are grateful to Dr. R. King for determination of the n.m.r. spectra, for the double resonance experiments, and for aid in the interpretation of these spectral results. It is a pleasure to acknowledge the assistance of Dr. G. Morris and L. Rodewald who carried out the computer work reported herein.

Reactions of Phosphorus Compounds. IX. The Opening of Epoxides with Tertiary Phosphines

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The product ratio data from the reaction of cis- and trans-4-octene oxide and cis- and trans-stilbene oxide with triphenyl- and tributylphosphine in the presence of excess m-chlorobenzaldehyde suggest the possible intervention of new intermediates in the Wittig reaction via which the two stereoisomeric betaines are equilibrated. The activation parameters for the partitioning of the betaine intermediates, from cis- and trans-ethyl phenylglycidate and tertiary phosphines, between ylid and aldehyde, and phosphine oxide and olefin, have been estimated. It has been shown that this partitioning is controlled by differences in entropy rather than differences in enthalpy.

Introduction

Recently,[1b] we proposed a mechanism for the Wittig reaction of stable ylids based in part upon data from the reaction of tertiary phosphines with *cis-* and *trans-*ethyl phenylglycidate in the presence of *m*-chlorobenzaldehyde.

$$R_3P + C_6H_5CH\underset{O}{-}CHCO_2C_2H_5 \longrightarrow \overset{+}{R_3P}-CHCO_2C_2H_5$$

The presence of ethyl *m*-chlorocinnamate among the reaction products provided the first conclusive demonstration that betaine formation in the reactions of stable ylids with aromatic aldehydes is reversible. The possibility existed, however, that attack of the phosphine occurred, to a significant extent, at the β-carbon atom,

(1) (a) A. J. Speziale and D. E. Bissing, *J. Am. Chem. Soc.*, **85**, 1888 (1963); (b) A. J. Speziale and D. E. Bissing, *ibid.*, **85**, 3878 (1963).

furnishing a new betaine (II) which could decompose reversibly to benzylidenetriphenylphosphorane (III) and ethyl glyoxylate (IV). The absence of *m*-chlorostilbene (III + *m*-chlorobenzaldehyde) suggested that either β-attack was unimportant or formation of II from ylid and carbonyl compound was irreversible. *trans*-Ethyl phenylglycidate reacts with triphenylphosphine ten times as fast as *trans*-stilbene oxide, and further, significant amounts of *m*-chlorostilbene were detectable among the reaction products of *trans*-stilbene oxide with tertiary phosphines in the presence of *m*-chlorobenzaldehyde. The most likely explanation for the absence of *m*-chlorostilbene in the glycidic ester reactions is predominant, if not exclusive, attack by the phosphine at the α-carbon atom.

In view of these results, a detailed study and mechanistic interpretation of the product ratios obtained upon treatment of several more epoxides with tertiary phosphines in the presence of *m*-chlorobenzaldehyde was undertaken in order to compare the decomposition of betaines derived from stable and unstable ylids and thereby gain a more thorough understanding of the over-all Wittig reaction.

Results

The reactions of *cis-* and *trans*-4-octene oxide, *cis-* and *trans*-stilbene oxide, and *cis-* and *trans*-ethyl phenylglycidate with triphenyl- and tributylphosphine in the presence of *m*-chlorobenzaldehyde were studied. The reactions were carried out in sealed glass tubes, with a 3 *M* excess of *m*-chlorobenzaldehyde as solvent. The 4-octene oxide reactions were studied at 160°, the stilbene oxide reactions at 160 and 220°, and the glycidic ester reactions at 100, 160, and 220°. After completion, the reaction mixtures were analyzed by g.p.c.

4-Octene Oxides. Table I contains the product ratio data, expressed in mole per cent, for the reactions of equimolar amounts of *cis-* and *trans*-4-octene oxide with triphenyl- and tributylphosphine at 160° in the presence of a 3 *M* excess of *m*-chlorobenzaldehyde. In all cases the reactions were incomplete, as evidenced by the presence of unreacted epoxide even though all of the phosphine had been consumed. The fate of the phosphine will be discussed later in this paper.

The ratios of k_{-1}/k_2 given in Table I are a measure of the relative ease of decomposition of the betaine intermediate to ylid and aldehyde (k_{-1}) and to phosphine oxide and olefin (k_2). These values were calculated

Table I. Reaction of R_3P + $C_3H_7CH\overset{O}{\overset{\displaystyle\diagdown\diagup}{}}CHC_3H_7$ + m-Chlorobenzaldehyde (160 ± 2°)

R	Epoxide	Reactn., %[b]	A[a] cis	A[a] trans	B[a] cis	B[a] trans	k_{-1}/k_2
C_4H_9	cis	77	16.4	40.6	17.2	26.8	0.78
C_4H_9	trans	40	49.1	7.6	15.3	28.0	0.77
C_6H_5	cis	95	30.5	54.7	6.3	8.5	0.18
C_6H_5	trans	42	72.7	11.8	7.0	8.5	0.18

[a] A = $C_3H_7CH{=}CHC_3H_7$; B = (3-chlorophenyl ring with $CH{=}CHC_3H_7$ substituent and Cl)
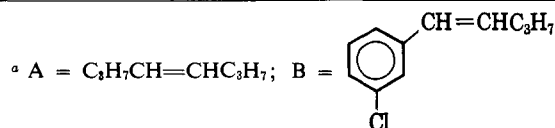
[b] Determined by comparison of unreacted epoxide with total amount of olefin formed.

Table II. Reaction of R_3P + $C_6H_5CH\overset{O}{\overset{\displaystyle\diagdown\diagup}{}}CHC_6H_5$ + m-Chlorobenzaldehyde

R	Epoxide	Temp., °C (±2°)	A[a] cis	A[a] trans	B[a] cis	B[a] trans	$k_{-1}{}^p/k_2{}^{p\,b}$
C_4H_9	cis	160	7.8	29.0	12.6	50.6	1.72
C_4H_9	trans	160	23.8	1.4	15.6	59.2	2.97
C_6H_5	cis	160	21.4	22.8	12.0	43.8	1.26
C_6H_5	trans	160	22.3	22.3	16.0	39.4	1.24
C_4H_9	cis	220	7.0	21.4	8.5	63.1	2.52
C_4H_9	trans	220	13.5	12.0	7.0	67.5	2.92
C_6H_5	cis	220	3.4	39.2	2.3	55.1	1.34
C_6H_5	trans	220	4.1	39.4	2.1	55.4	1.35

[a] A = $C_6H_5CH{=}CHC_6H_5$; B = (3-chlorophenyl ring with $CH{=}CHC_6H_5$ substituent and Cl)

[b] "p" denotes attack of the phosphine at a carbon atom adjacent to a phenyl group.

by dividing the total amount of 1-(m-chlorophenyl)-pentene-1 by the total amount of 4-octene in each case.[2] A necessary assumption in these calculations is that all of the butylidenetriphenylphosphorane formed by decomposition of the betaines reacts with m-chlorobenzaldehyde rather than butyraldehyde. In order to show that m-chlorobenzaldehyde is more reactive than butyraldehyde, competition experiments were performed by slowly adding a solution of the ylid in ether to a mixture of excess amounts of each aldehyde. When the ylid, butyraldehyde, and m-chlorobenzaldehyde in the ratio of 1:3:3 were used, the m-chloro olefin predominated by about 10:1. When the ratio of starting materials was 1:1:3 the predominance of the m-chloro olefin was 32:1.

It was previously observed[1] that cis-ethyl cinnamate is rapidly isomerized to trans-ethyl cinnamate by tributylphosphine and to a lesser extent by triphenylphosphine. None of the other reactants or products of the ring opening reaction influenced the stereochemistry of the olefin. However, neither cis- nor trans-4-octene was isomerized by the phosphines under the reaction conditions.

Stilbene Oxides. The product ratio data obtained from reaction of cis- and trans-stilbene oxide with triphenyl- and tributylphosphine at 160 and 220° in the presence of a 3 M excess of m-chlorobenzaldehyde are given in Table II. Separate experiments, under the same conditions, showed that cis-stilbene is isomerized to trans-stilbene by tributylphosphine at a rate which could influence the stereochemical ratio of olefins. On the other hand, the isomerization of cis-stilbene by triphenylphosphine, while not fast enough at 160° to affect the product ratios, becomes significant at 220°. Competition experiments of benzylidenetriphenylphosphorane for benzaldehyde and m-chlorobenzaldehyde gave the following results. When present in a ratio of 1:3:3 the ratio of m-chlorostilbene to stilbene was 19:1. Even when the ratio of starting materials was 1:3:1 the ratio of substituted olefin to unsubstituted olefin was still 3:1. Since, in the sealed-tube reactions of phosphines with cis- and trans-stilbene oxides, m-chlorobenzaldehyde was always present in at least a 5:1 excess over benzaldehyde, the total amount of

m-chlorostilbene as compared to stilbene was used to calculate the values of $k_{-1}{}^p/k_2{}^p$ as given in Table II.

Ethyl Phenylglycidates. The product ratios obtained from the reactions of cis- and trans-ethyl phenylglycidate with triphenyl- and tributylphosphine at 100, 160, and 220° in the presence of a 3 M excess of m-chlorobenzaldehyde are reported in Table III. The results in these reactions are complicated by the fact that the phosphines may and do attack both the α- and the β-carbon atoms. In the case of α-attack the incorporation products with m-chlorobenzaldehyde are cis- and trans-ethyl m-chlorocinnamate while the incorporation products for β-attack are cis- and trans-m-chlorostilbene. Although it has been shown that β-attack is unimportant in refluxing ethanol (see Introduction), the present experiments show that at higher temperature the m-chlorostilbenes become major products of the reaction (Table III). Since direct decomposition of the betaines derived by attack of the phosphine at either the α- or β-carbon atoms yields ethyl cinnamate, the calculation of k_{-1}/k_2 for the reaction involving α-attack becomes exceedingly difficult. The estimation of these parameters will be discussed in a later section of the paper.
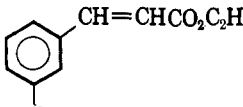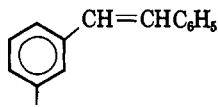
It has been reported[1] that carbethoxymethylenetriphenylphosphorane much prefers m-chlorobenzaldehyde in competition experiments of this ylid for benzaldehyde and m-chlorobenzaldehyde. It was also shown that the concentration of m-chlorobenzaldehyde had no effect upon the relative amounts of ethyl m-chlorocinnamate and ethyl cinnamate formed during the reaction. Consequently, it is likely that all of the ylid derived from decomposition of the intermediate betaines reacts with m-chlorobenzaldehyde. It was further reported[1] that both triphenyl- and tributylphosphine isomerize cis-ethyl cinnamate to trans-ethyl cinnamate. This isomerization is also important in the present study.

Discussion of Results

There is an increasing amount of evidence that nucleophilic attack of a tertiary phosphine on an epoxide occurs primarily at carbon. Our previous results[1] are interpretable in terms of exclusive attack at carbon. Denney and Boskin[3] found that the product ratios from

(2) Using the data in the first line of Table I, the sum of cis- and trans-1-(m-chlorophenyl)pentene-1 (44%) divided by the sum of cis- and trans-4-octene (56%) is 0.78.

(3) D. B. Denny and M. S. Boskin, *Chem. Ind.* (London), 330 (1959).

Table III. Reaction of R_3P + $C_6H_5CH\text{-}CHC_6H_5$ (epoxide) + (m-ClC₆H₄CHO)

R	Epoxide	Temp., °C. (±2°)	$C_6H_5CH=CHCO_2C_2H_5$		(ClC₆H₄) $CH=CHCO_2C_2H_5$		(ClC₆H₄) $CH=CHC_6H_5$		$k_{-1}^e/k_2^{e\ a}$
			cis	trans	cis	trans	cis	trans	
C_4H_9	cis	100	0	42.3	0	55.9	Trace	1.8	1.3
C_4H_9	trans	100	0	24.5	0	74.5	Trace	1.0	3.0
C_6H_5	cis	100	3.9	59.7	5.0	30.2	Trace	1.2	0.55
C_6H_5	trans	100	14.8	9.8	4.9	70.5	Trace	Trace	3.1
C_4H_9	cis	160	0	32.4	0	55.6	2.7	9.3	2.2
C_4H_9	trans	160	0	20.9	0	76.2	0.6	2.3	3.8
C_6H_5	cis	160	2.1	37.8	3.6	40.7	3.6	12.2	1.6
C_6H_5	trans	160	8.9	6.8	4.3	62.1	5.5	12.4	51
C_4H_9	cis	220	0	24.8	0	46.2	3.4	25.6	3.5
C_4H_9	trans	220	0	19.7	0	70.4	2.3	7.6	4.3
C_6H_5	cis	220	0	24.3	4.0	42.3	6.1	23.3	19
C_6H_5	trans	220	4.8	11.1	6.9	57.2	5.3	14.7	58

ᵃ "e" denotes attack of the phosphine at the carbon atom adjacent to the ester group. These values were estimated as described in the Discussion section.

the reaction of cis- and trans-2-butene oxide with tributylphosphine demand at least 75% carbon attack and, since it is now known that certain ylids form their betaines reversibly,[1] it is possible to interpret the remaining 25% in terms of carbon attack. Scott[4] found that ethylene and propylene oxides were opened by triethyl phosphite and proposed carbon attack. Wittig and Haag[5] reported that reaction of trans-ethyl phenylglycidate with triphenylphosphine gave equal amounts of cis- and trans-ethyl cinnamate. Since it is known[1] that triphenylphosphine isomerizes cis-ethyl cinnamate to trans-ethyl cinnamate and that the betaine, once formed, decomposes to ylid and aldehyde, these data are also explicable by predominant, if not exclusive, carbon attack. Nucleophilic attack upon an epoxide occurs with inversion of configuration.[6] Tömösközi[7] has shown recently that reaction between optically active styrene oxide and phosphonate carbanions proceeds with inversion at the optically active center.

Assuming that attack of the phosphine upon the epoxide occurs with inversion at carbon, the general

cis epoxide

$R_3P=CHR'' + R'CHO$

$m\text{-}ClC_6H_4CHO$

$m\text{-}ClC_6H_4CH=CHR'' + R_3P=O$
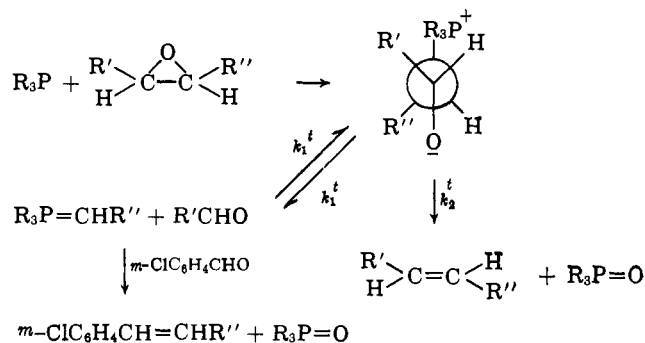
(4) C. B. Scott, J. Org. Chem., 22, 1118 (1957).
(5) G. Wittig and W. Haag, Ber., 88, 1654 (1955).
(6) (a) D. Reulos, Compt. rend., 216, 774 (1943); (b) D. Reulos and C. Collin, ibid., 218, 795 (1944); (c) F. Bottari and B. Machehia, Farmaco (Pavia) Ed., sci., 15, 726 (1960); (d) R. E. Parker and N. S. Isaacs, Chem. Rev., 59, 737 (1959).
(7) I. Tömösközi, Tetrahedron, 19, 1969 (1963).

reaction schemes for the cis and trans epoxides are shown here. The rate constants k_1, k_{-1}, and k_2 are defined in terms of the stereochemistry of the betaines and not that of the starting epoxide.

trans epoxide

$R_3P=CHR'' + R'CHO$

$m\text{-}ClC_6H_4CHO$

$m\text{-}ClC_6H_4CH=CHR'' + R_3P=O$

$R = C_4H_9, C_6H_5$
$R' = C_6H_5, C_3H_7$
$R'' = CO_2C_2H_5, C_6H_5, C_3H_7$
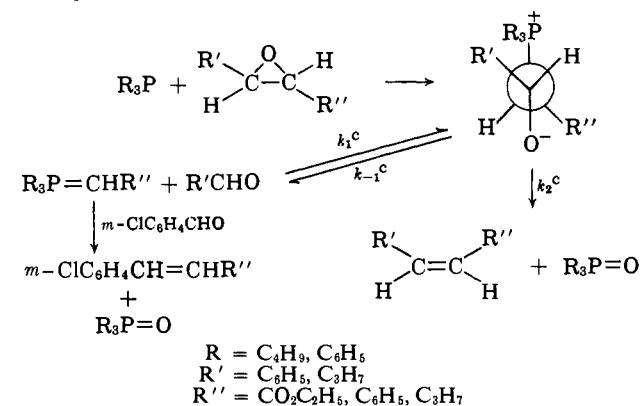
Wittig and co-workers[8] isolated the protonated betaine V by treatment of the reaction mixture of methylenetriphenylphosphorane and benzaldehyde with hydrogen iodide. Since V, on heating, gave triphenyl-

$(C_6H_5)_3\overset{+}{P}\overset{I^-}{—}CH_2$
$HO—CHC_6H_5$
V
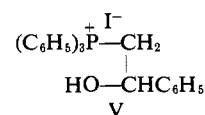
phosphine oxide and styrene and only trace amounts of 1,1-diphenylethylene when heated in the presence of benzophenone, irreversible formation of the betaine was proposed.
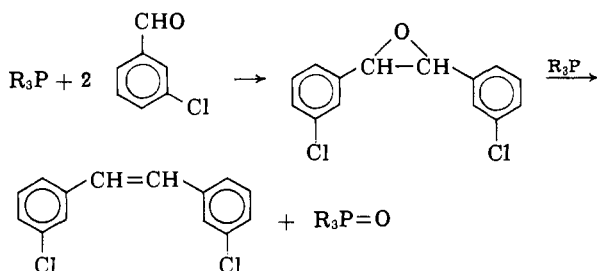
Recently, however, Hudson and co-workers[9] isolated this same betaine as a lithium bromide–ether complex which, on heating, yielded benzaldehyde and no olefinic products. Reversible betaine formation and rate-

(8) G. Wittig, H. Weizmann, and M. Schlosser, Ber., 94, 676 (1961).
(9) S. Fliszar, R. F. Hudson, and G. Salvadori, Helv. Chim. Acta., 46, 1580 (1963).

determining decomposition of the betaine to phosphine oxide and olefin were therefore suggested.

4-Octene Oxides. When either *cis-* or *trans-*4-octene oxide is allowed to react with tributyl- or triphenylphosphine in the absence of *m*-chlorobenzaldehyde, only the expected products are formed, *e.g.*, *cis-* and *trans-*4-octene and phosphine oxide. The reaction is exceedingly complex when carried out in the presence of a threefold excess of *m*-chlorobenzaldehyde. Although all of the phosphine was converted to phosphine oxide,[10] there remained significant amounts of unreacted epoxide. Further, g.p.c. analysis showed the presence of several extraneous products not observed in the reactions carried out in the absence of *m*-chlorobenzaldehyde. One of these has been identified as 3,3′-dichlorostilbene and is undoubtedly formed by reaction of phosphine with *m*-chlorobenzaldehyde. This reaction could account for the fact that the rate of disappearance of phosphine is greater than that of the epoxide. Hexa-

methylphosphorous triamide reacts similarly with aldehydes.[11] The 3,3′-dichlorostilbene is assumed to be *trans* since it has a sharp melting point and exhibits no carbon double bond stretching absorption in the infrared.[12] This side reaction takes place to a greater extent with tributylphosphine than triphenylphosphine. It is not observed with any of the other epoxides. It is likely that the phosphines react much more rapidly with the stilbene oxides and glycidic esters than with *m*-chlorobenzaldehyde, while the opening of the octene oxides by phosphine is slow enough to permit competition of the side reaction.[13]

The large amounts of *cis*-4-octene obtained from *cis*-4-octene oxide (Table I) cannot be explained in terms of the general mechanism proposed above. If S$_N$2 attack of the phosphine occurs with inversion at carbon, the product of direct decomposition of the betaine would be *trans*-4-octene. Similarly, smaller, but still significant amounts of *trans*-4-octene are obtained from the *trans* epoxide. As mentioned earlier, olefin isomerization was found to be unimportant under the reaction conditions.

There are two reasonable explanations for the formation of *cis* olefin from *cis* epoxide and *trans* olefin from *trans* epoxide. The first involves nucleophilic attack of the phosphine at oxygen leading to an intermediate (VI) similar to that proposed by Denney for

episulfides.[3] A second plausible explanation entails partial equilibration of the stereoisomeric betaines *via* an intermediate ylid (VII). This mechanism, which

has also been suggested by Trippett,[14] would require abstraction of a relatively nonacidic proton by oxygen, and this reaction would have to be fast enough to compete with betaine decomposition *via* the alternate routes. This point will be considered further later in this paper.

Since the reactions of 4-octene oxides with tertiary phosphines in the presence of *m*-chlorobenzaldehyde are very complex, quantitative significance cannot be placed upon the values of k_{-1}/k_2 (Table I). These calculations were based on the assumption that all olefins arose *via* the generalized scheme described above. The detection of 1-(*m*-chlorophenyl)pentene-1, however, substantiates the conclusions of Hudson and co-workers[9] that betaine formation from unstable ylids and carbonyl compounds is reversible. The greater amount of incorporation of *m*-chlorobenzaldehyde with tributylphosphine than with triphenylphosphine is consistent with the proposed mechanism of the Wittig reaction,[1b] *e.g.*, the phenyl group attached to phosphorus facilitates direct decomposition of the betaines to phosphine oxide and olefin.

Stilbene Oxides. The reactions of *cis-* and *trans*-stilbene oxide with tertiary phosphines are much less complex than those of the 4-octene oxides, at least from the viewpoint of number of products. Only very minor peaks in the g.p.c. spectrum remain unidentified.

The values of $k_{-1}{}^P/k_2{}^P$ (Table II) were calculated by dividing the amount of *m*-chlorostilbene (*cis* plus *trans*) by the amount of stilbene (*cis* plus *trans*). In each case this parameter is greater than unity, indicating a preference for betaine decomposition to ylid and aldehyde. With tributylphosphine, at both temperatures, this preference is greater for the *trans* epoxide, which initially yields *cis* betaine, than for the *cis* epoxide which furnishes *trans* betaine. These results are consistent with the observed stereospecificity of the reaction of the ylid with benzaldehyde,[15,16] although the values of $k_{-1}{}^P/k_2{}^P$ obtained at 220° (2.52 and 2.92) suggest that the reaction of benzylidenetriphenylphosphorane and benzaldehyde would be almost completely nonstereospecific at this temperature.

(10) In the reactions involving triphenylphosphine, small amounts of unreacted phosphine were detected by g.p.c. With tributylphosphine, however, there was no unreacted phosphine.
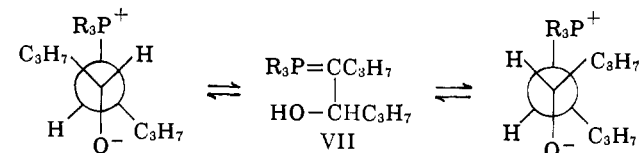
(11) V. Mark, *J. Am. Chem. Soc.*, **85**, 1884 (1963).

(12) L. J. Bellamy, "The Infrared Spectra of Complex Organic Molecules," John Wiley and Sons, Inc., New York, N. Y., 1958, p. 38.

(13) Another of the anomalous products observed in the reaction of 4-octene oxides with phosphines in the presence of *m*-chlorobenzaldehyde is 4-octanone. The mode of formation of this compound has been discussed in a recent communication: D. E. Bissing and A. J. Speziale, *J. Am. Chem. Soc.*, **87**, 1405 (1965).

(14) S. Trippett, *Quart. Rev.* (London), **17**, 406 (1963).

(15) For a thorough discussion of this point see ref. 1b.

(16) A. Blade-Font, C. A. Vander Werf, and W. E. McEwen, *J. Am. Chem. Soc.*, **82**, 2396 (1960).

Although *cis*-stilbene is isomerized to *trans*-stilbene by tributylphosphine at 160°, this reaction is not important during the ring opening reaction. Since direct decomposition of the *cis* betaine (derived from *trans* epoxide) yields *cis*-stilbene, the presence of only 1.4 mole % *trans*-stilbene in this reaction clearly indicates that reaction of phosphine with epoxide is faster than isomerization of *cis*-stilbene. At 220° the isomerization reaction competes well with attack on the epoxide.

The source of *cis*-stilbene from *cis* epoxide is not known. It is conceivable that a small amount of direct deoxygenation of the epoxide occurs. Possible betaine equilibration will be discussed later to explain the product ratios from reaction of the stilbene oxides with triphenylphosphine.

The reaction of triphenylphosphine with the stilbene oxides is more complex. The calculated values of $k_{-1}{}^p/k_2{}^p$ for both *cis* and *trans* epoxides are constant at each temperature (Table III). Further, the relative amounts of *cis* and *trans* olefins are approximately the same. There are two reasonable explanations for the phenomenon. Either the epoxides undergo prior stereochemical equilibration, or the betaines, once formed, are equilibrated *via* an intermediate ylid. In order to test these hypotheses, the reactions of both epoxides with triphenylphosphine were interrupted after approximately 1 half-life and the mixture was subjected to g.p.c. and n.m.r. analysis. No evidence for epoxide isomerization could be found; each had retained its stereochemical integrity. This leaves betaine equilibration as the only reasonable explanation of the observed product ratios. If the betaines undergo
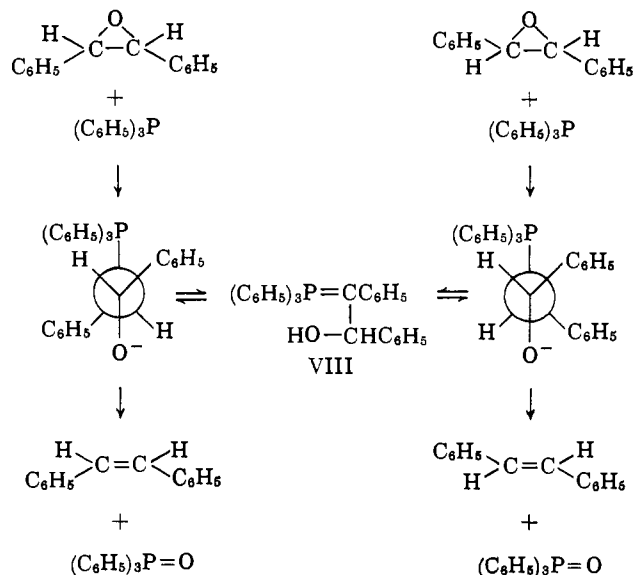
equilibration, the ylid intermediate VIII could react with *m*-chlorobenzaldehyde to form the allyl alcohol
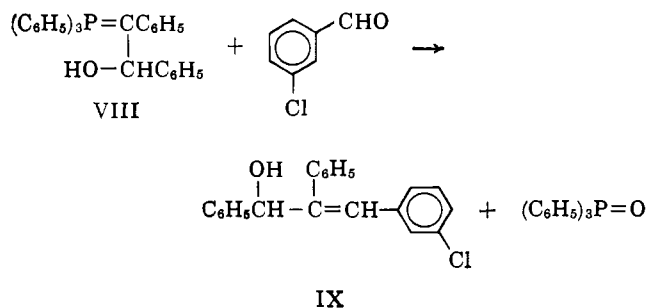
IX. An authentic sample of IX was prepared. Its retention time on the g.p.c. columns tried was the same as that of triphenylphosphine oxide. The entire triphenylphosphine oxide peak was collected from the analytical instrument and chromatographed on silica gel. IX was shown to be absent by infrared spectroscopy.

The absence of IX does not necessarily eliminate the possible equilibration of the betaines. The ylid VIII is very hindered and it is possible that it would react slowly, if at all, with *m*-chlorobenzaldehyde and that proton abstraction necessary for equilibration would be faster.

Ethyl Phenylglycidates. The reaction of *cis*- and *trans*-ethyl phenylglycidate with tertiary phosphines is complicated by the fact that the phosphine may attack either carbon atom yielding two different betaines, each of which may partition itself between the two reaction paths. Since $k_{-1}{}^p/k_2{}^p$ values are not available for II, it is
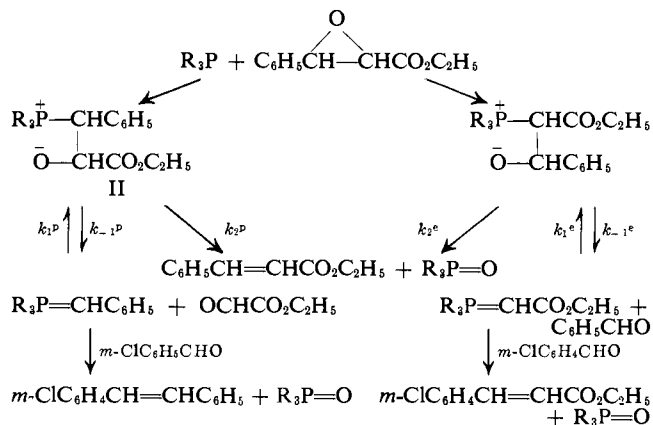
impossible to calculate accurately the values of $k_{-1}{}^e/k_2{}^e$. However, these values may be estimated if it is assumed that $k_{-1}{}^p/k_2{}^p$ are the same as those calculated for the corresponding betaines derived from the stilbene oxides. Since the ylid derived from the stilbene oxide reaction and that from β-attack on the glycidic esters are the same, it might be expected that the values of k_{-1}/k_2 for the two betaines would parallel each other. From a knowledge of $k_{-1}{}^p/k_2{}^p$ for the stilbene oxides and the amount of *m*-chlorostilbene formed in the glycidic ester reaction, the fraction of ethyl cinnamate derived from attack of the phosphine at the β-carbon atom may be estimated, and the $k_{-1}{}^e/k_2{}^e$ values (Table III) thereby calculated.[17]

Since it is known that both triphenyl- and tributylphosphine isomerize *cis*-ethyl cinnamate and *cis*-ethyl *m*-chlorocinnamate to the corresponding *trans* olefins,[1] the relative amounts of *cis* and *trans* olefins listed in Table III are of little mechanistic significance. However, certain trends in the values of $k_{-1}{}^e/k_2{}^e$, which are probably not a function of their method of estimation, are significant. For each epoxide, as temperature is increased the estimated values of $k_{-1}{}^e/k_2{}^e$ increase, in some cases quite rapidly. In the reaction of the glycidic

(17) As a sample calculation consider the data for tributylphosphine and *cis*-ethyl phenylglycidate at 160° (Table III). The corresponding value of $k_{-1}{}^p/k_2{}^p$ (Table II) is 1.72 and the amount of *m*-chlorostilbene (*cis* plus *trans*) is 12.0%. Therefore, $12.0/1.72 = 7.0\%$ ethyl cinnamate would be expected to be derived from β-attack on the glycidic ester. The amount derived from α-attack, then, is the total amount of ethyl cinnamate (32.4%) less the amount due to β-attack. Hence, $k_{-1}{}^e/k_2{}^e$ can be calculated by dividing the total amount of ethyl *m*-chlorocinnamate by the amount of ethyl cinnamate due to α-attack, *e.g.*, $k_{-1}{}^e/k_2{}^e = 55.6/(32.4 - 7) = 2.2$.

1.7 ○ cis-C₆H₅CH—CHCO₂C₂H₅ + (C₄H₉)₃P + m-ClC₆H₄CHO $\Delta\Delta H^*$=-2.9 k.cal/mole
1.6
1.5 □ trans-C₆H₅CH—CHCO₂C₂H₅ + (C₄H₉)₃P + m-ClC₆H₄CHO $\Delta\Delta H^*$=-1.1 k.cal/mole
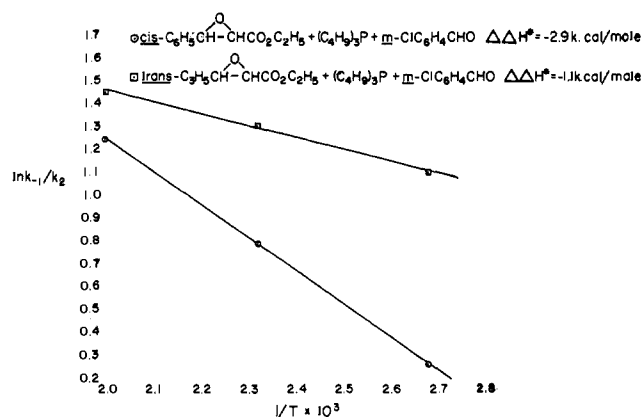
$\ln k_{-1}/k_2$

Figure 1.

esters with tributylphosphine k_{-1}^e/k_2^e for the *trans* epoxide (which furnishes *cis*-betaine) are larger at each temperature than the corresponding values for the *cis* epoxide. At 100° the *cis* betaine decomposes to ylid and aldehyde three times as fast as it decomposes to olefin and phosphine oxide, while the corresponding ratio for the *trans* betaine is only 1.3. Similarly, at 160°, these ratios are 3.8 and 2.2, respectively, and at 220°, 4.3 and 3.5. These values confirm the earlier observation[1b] that the *trans* betaine is better able to decompose directly to phosphine oxide and olefin than is the *cis* betaine. This difference in the behavior of the *cis* and *trans* betaines accounts at least in part for the observed stereospecificity of the reactions of stable ylids with carbonyl compounds.[1b,18] It should be noted, however, that at the higher temperatures the k_{-1}^e/k_2^e values for the *cis* and *trans* betaines approach each other quite closely, suggesting that the reaction of carbethoxymethylenetriphenylphosphorane with benzaldehyde would lose much of its stereospecificity under these conditions.

If the Arrhenius equation[19] is applied to the data obtained from the reaction of *cis*- and *trans*-ethyl phenylglycidate with tributylphosphine, the difference in activation enthalpies for the two decomposition pathways may be calculated (eq. 1 and 2). A plot of $\ln k_{-1}^e/$

$$\ln k_{-1}^e/k_2^e = (E_2 - E_1)/RT + \ln C \qquad (1)$$

$$\ln k_{-1}^e/k_2^e = \Delta\Delta H^*/RT + \ln C \qquad (2)$$

k_2^e *vs.* $1/T$ should be linear with slope $\Delta\Delta H^*/R$. Figure 1 contains plots of data obtained for both *cis* and *trans* epoxides. The slopes of both lines are negative, indicating that $\Delta H_{-1}^* > \Delta H_2^*$. However, the product ratios (Table III) demand that the rate of decomposition of the betaines to ylid and aldehyde be greater than the rate of decomposition to olefin and phosphine oxide, *e.g.*, $k_1 > k_2$ or $\Delta F_2^* > \Delta F_{-1}^*$. This apparent anomaly can be nicely explained in terms of activation entropy.

The difference in free energies of activation for the two decomposition pathways may also be calculated (eq. 3 and 4). Knowledge of $\Delta\Delta F^*$ and $\Delta\Delta H^*$ allows

$$[\ln k_{-1}^e/k_2^e = (\Delta F_2^* - \Delta F_{-1}^*)/RT \qquad (3)$$

$$\ln k_{-1}^e/k_2^e = \Delta\Delta F^*/RT \qquad (4)$$

the facile calculation of $\Delta\Delta S^*$ (eq. 5 and 6).

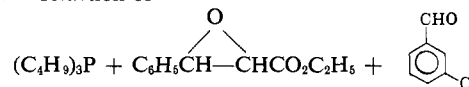(18) H. O. House and G. H. Rasmusson, *J. Org. Chem.*, **26**, 4278 (1961).
(19) A. A. Frost and R. G. Pearson, "Kinetics and Mechanism," John Wiley and Sons, Inc., New York, N. Y., 1961, p.23.

$$\Delta\Delta F^* - \Delta\Delta H^* = -T(\Delta S_2^* - \Delta S^*_{-1}) \qquad (5)$$

$$\frac{\Delta\Delta F^* - \Delta\Delta H^*}{T} = -\Delta\Delta S^* \qquad (6)$$

The calculated values for the activation parameters are reported in Table IV.

Table IV. Reaction of

$$(C_4H_9)_3P + C_6H_5CH\!-\!CHCO_2C_2H_5 +$$

Epoxide	Temp., °C.	$\Delta\Delta H^*$, (kcal./ mole	$\Delta\Delta F^*$, kcal./ mole	$\Delta\Delta S^*$, e.u.
cis	100	−2.9	0.19	−8.3
trans	100	−1.1	0.82	−5.1
cis	160	−2.9	0.68	−8.3
trans	160	−1.1	1.15	−5.2
cis	220	−2.9	1.22	−8.4
trans	220	−1.1	1.43	−5.1

Because of the inaccuracies inherent to the calculation of k_{-1}^e/k_2^e it is probable that little quantitative significance can be placed upon the values of the activation parameters reported in Table IV. However, the product ratios listed in Table III indicate that the application of any reasonable correction factor for attack of the phosphine at the β-carbon atom will not change the fact that k_{-1}^e/k_2^e is greater than unity and increases with increasing temperature. Therefore, the signs associated with the activation parameters are almost certainly correct, and certain qualitative conclusions may be drawn.

The calculated values of the activation parameters indicate that the term $T\Delta\Delta S^*$ contributes to a greater extent to $\Delta\Delta F^*$ than does $\Delta\Delta H^*$. Consequently, the partitioning of the betaine intermediate is controlled by the difference in activation entropy for the two decomposition pathways rather than by the difference in activation enthalpy. The negative values of $\Delta\Delta S^*$ demand that there be a larger gain (smaller loss) in entropy for decomposition of the betaines to ylid and aldehyde than to phosphine oxide and olefin. This is entirely reasonable if it is assumed that X represents the transition state for decomposition of the betaine to ylid and aldehyde and XI the transition state for decomposition to olefin and phosphine oxide. XI undoubtedly

X

XI
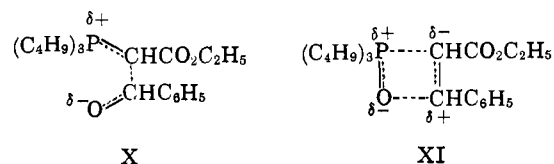
possesses a greater degree of geometrical construction than does X. Consequently, the decomposition of the betaine *via* XI would be expected to proceed with a smaller gain (larger loss) in entropy than decomposition *via* X. In view of the large negative entropies of activation observed for the reactions of stable ylids and aromatic aldehydes in benzene[1b] and because betaine decomposition *via* either of the alternate routes even-

tually furnishes two molecules from a single intermediate, it is probable that a positive entropy of activation is associated with both of the reaction paths. Therefore, $\Delta\Delta S^*$ is most likely the difference between two positive numbers.

Unfortunately, treatment of the data from the reactions of triphenylphosphine with the two glycidic esters in the same manner fails completely. Plots of $\ln k_{-1}{}^e/k_2{}^e$ vs. $1/T$ were nonlinear. At higher temperatures the values of k_{-1}/k_2 for these reactions suggest that betaine formation from ylid and aldehyde is approaching rapid reversibility. It is important to note that, in these reactions also, product ratios are probably entropy controlled since the same trends as observed with tributylphosphine are noted here.

In conclusion, a comparison of the amounts of incorporation of m-chlorobenzaldehyde for the three sets of epoxides studied shows that the amounts of incorporation increases with increasing stability of the ylid derived from decomposition of the betaine. The least incorporation product is observed with the octene oxides, the stilbene oxides are intermediate, and the glycidic esters produce the most incorporation product. This trend is entirely reasonable in terms of the stability of the ylid formed in each case; carbethoxymethylenetriphenylphosphorane is more stable than benzylidenetriphenylphosphorane which in turn is more stable than butylidenetriphenylphosphorane.

Experimental[20]

cis- and trans-4-octene,[21] as well as cis- and trans-stilbene, were purchased and shown to be pure by g.p.c. cis- and trans-ethyl cinnamate, cis- and trans-ethyl m-chlorocinnamate, and cis- and trans-m-chlorostilbene were available from previous work.[1b] All aldehydes were purchased, twice distilled, and stored cold in the presence of hydroquinone.

Butyltriphenylphosphonium bromide was prepared according to the procedure of Mechoulam and Sondheimer,[22] m.p. 241–243° (lit.[22] m.p. 242–243°).

cis- and trans-1-(m-Chlorophenyl)penetene-1. Twenty grams (0.05 mole) of butyltriphenylphosphonium bromide was suspended in 200 ml. of dry hexane under nitrogen and 0.05 mole of n-butyllithium in hexane was added dropwise. After the addition was complete, the suspension was stirred for 2 hr. and a solution of 7.0 g. (0.05 mole) of m-chlorobenzaldehyde in 50 ml. of hexane was added rapidly. The solution was stirred at room temperature for 10 hr. and filtered. The solvent was removed in vacuo and the residue was distilled to yield 3.2 g. (29%) of a colorless liquid, b.p. 125–127° (18 mm.).

Anal. Calcd. for $C_{11}H_{13}Cl$: C, 73.13; H, 7.25; Cl, 19.62. Found: C, 73.30; H, 7.12; Cl, 19.60.

Gas chromatographic and n.m.r. analysis of this liquid showed that it was a mixture of 60% trans and 40% cis olefin.

cis-4-Octene Oxide. A solution of 5.0 g. (0.045 mole) of cis-4-octene in 50 ml. of chloroform was cooled to 0° in an ice bath and a solution of 9.0 g. (0.045 mole) of m-chloroperbenzoic acid (85%)[23] in 75 ml. of chloro-

form was added, maintaining the temperature at 0° during the addition. The mixture was stirred overnight at room temperature and m-chlorobenzoic acid was removed by filtration. The chloroform solution was washed with 10% sodium bicarbonate solution and dried over anhydrous sodium sulfate, and the solvent was removed in vacuo. The residue was distilled, yielding 3.4 g. (60%) of a colorless liquid, b.p. 69° (32 mm.).

Anal. Calcd. for $C_8H_{16}O$: C, 74.95; H, 12.58. Found: C, 74.77; H, 12.44.

trans-4-Octene Oxide. This compound was prepared in 70% yield exactly as described for cis-4-octene oxide; b.p. 67° (34 mm.).

Anal. Calcd. for $C_8H_{16}O$: C, 74.95; H, 12.58. Found: C, 75.09; H, 12.54.

cis-Stilbene Oxide. This compound was prepared in 55% yield according to the procedure of Curtin,[24] substituting m-chloroperbenzoic acid for perbenzoic acid; m.p. 40–40.5 (lit. 37.0–37.5°,[24] 40°,[25] and 42°[26]).

trans-Stilbene Oxide. This compound was synthesized in 90% yield in a manner similar to that described for the cis epoxide; m.p. 68.5–69° (lit.[24] 69–69.5°).

Isolation of 3,3-Dichlorostilbene. A mixture of 5.0 g. (0.036 mole) of m-chlorobenzaldehyde and 7.0 g. (0.035 mole) of tributylphosphine was placed in a glass tube and flushed thoroughly with nitrogen, and the tube was sealed. The tube was heated at 160° for 13 days, cooled, and opened. The reaction mixture was subjected to g.p.c. analysis which showed that most of each of the reactants had disappeared with the appearance of two new peaks, one of which corresponded to tributylphosphine oxide. The mixture was chromatographed on alumina, eluting with ligroin, and a light yellow solid (1.4 g.) was isolated which, after recrystallization from ethanol–water, melted at 94–95°.

Anal. Calcd. for $C_{14}H_{10}Cl_2$: C, 67.45; H, 4.05; Cl, 28.50. Found: C, 67.16; H, 4.15; Cl, 28.65.

The g.p.c. retention time of this compound corresponded exactly to that observed for the same compound in the g.p.c. spectrum of the 4-octene oxide reaction mixtures.

1-Benzoyl-1-phenyl-2-(m-chlorophenyl)ethylene. To a solution of 27.3 g. (0.14 mole) of deoxybenzoin and 19.6 g. (0.14 mole) of m-chlorobenzaldehyde in 100 ml. of benzene was added 0.6 ml. of piperidine and the solution was refluxed for 16 hr., water being removed by azeotropic distillation during the reaction. The solution was cooled and the solvent was removed in vacuo; all attempts to crystallize the yellow oil failed. The oil was distilled, yielding 31.0 g. (70%) of a light yellow, very viscous oil, b.p. 212–215° (0.6 mm.). The infrared and n.m.r. spectra were consistent with the proposed structure.

Anal. Calcd. for $C_{21}H_{15}ClO$: C, 79.11; H, 4.74; Cl, 11.12. Found: C, 79.02; H, 4.86; Cl, 10.98.

1,2-Diphenyl-3-(m-chlorophenyl)allyl Alcohol (IX). To a solution of 1.0 g. (0.027 mole) of lithium aluminum hydride in 100 ml. of anhydrous ether was added a solution of 5.0 g. (0.016 mole) of 1-benzoyl-1-phenyl-

(20) Melting points are uncorrected.
(21) Purchased from Chemical Samples Co., Columbus 14; Ohio.
(22) R. Mechoulam and F. Sondheimer, J. Am. Chem. Soc., 80, 4386 (1958).
(23) Obtained from FMC Corp.

(24) D. Y. Curtin and D. B. Kellom, J. Am. Chem. Soc., 75, 6011 (1953).
(25) S. Boeseken and G. C. C. C. Scheider, J. prakt. Chem., 131, 285 (1931).
(26) J. Read and I. G. M. Campbell, J. Chem. Soc., 2378 (1930).

2-(m-chlorophenyl)ethylene in 50 ml. of ether at such a rate that the ether refluxed gently. The solution was stirred for 30 min. after addition, then ethyl acetate was added to decompose the excess lithium aluminum hydride. Enough 6 N hydrochloric acid was added to solubilize the aluminum salts, and the ether layer was separated, washed with 10% sodium bicarbonate solution, and dried over anhydrous magnesium sulfate. The ether was removed *in vacuo* and the oily residue was purified by chromatography on alumina to give 4.3 g. (80%) of a colorless oil which by g.p.c. was shown to be a mixture of two compounds, presumably the *cis* and *trans* olefin. The infrared and n.m.r. spectra were consistent with the proposed structure.

Anal. Calcd. for $C_{21}H_{17}ClO$: C, 78.75; H, 5.34; Cl, 11.06. Found: C, 78.76; H, 5.35; Cl, 11.01.

Attempted Isolation of IX from Reaction Mixture. The g.p.c. retention time of IX was found to be the same as that of triphenylphosphine oxide; hence the phosphine oxide from the reaction mixtures was collected from the analytical g.p.c. The collected material was chromatographed on silica gel using 50% benzene–chloroform (v./v.) for elution. Under these conditions, triphenylphosphine oxide was not eluted in control experiments while IX was eluted very well. After chromatography, the solvent was evaporated *in vacuo*, but the infrared spectrum of the residue failed to show OH absorption characteristic of IX. Characteristic absorption in the region of 11 μ was also absent; hence it was concluded that IX was not present among the reaction products.

Competition Experiments. All competition experiments of a single ylid for a pair of aldehydes were conducted in the same manner. The ylid was prepared from the phosphonium salt and butyllithium in benzene or ether, under nitrogen, in a flask containing an outlet at the bottom. After preparation, the ylid was added dropwise to a solution containing an excess of both benzaldehyde (n-butraldehyde) and m-chlorobenzaldehyde, and the solution was stirred for several hours. The solution was then analyzed by g.p.c. under conditions which will be described later. In every case, m-chlorobenzaldehyde was found to be much more reactive than benzaldehyde (n-butraldehyde).

Sealed-Tube Reactions. The sealed-tube reactions were all carried out in the same fashion and description of a typical experiment will suffice. A solution of 0.00474 mole of epoxide, 0.00474 mole of phosphine, and 0.0142 mole of m-chlorobenzaldehyde was placed in the tube and thoroughly degassed with nitrogen. The tube was then immediately sealed, placed in an oil bath whose temperature was maintained constant ($\pm 2°$) by a Thermowatch unit, and allowed to remain there for a specified period of time.[27] The contents were then analyzed by g.p.c. using an internal standard. In the reactions involving the stilbene oxides and tributylphosphine it was necessary to remove the tributylphosphine oxide before analysis by extraction of the solution with concentrated hydrochloric acid.

Chromatographic Analyses. The mixture of *cis*- and *trans*-4-octene was difficult to resolve. However, this was accomplished by using an 8-m. column of 20% Carbowax 1000 on 60–80 firebrick, maintained isothermally at 80°.[28] Even under these conditions base line resolution was not attained, and the data in Table I must be considered less precise than that for the other systems in which complete separation was achieved. After determination of the relative amounts of *cis*- and *trans*-4-octene in each mixture, the remainder of the components was determined using a 6-ft. column of 10% Silicone Rubber SE-30 on 60-80 Diatoport S.

The stilbene oxide reaction mixtures were separated and analyzed using a 6-ft. column of 10% Apiezon L on 60–80 Chromosorb W. The silicone rubber column described above was also used to some extent. The glycidic ester reactions were analyzed as described earlier.[1b]

(27) The time required to complete the reactions varied from a few hours for the glycidic esters to 2 weeks for octene oxides.
(28) Information concerning the separation of *cis*- and *trans*-4-octene, kindly supplied by Dr. George B. Butler, University of Florida, is gratefully acknowledged.