd.	Carbon, % Found	Hydrogen, % Calcd.	Hydrogen, % Found
DL-*erythro*-acetate	109–110	90		$C_{17}H_{18}O_2$	80.28	80.34	7.13	7.39
DL-*threo*-acetate	38–39	87		$C_{17}H_{18}O_2$	80.28	80.24	7.13	7.27
L-*erythro*-acetate	57–58	94	+66.4°[a]	$C_{17}H_{18}O_2$	80.28	80.05	7.13	7.14
D-*erythro*-acetate	59–60	91	−68.4[a]	$C_{17}H_{18}O_2$	80.28	80.32	7.13	7.21
L-*threo*-acetate	Oil[b]	82	+7.0[d]	$C_{17}H_{18}O_2$	80.28	80.51	7.13	7.36
D-*threo*-acetate	Oil[c]	86	−7.1[d]	$C_{17}H_{18}O_2$	80.28	80.47	7.13	7.35
DL-*erythro*-formate	101–102	60		$C_{16}H_{16}O_2$	79.97	79.69	6.71	6.75
D-*erythro*-formate	88–89	54	−88.2[a]	$C_{16}H_{16}O_2$	79.97	79.92	6.71	6.86
L-*erythro*-formate	88–89	57	+87.1[a]	$C_{16}H_{16}O_2$	79.97	79.64	6.71	6.68

[a] *c* 5% ($CHCl_3$). [b] $n^{25}D$ 1.5414. [c] $n^{25}D$ 1.5412. [d] *c* 8.5% ($CHCl_3$).

formate was obtained. The filtrates were again reworked to give an additional 0.6 g. of material. The three samples of formates were combined and recrystallized from pentane to give a total of 5.2 g. of pure formate, m.p. 88–89° (see Table IV). A small sample of this material was reduced with lithium aluminum hydride to give a 92% yield of D-*erythro*-1,2-diphenyl-1-propanol, m.p. 71.5–72.5° (undepressed by admixture with an authentic sample[6b]), $[\alpha]^{23}D$ −67.1° (*c* 5% in $CHCl_3$).

A mixture of formates rich in *threo* material was prepared as follows. A solution of 4.0 g. of D-*erythro*-formate in 4 ml. of pure chloroform was dissolved in 200 ml. of pure dry formic acid, and the resulting solution was allowed to stand at room temperature for 24 hours. The *erythro*-formate was recovered as in the above procedure (2.2 g.), and the ether filtrate was concentrated to an oil which was flash distilled at 1 mm. to give 1.7 g. of a colorless oil. This material was demonstrated to be 80% D-*threo*-formate, 20% D-*erythro*-formate through its reduction to the alcohol with lithium aluminum hydride to give material $[\alpha]^{24}D$ −49.5° (*c* 3.59 in $CHCl_3$). The above formate mixture rich in the *threo* isomer was used in the equilibration experiment (run 10).

Control Runs for the Solvolysis Experiments.—As a control for runs 7 and 8, a mixture of 2.54 g. of D-*threo*-acetate ($n^{25}D$ 1.5411 and $[\alpha]^{23}D$ −7.1° at *c* 8.6 in $CHCl_3$) and 50 ml. of the solution used for acetolysis (only 0.3 equivalent of base was present) was allowed to stand at 25° for 116 hours. The product was isolated as in runs 1–8, wt., 2.50 g. (98% recovery), $n^{25}D$ 1.5412, $[\alpha]^{23}D$ −7.0° (*c* 9.5 in $CHCl_3$).

In run 9 (control for runs 1–6), a solution of 1.15 g. of pure D-*erythro*-formate dissolved in 3 ml. of pure chloroform was dissolved in enough pure dry formic acid to give a total volume of 50 ml. of solution. This solution was allowed to stand at 25° for 96 hours (the rotation of the solution had ceased to change), the formate was recovered and was reduced to an alcohol mixture as in the above procedures. The result of the analysis of this alcoholic mixture is recorded in Table I.

Run 10 was the same as run 9 except that a mixture of 80% D-*threo*–20% D-*erythro*-formate was used as starting material, and the reaction mixture was allowed to stand only 24 hours.

The Reaction of the Isomers of 1,2-Diphenyl-1-propanol with Thionyl Chloride (Procedure A).—This procedure is illustrated by a description of run 13 (Table III). To 175 g. (1.47 moles) of thionyl chloride[18] at 0° was added in small portions (five minutes) 10.6 g. (0.050 mole) of pure (+)-L-*erythro*-1,2-diphenyl-1-propanol. The resulting solution was allowed to stand at room temperature for ten hours, and the excess thionyl chloride was evaporated under 20 mm. of pressure at room temperature. The residual oil was mixed with 20 ml. of dry ether, and the resulting solution was evaporated under reduced pressure. The residual oil was shaken with a mixture of ether and ice-water, the ether layer was washed with cold dilute sodium hydroxide solution, and then with water. The solution was then dried and the ether was evaporated. The residual oil was dissolved in 10 ml. of warm absolute ethanol (40°) and allowed to stand at room temperature for one to two hours. The mixture was filtered to give the solid L-*erythro*-isomer, which was recrystallized once from boiling absolute ethanol to give 4.26 g. of material (37% yield), m.p. 141–142°, $[\alpha]^{25}D$ +97.0° (*c* 4.1 in $CHCl_3$).

The filtrates were combined, concentrated under reduced pressure to a small volume (10 ml.) and cooled to 0°. The well-formed crystals that separated were collected and recrystallized from a small amount of ethanol to give (including a second crop) 6.44 g. (56% yield) of the L-*threo* isomer, m.p. 43–44°, $[\alpha]D$ +7.1° (*c* 6% $CHCl_3$). Repeated recrystallization of this material in which the second crop was selected gave material, m.p. 43–44°, $[\alpha]D$ +2.2° (*c* 2% $CHCl_3$). Apparently the last few per cent. of *erythro*-halide is removed only with difficulty. This material solvolyzes in boiling ethanol and during the recrystallization steps care must be taken not to heat the solution over 40° and not to leave the solution at this temperature any longer than necessary.

Run 14 of Table III was similar to run 13 except that the molar ratio of thionyl chloride to starting alcohol was 10 to 1. The crude product had a rotation of $[\alpha]^{23}D$ +10.1° (*c* 5 in $CHCl_3$) whereas the recrystallized material (88% yield) had a rotation of $[\alpha]^{23}D$ +7.1 (*c* 5 in $CHCl_3$). In runs 12 and 15 the thionyl chloride (0°) was added all at once to the alcohol, and in runs 13 and 16 the alcohol was added in portions at 0° to the thionyl chloride. In each case the m.p. of racemic *erythro*-chloride isolated was 139–140° and the m.p. of the racemic *threo*-chloride was 53–54°.

Reaction of the Isomers of 1,2-Diphenyl-1-propanol with Phosphorus Pentachloride (Procedure B).—A description of run 18 illustrates the procedure. To 25 g. (0.12 mole) of phosphorus pentachloride cooled to 0° was added in portions 10.61 g. (0.05 mole) of racemic *erythro*-alcohol. After the addition was complete a vigorous reaction occurred. After the mixture had stood at 0° for 20 minutes it was warmed to 50° for 10 minutes and finally stirred with ice. The product was extracted with ether, the ether solution was washed with water, with a 3 *N* sodium hydroxide solution and again with water. The ether layer was dried, the solvent was evaporated, and the diastereomeric chlorides were separated as in Procedure A. In both of runs 17 and 18, the *erythro*-chloride melted at 139–140° and the *threo*-chloride at 53–54°.

Reaction of the Isomers of 1,2-Diphenyl-1-propanol with Phosphorus Tribromide (Procedure C).—The procedure is illustrated with a description of run 22. To 21.2 g. (0.10 mole) of (+)-L-*threo*-1,2-diphenyl-1-propanol[3b] at 0° was added 81 g. (0.30 mole) of cold (0°) phosphorus tribromide (Eastman Kodak Co. white label). The resulting solution was allowed to stand at 0° for 25 minutes and then poured onto ice. After the resulting mixture had been stirred, it was extracted with a one-to-one ether–pentane solution. The organic layer was washed with water, with a 1 *N* sodium hydroxide solution, with water, and was dried and evaporated to an oil which partially solidified upon standing at room temperature for a few hours. To this mixture of diastereomers was added about 40 ml. of absolute alcohol; the mixture was stirred and filtered. The solid was dissolved in a minimum of hot chloroform, the solution was filtered and absolute ethanol was added until crystals appeared. After coming to room temperature the resulting mixture was filtered to give 4.0 g. (14%) of (+)-L-*erythro*-1,2-diphenyl-1-propyl bromide, m.p. 158–159°, $[\alpha]^{22}D$ +136.5° (*c* 4.5 in $CHCl_3$). The melting point of this substance varies between 132 and 159° depending on the solvent from which it is recrystallized. In some cases, the material appeared to be a mixture of

(18) Reagent was purified by the method of D. L. Cottle, THIS JOURNAL, **68**, 1380 (1946).

polymorphic forms with a fairly wide melting point range. The melting point depended greatly on the rate of heating.

The initial filtrate (see above) was cooled and the solid that separated was collected to give material which upon recrystallization from warm absolute ethanol (40°) gave (−)-L-*threo*-1,2-diphenyl-1-propyl bromide, wt. 20.0 g. (including second crops), m.p. 60–61°, $[\alpha]^{21}D$ −51.6° (*c* 3.8 in $CHCl_3$). This material solvolyzes rapidly in warm ethanol, and therefore the recrystallizations must be conducted rapidly. The above material was fractionally recrystallized (five cycles) from ethanol, the tail crop being collected in each case. The highest rotation obtainable was $[\alpha]^{23}D$ −54.2° (*c* 5.1 in $CHCl_3$). This material is unstable in the presence of water and can only be stored when dry and at 0°. When a sample of this bromide is put on wet blue litmus paper, the paper changes color within a few seconds.

The physical properties of the products obtained in the other runs are as follows: run 19, racemic *erythro*-bromide, m.p. 149–154°, and racemic *threo*-bromide, m.p. 60–61°; run 20, (+)-L-*erythro*-bromide, m.p. 158–159°, $[\alpha]^{20}D$ +135.8° (*c* 5.4 in $CHCl_3$) and (−)-L-*threo*-bromide, m.p. 59–61°, $[\alpha]^{20}D$ −54.5 (*c* 5.9 in $CHCl_3$); run 21 racemic *erythro*-bromide, m.p. 153–157°, and racemic *threo*-bromide, m.p. 60–61°. Since the melting points of both the racemic and active *erythro*-bromides were very erratic, the purity of the halides was checked by converting samples of the halide to olefin with alcoholic KOH solution.[6c] In every case, pure *cis*-α-methylstilbene appeared as the only product of the reaction.

Reaction of the Isomers of 1,2-Diphenyl-1-propanol with Hydrobromic Acid–Sulfuric Acid Mixtures (Procedure D).—The procedure is best illustrated with a description of run 23. A mixture of 5.0 g. (0.0235 mole) of racemic *erythro*-1,2-diphenyl-1-propanol, 20 ml. of 48% aqueous hydrobromic acid and 1 ml. of concentrated sulfuric acid was stirred vigorously for 24 hours at room temperature. Two phases were present throughout the reaction. The products were isolated as in procedure C. In both runs the physical properties of the products were as follows: DL-*erythro*-bromide, m.p. 155–159° (undepressed by admixture with an authentic sample); DL-*threo*-bromide, m.p. 60–61° (undepressed by admixture with an authentic sample). Conversion of a sample of the *erythro*-bromide to olefin produced pure *cis*-α-methylstilbene.[6c]

Control Experiments for Reactions of 1,2-Diphenyl-1-propanol with Halogenating Agents.—Since the *threo*-chloride appeared to be the more labile isomer, and since only this isomer was soluble in the reagents in question, the control experiments were carried out with this material as follows.

Control in Thionyl Chloride.—Pure racemic *threo*-chloride (11.5 g., 0.05 mole) was melted and dissolved in 2.3 g. (0.05 mole) of absolute ethanol. This solution was submitted to procedure A utilizing 60 g. (0.5 mole) of thionyl chloride and an addition time of 25 minutes. No *erythro*-chloride was obtained, and 11.2 g. (98% yield) of *threo*-chloride was recovered, m.p. 53.5–54.5° (undepressed by admixture with an authentic sample). A mixture of 0.5 g. of racemic *threo*-chloride and 0.1 g. of *erythro*-chloride was dissolved in 5 ml. of boiling absolute ethanol, and the resulting solution was allowed to cool slowly to room temperature. The solid that separated was recrystallized from ethanol to give 78 mg. of pure *erythro*-chloride, m.p. 139–140° (undepressed by admixture with an authentic sample). A second crop of 16 mg. of impure *erythro*-chloride was also isolated. From the initial filtrates was recovered 0.46 g. of *threo*-chloride, m.p. 53–54° (undepressed by admixture with an authentic sample).

Control in Phosphorus Pentachloride.—Racemic *threo*-chloride (3.53 g.) was melted and mixed with 8.3 g. of phosphorus pentachloride, and the resulting mixture was heated at 100° for 20 minutes. The starting material was recovered by procedure B, wt. 3.35 g., m.p. 53.4–54.5° (undepressed by admixture with authentic material). No *erythro*-chloride was evident.

Control in Phosphorus Tribromide.—Dry hydrogen bromide was passed (20 minutes at 0° and two hours at 25°) through a solution of pure racemic *threo*-bromide (11.0 g.) in 32.4 g. of phosphorus tribromide. The mixture was heated as described in procedure C to give 1.02 g. (9% yield) of *erythro*-bromide, m.p. 157–159° (undepressed by admixture with an authentic sample). This material was converted to *cis*-α-methylstilbene (90% yield, m.p. 47.5–48.5°). A total of 9.42 g. (85% yield) of *threo*-bromide was recovered, m.p. 60–61° (undepressed by admixture with an authentic sample).

Control in Sulfuric Acid–Hydrobromic Acid.—Pure *threo*-bromide (10.0 g.) was carefully melted and mixed with 40 ml. of 48% aqueous hydrobromic acid and 2 ml. of concentrated sulfuric acid. The mixture was allowed to stand with occasional shaking for 24 hours. When worked up as in procedure D, this mixture yielded 0.52 g. (5% yield) of *erythro*-bromide, m.p. 149–154°. This material with ethanolic potassium hydroxide gave *cis*-α-methylstilbene[6c] (84%, m.p. 47–48°). A total of 9.2 g. (92% yield) of *threo*-bromide was recovered, m.p. 60–61° (undepressed by admixture with an authentic sample).

Preparation of 1,1-Diphenyl-2-propanol.—A solution of 189 g. of 1,1-diphenylacetone[19] in 500 ml. of dry ether was added dropwise to a stirred mixture of 20 g. of lithium aluminum hydride and dry ether. The reaction mixture was decomposed on ice, the ether layer was washed with aqueous acid, with sodium carbonate solution, and dried. The solvent was evaporated, and the residual oil was crystallized from pentane to give 176 g. (92% yield) of 1,1-diphenyl-2-propanol, m.p. 60–63°. A sample of this material was recrystallized eight times from pentane to give a pure sample for analysis and for the infrared spectra, m.p. 63–64°.[20]

Anal. Calcd. for $C_{15}H_{16}O$: C, 84.87; H, 7.60. Found: C, 84.84; H, 7.71.

The *p*-bromobenzenesulfonate of this alcohol was prepared in 84% yield by the usual method,[6c] m.p. 98.5–99°.

Anal. Calcd. for $C_{21}H_{19}O_3SBr$: C, 58.47; H, 4.44. Found: C, 58.45; H, 4.67.

Preparation of 1,2-Diphenyl-2-propanol.—This compound was prepared by the action of methylmagnesium iodide on desoxybenzoin[21] to give a 90% yield of material, b.p. 131–132° (3–4 mm.), $n^{25}D$ 1.5730, m.p. 50–51°.

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(21) C. Hell, *Ber.*, **37**, 457 (1904).