[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, MASSACHUSETTS INSTITUTE OF TECHNOLOGY]

The Infrared Spectra of Glycidic Esters

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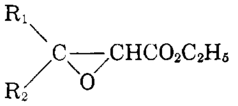
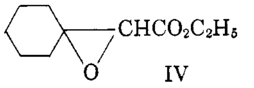
The infrared spectra of the glycidic esters I–V and ethyl tetrahydrofuroate have been found to possess two bands in the carbonyl region neither of which can be attributed to the presence of an impurity. These bands have been assigned to rotational isomers of the structures studied.

During the course of characterizing the glycidic esters I and II for isomerization studies[2] we observed that the infrared spectrum of each compound exhibited two partially resolved absorption bands in the region attributable to the stretching vibration of carbonyl functions. Concurrently, Morris and Young recorded[3] the observation of double carbonyl peaks in the infrared spectra of a series of glycidic esters which they had prepared. These workers also reported that the doublet which they observed when the spectra were determined in carbon tetrachloride solution became a single peak when the spectra were measured in solvents capable of forming hydrogen bonds (*e.g.*, chloroform). This double carbonyl peak was attributed[3] to the existence of the glycidic esters as dimers in non-polar media.

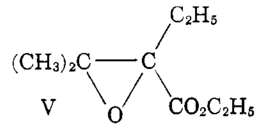
Before considering explanations for the aforementioned observations, it seemed prudent to exclude the possible presence of isomeric contaminants in the compounds studied. For this purpose we investigated the glycidic esters I-V. The infrared spectra of esters I and V were previously described.[3] The evidence for the homogeneity of compounds I and III-V is discussed in the Experimental sections of this paper and the accompanying paper.[2] However, it was apparent that the ester II was a mixture of two components, possibly diastereoisomers, which could be partially separated by fractional distillation.



I, $R_1 = H$, $R_2 = C_6H_5$
II, $R_1 = CH_3$, $R_2 = C_6H_5$
III, $R_1 = R_2 = C_6H_5$



IV

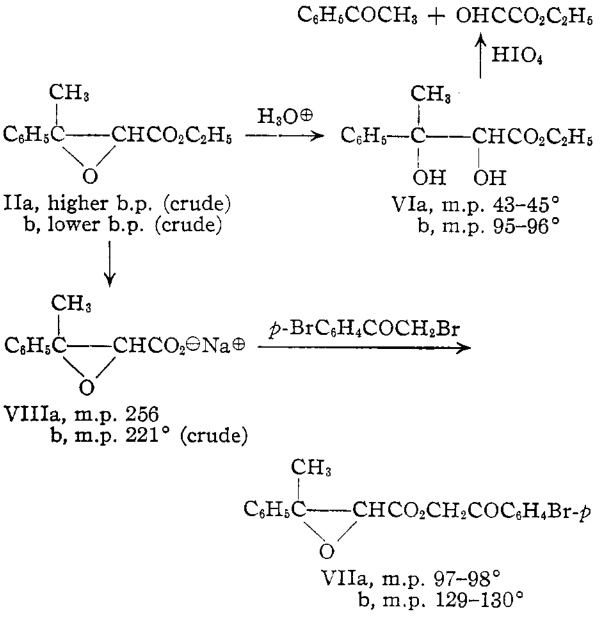


V

The sequence of transformations outlined in the accompanying equations was used to demonstrate that the two components present in the crude glycidic ester II were, in fact, diastereoisomeric. Further, the sequence established that diastereoisomer of structure II with the higher boiling point and refractive index was related to the diol VIa, m.p. 43-45°, and has the same configuration as the *p*-bromophenacyl ester VIIa, m.p. 97-98°. Unfortunately, the configurational relationship between the diols VI and the esters which are their precursors is questionable. Although the acidic hydrolysis of simple ethylene oxide derivatives is known to occur with inversion of configuration, two examples, similar to the ester II in structure, have been reported[4,5] in which the oxirane ring has been opened with retention of configuration.

The positions and relative intensities of the bands attributable to carbonyl functions in the infrared spectra[6,7] of the compounds studied are summarized in Table I. None of the spectra exhibited absorption in the 3 μ region attributable to a hydroxyl function.

As indicated earlier, the presence of two carbonyl bands in the infrared spectra of glycidic esters has been ascribed[3] to the existence of the compounds as dimers, formulated as structure IX, which permit coupling of the two carbonyl stretching vibrations. However, these authors found[3] by cryoscopic molecular weight determinations that the glycidic esters, existed as monomers, not dimers, in non-polar solvents. Furthermore, the general shapes of the two carbonyl bands were observed[3] to be independent of the concentrations of the



IIa, higher b.p. (crude)
b, lower b.p. (crude)

VIa, m.p. 43-45°
b, m.p. 95-96°

VIIIa, m.p. 256
b, m.p. 221° (crude)

VIIa, m.p. 97-98°
b, m.p. 129-130°

$$\text{VIIIa} \xrightarrow[\text{2, } C_2H_5I]{\text{1, } Ag^{\oplus}} \text{IIa (crude)} \xrightarrow{H_3O^{\oplus}} \text{VIa}$$

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[1] National Science Foundation Predoctoral Fellow, 1956-1958.

[2] H. O. House, J. W. Blaker and D. A. Madden, THIS JOURNAL, **80**, 6386 (1958).

[3] H. H. Morris and R. H. Young, Jr., *ibid.*, **79**, 3408 (1957).

[4] The reaction of the dypnone oxides with hydrogen chloride was reported by H. H. Wasserman and N. E. Aubrey, *ibid.*, **78**, 1726 (1956).

[5] The hydrolysis of the α-methylstilbene oxides with aqueous acid was reported by J. H. Brewster and J. T. Rudesill, Abstracts 133rd Meeting of the American Chemical Society, San Francisco, Calif., April 13-18, 1958, p. 8-N.

[6] Determined in carbon tetrachloride solution.

[7] Determined as 2% solutions.

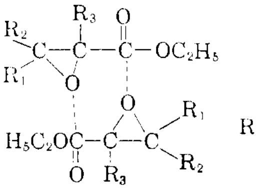
TABLE I

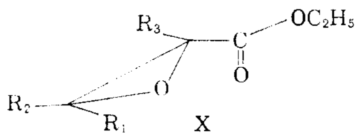
Compound	ν_1	ν_2	Optical density ratio (band 1/band 2)
I	1752	1732	1.38
II	1750	1726	1.43
III	1760	1728	0.70
IV	1751	1726	1.62
V	1750	1726	0.82
XII	1750	1730	1.16
XIII	1691[a]	1679	0.59
XIV	1691[a]	1680	0.52
XV	1691[a]	1683	0.673
XVI	1690	..	...

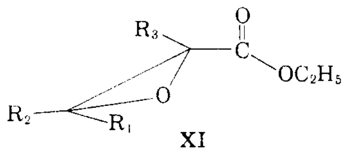
[a] This band was present as a shoulder. Consequently, both the position of the band and its optical density are subject to error.

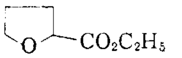
glycidic esters indicating that reversible intermolecular interactions are not responsible for the two absorption bands observed. These observations provide compelling evidence that the factor(s) responsible for the presence of two carbonyl absorption bands in the infrared spectra of glycidic esters are intramolecular in nature.

The most plausible explanation for the presence of two carbonyl absorption bands in the infrared is apparent from examining the two conformations X and XI of a glycidic ester in which the plane of the carbethoxyl group is approximately perpendicular to the plane defined by the groups R_1, R_2 and R_3. Inspection of molecular models leaves little doubt that these two conformations should be favored if steric interference between the carbethoxyl function and the group R_1 is to be minimized. Steric interference between the group R_3 and the carbethoxyl function (present in conformation X) would appear to be less important. Since the C═O and C–O dipoles are oriented in opposite directions in conformation XI, the infrared spectrum of this structure would be expected to have a normal ester carbonyl absorption band in the range 1730–1740 cm.$^{-1}$, while in conformation X, where the aforementioned dipoles are oriented in the same direction, an elevation of the carbonyl vibration frequency would be expected.[8] These considerations are exactly parallel to those employed to interpret the infrared spectra of the α-halo ketones and α-halo esters.[9]


IX



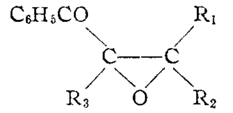

XI


XII

When the infrared spectra of glycidic esters II, IV and V in chloroform solution were examined, it was apparent that two bands were still present, the second band being a shoulder.[10] For example, the two bands in the infrared spectrum[7,11] of the ester II (a sample of the same composition as that used for the data in Table I) are found at 1742 and 1718 cm.$^{-1}$ with an optical density ratio of 1.71. The substantial increase in extinction ratio from the value (1.43) obtained in carbon tetrachloride solution suggests that the conformation X, the conformation with the higher dipole moment, is stabilized by polar solvents. Such an effect is in complete agreement with studies of the infrared spectra of α-bromocyclohexanone in various solvents previously reported.[12]

The foregoing explanation of the two carbonyl absorption peaks observed in the infrared spectra of glycidic esters is based only on the geometry of substituents bonded to the oxirane ring and presumes no special electronic effects such as three-ring hyperconjugation. To explore the validity of this presumption, the infrared spectrum[6,7] of ethyl tetrahydrofuroate (XII) was examined. This ester XII, like the glycidic esters previously discussed, would be expected to exist in two favored conformations analogous to structures X and XI. As indicated in Table I the spectrum of the ester XII does exhibit two bands in the carbonyl region.

The infrared spectra[6,7] of several α,β-epoxy ketones XIII-XVI[13] also were examined. As indicated in Table I, the spectra of three of the four ketones exhibit a shoulder on the more intense carbonyl absorption band.[14] The band separation (*ca.* 10 cm.$^{-1}$) observed in the α,β-epoxy ketone spectra is much less than the separation (*ca.* 20 cm.$^{-1}$) observed in the glycidic ester spectra. A similar trend is observed in the infrared spectra of α-halo ketones (separation *ca.* 20 cm.$^{-1}$) and α-halo esters (separation *ca.* 25 cm.$^{-1}$).[9]



XIII, $R_1 = C_6H_5$, $R_2 = H$, $R_3 = C_2H_5$
XIV, $R_1 = H$, $R_2 = C_6H_5$, $R_3 = C_2H_5$
XV, $R_1 = R_2 = H$, $R_3 = C_2H_5$
XVI, $R_1 = R_2 = H$, $R_3 = C_6H_5$

It was of interest to consider whether the relative intensities observed (Table I) for the two carbonyl bands present in the glycidic ester spectra could be related to the configurations of the compounds. Thus, if the molecule exists largely as conformation X, the ratio of the optical density of

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[8] This explanation was considered by Morris and Young (ref. 3), but rejected on the grounds that the extinction coefficients of the two observed bands were approximately equal in most cases. However, if one considers that the majority of the glycidic esters measured by these workers had small groups R_1 and R_2 (structure X) of comparable size, the observed similarity of band intensities is not surprising.

[9] For an extensive discussion with leading references see L. J. Bellamy and R. L. Williams, *J. Chem. Soc.*, 4294 (1957).

[10] Both this shoulder and the expected intensity changes subsequently discussed are evident in several of the spectra published by Morris and Young (ref. 3).

[11] Determined in chloroform solution.

[12] J. Allinger and N. L. Allinger, *Tetrahedron*, **2**, 64 (1958).

[13] The preparation and characterization of these compounds has been described previously [H. O. House, D. J. Reif and R. L. Wasson, THIS JOURNAL, **79**, 2490 (1957); H. O. House and D. J. Reif, *ibid.*, **79**, 6491 (1957)].

[14] We are indebted to Professor Norman H. Cromwell for calling our attention to the presence of this shoulder.

the higher frequency band to the optical density of the lower frequency band would be expected to be greater than one. Conversely, the ratio should be less than one if the conformation XI predominates. Since the molecular extinctions of the two conformers are not known, the concentrations of the two conformers are not necessarily equal when this ratio has a value of one.[15] Among the factors which might be expected to influence the proportions of the conformations X and XI present in solutions of various glycidic esters in a common solvent, the steric interactions between the carbethoxyl group and the groups R_3 and, especially, R_1 would be expected to be one of the most important. Thus, if the group R_1 is large, the conformation XI, which minimizes steric interaction between the carbethoxyl group and the group R_1, should be favored and the optical density ratio should be less than one.

Inspection of Table I illustrates the qualitative correctness of this idea. For example, the ester III in which the group R_1 of conformations X and XI is a phenyl group has an optical density ratio of 0.70. With esters V and IV, in which the group R_1 becomes progressively smaller, the optical density ratio increases as expected. Similarly, the ester I, believed to have the *trans* configuration,[2] has an optical density ratio in accord with this configurational assignment. The optical density ratios for various fractions from the distillation of the mixture of diastereoisomers of ester II increase in value (from 0.80 to 1.75) as the boiling point and refractive index of the fractions increases. This observation suggests that the diastereoisomer of the ester II with the higher boiling point and refractive index has the *trans* configuration.

An observation made during the course of the saponification of the glycidic ester II provides a reason for the presence of impurities frequently present in the products obtained by decarboxylation of glycidic esters. After an aqueous solution of the sodium salt VIII had been heated to 80° for 1 hr., it was possible to isolate 12% of acetophenone from the reaction mixture. This ketone, presumably formed by hydrolysis of the oxirane ring and a subsequent retrograde aldol condensation, was clearly not present in the original sodium salt VIII. This observation suggested than any procedure which involves heating a glycidic ester with aqueous alkali[16] as part of the degradation of the glycidic ester to a carbonyl compound would be undesirable. Thus, following the procedure previously described,[16] a sample of the glycidic ester II was converted to crude α-phenylpropionaldehyde. The product obtained in this way was found to contain 32% acetophenone. By altering the procedure (see Experimental section) to avoid heating the ester II, its sodium salt VIII or the free acid with water, the α-phenylpropionaldehyde produced contained less than 2% of acetophenone.

Experimental[17]

Ethyl β,β-Pentamethyleneglycidate (IV).—This glycidic ester, b.p. 105° (4.5 mm.), $n^{27}_{\rm D}$ 1.4570 [lit.[18] b.p. 134–137° (21 mm.), $n^{25}_{\rm D}$ 1.4568–1.4577], was prepared as previously described.[18] The ultraviolet spectrum of the product has only slight end absorption with an extinction of 185 at 210 mμ. The nuclear magnetic resonance spectrum[19,20] exhibits a quadruplet (center at −26 sec.$^{-1}$) and a triplet (center at −143 sec.$^{-1}$) attributable to an ethoxyl function, a singlet at −63 sec.$^{-1}$ (hydrogen atom bonded to oxirane ring) and a broad, partially-resolved band with its center at −185 sec.$^{-1}$ (CH_2 groups of cyclohexane ring). The vapor-phase chromatogram (di-2-ethylhexyl sebacate packing) had only a single major peak.

Ethyl β,β-Dimethyl-α-ethylglycidate (V).—This glycidic ester, b.p. 69° (5 mm.), $n^{28}_{\rm D}$ 1.4232 [lit.[21] b.p. 74° (4 mm.), $n^{20}_{\rm D}$ 1.4252], was prepared as previously described.[21] The ultraviolet spectrum of the ester exhibits only end absorption, the extinction being 300 at 212 mμ. The vapor-phase chromatograms (di-2-ethylhexyl sebacate or polyethylene glycol packing) of samples of the product have single major peaks. After a sample of the ester had been stirred with 10% aqueous sodium hydroxide at room temperature for 2 hr., the infrared spectrum of the recovered ester (87% recovery) was identical with the spectrum of the starting material. The nuclear magnetic resonance spectrum[19,20] has no absorption attributable to ethylenic hydrogen atoms and exhibits a quadruplet in the range −16 to −39 sec.$^{-1}$ (CH_2 of an ethoxyl group) as well as a series of partially resolved bands in the region −137 to −160 sec.$^{-1}$. The lack of resolution of this latter group of bands prevented us from making assignments.

Ethyl β,β-Diphenylglycidate (III).—This glycidic ester, m.p. 48–49° (lit.[22] 48–49°), was prepared as previously described[22] except that sodium hydride was used as the base. The ultraviolet spectrum of the product has a series of weak bands in the region 250–270 mμ (non-conjugated phenyl group), maximum at 258 mμ (ε 470).

Ethyl Tetrahydrofuroate (XII).—Hydrogenation of ethyl furoate in the presence of platinum oxide at room temperature and atmospheric pressure afforded the tetrahydro ester, b.p. 51° (1 mm.), $n^{29}_{\rm D}$ 1.4310 [lit.[23] 82° (11 mm.), $n^{18}_{\rm D}$ 1.4455]. Fractional distillation of the product through an 18-in. spinning band column gave fractions boiling at 65° (1 mm.), $n^{29}_{\rm D}$ 1.4306–1.4309. The infrared spectrum[6] of the product lacks absorption at 1585 cm.$^{-1}$ characteristic of ethyl furoate (see also Table I) and lacks absorption in the 3 μ region attributable to a hydroxyl function. The ultraviolet spectrum of the product exhibits only weak end absorption.

A 0.5-g. sample of the ester was stirred with excess 28% aqueous ammonium hydroxide for 18 hr. The reaction mixture was extracted with ether and the extract was dried and concentrated. The amide of tetrahydrofuroic acid separated from the ether as white plates, m.p. 78–79° (lit.[24] 80°), yield 0.25 g. (60%). The infrared spectrum[11] of the amide has a series of bands in the region 3500–3200 cm.$^{-1}$ (N–H stretching) as well as a broad band at 1670 cm.$^{-1}$ (amide C=O) and a band at 1595 cm.$^{-1}$ (NH_2 deformation).

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[15] A study of the infrared spectra of α-bromo keto steroids by R. N. Jones, D. A. Ramsay, F. Herling and K. Dobriner, [THIS JOURNAL, **74**, 2828 (1952)] suggests that the molecular extinction of conformation X should have a slightly lower value than the molecular extinction of conformation XI.

[16] M. S. Newman and B. J. Magerlein, *Org. Reactions*, **5**, 413 (1949); M. S. Newman and R. D. Closson, THIS JOURNAL, **66**, 1553 (1944).

[17] All melting points are corrected and all boiling points are uncorrected. The ultraviolet spectra were determined in 95% ethanol with a Cary recording spectrophotometer, model 11 MS. The infrared were determined either with a Perkin–Elmer, model 21, or with a Baird, model B, infrared recording spectrophotometer fitted with either a sodium chloride or a calcium fluoride prism. The microanalyses were performed by Dr. S. M. Nagy and his associates.

[18] W. S. Johnson, J. S. Belew, L. J. Chinn and R. H. Hunt, THIS JOURNAL, **75**, 4995 (1953); R. H. Hunt, L. J. Chinn and W. S. Johnson, *Org. Syntheses*, **34**, 54 (1954).

[19] Determined as a pure liquid.

[20] Determined with a Varian Associates high-resolution nuclear magnetic resonance spectrometer, model V4300B. The radio signal used had a frequency of 40 mc. The peak positions are expressed as cycles per second relative to the proton resonance of water, a positive shift denoting a shift in the direction of increasing resonance frequency at constant magnetic field strength.

[21] H. H. Morris and R. H. Young, Jr., THIS JOURNAL, **77**, 6678 (1955).

[22] F. F. Blicke and J. A. Faust, *ibid.*, **76**, 3156 (1954).

[23] W. E. Kaufmann and R. Adams, *ibid.*, **45**, 3029 (1923).

[24] H. Wienhaus and H. Sorge, *Ber.*, **46**, 1927 (1913).

Ethyl β-Methyl-β-phenylglycidate (II).—A sample of this ester, b.p. 138° (6 mm.), $n^{27}\text{D}$ 1.5027, whose preparation was described elsewhere,[3] was used to obtain the data for Table I. The ultraviolet spectrum exhibits end absorption and a series of weak bands [*e.g.*, λ 258 mμ (ε 200)] in the region 250–270 mμ (non-conjugated phenyl group). The nuclear magnetic resonance spectrum[19,20] of the product has no peaks attributable to hydrogen atoms bonded to non-aromatic double bands. The spectrum has a broad peak with its center at +74 sec.$^{-1}$ (aromatic C–H) plus a series peaks which can be assigned to the two diastereoisomeric forms of structure II in the following way. A triplet with its center at −129 sec.$^{-1}$ (CH_3 adj. to CH_2), a singlet at −112 sec.$^{-1}$ (CH_3 bonded to oxirane ring) and a singlet at −56 sec.$^{-1}$ (hydrogen atom bonded to oxirane ring) may be assigned to the diastereoisomer with the higher boiling point and refractive index. Similarly, a triplet with its center −144 sec.$^{-1}$, a singlet at −105 sec.$^{-1}$ and a singlet at −47 sec.$^{-1}$ may be assigned to the diastereoisomer with lower boiling point and refractive index. In addition, a series peaks present in the region −20 to −52 sec.$^{-1}$ can be attributed to the methylene groups of the ethoxyl functions in the two diastereoisomers. The band intensity changes observed in the nuclear magnetic resonance spectrum of a later fraction, $n^{27}\text{D}$ 1.5077, from the fractional distillation of the crude glycidic ester II are in accord with the above assignments. The relative intensities of the bands at 1751 and 1726 cm.$^{-1}$ in the infrared spectra of the various glycidic ester fractions were also observed to change. In the fractions of lower boiling point and refractive index the band at 1726 cm.$^{-1}$ was the more intense while the reverse was true with fractions of higher boiling point and refractive index.

The glycidic ester II did not react with a solution of bromine in carbon tetrachloride, gave no color with ethanolic ferric chloride, gave a negative Beilstein test for halogen and gave no precipitate with 2,4-dinitrophenylhydrazine reagent. A sample of the glycidic ester II was prepared by reaction of ethyl 2-chloro-3-hydroxy-3-phenylbutyrate, b.p. 124° (2 mm.) [lit.[25] 166–167° (5 mm.)], with one equivalent of potassium *t*-butoxide in *t*-butyl alcohol. The infrared spectrum of resulting product, b.p. 118° (2.5 mm.), $n^{31}\text{D}$ 1.5031, is identical with the spectrum of a sample of the ester prepared by the condensation of acetophenone with ethyl chloroacetate.

Ethyl 2,3-Dihydroxy-3-phenylbutyrate (VI).—A mixture of 10 g. (0.05 mole) of ethyl β-methyl-β-phenylglycidate, $n^{27}\text{D}$ 1.5027, and 50 ml. of 30% aqueous sulfuric acid, previously cooled to 10°, was stirred for 20 min. and then extracted with three 50-ml. portions of ether. The combined extracts were washed with saturated, aqueous sodium bicarbonate, dried over magnesium sulfate and concentrated. Distillation of the residue afforded 7.62 g. of colorless liquid which was taken up in a petroleum ether–ether mixture. A series of fractional crystallizations separated 2.65 g. (26%) of the higher-melting diol as colorless needles, m.p. 95–96°. The infrared spectrum[26] has bands at 3520 cm.$^{-1}$ (associated O–H) and 1725 cm.$^{-1}$ (ester C=O); the ultraviolet spectrum has end absorption and series of weak bands [*e.g.* 257 mμ (ε 135)] in the region 250–270 mμ (non-conjugated phenyl group).

Anal. Calcd. for $C_{12}H_{16}O_4$: C, 64.28; H, 7.18. Found: C, 64.05; H, 7.34.

The mother liquors from the above crystallization afforded 3.87 g. (38%) of a lower-melting diol as colorless prisms, m.p. 43–45°. The infrared spectrum[26] of this product has a band at 3520 cm.$^{-1}$ (associated O–H) with a shoulder at 3580 cm.$^{-1}$ (unassociated O–H) as well as a band at 1725 cm.$^{-1}$ (ester C=O); the ultraviolet spectrum is essentially identical with the spectrum of the higher-melting diol.

Anal. Calcd. for $C_{12}H_{16}O_4$: C, 64.28; H, 7.18. Found: C, 64.17; H, 7.21.

Distillation of the residues from the mother liquor of the above crystallizations gave 1.1 g. of liquid which has an infrared spectrum comparable to the spectra of the pure diols. Cleavage of a portion of this oil with periodate as subsequently described gave derivatives of acetophenone (74% yield) and ethyl glyoxylate (47% yield).

An analogous reaction with one of the later fractions, $n^{27}\text{D}$ 1.5077, from the distillation of the glycidic ester II gave the diol, m.p. 95–96°, in 9% yield and the diol, m.p. 43–45°, in 49% yield. Similarly, hydrolysis of one of the earlier fractions, $n^{28}\text{D}$ 1.4987, gave the diol, m.p. 95–96°, in 46% yield and the diol, m.p. 43–45°, in 3% yield.

Periodate Cleavage of Ethyl 2,3-Dihydroxy-3-phenylbutyrate (VI).—A mixture of 224 mg. (0.001 mole) of the diol, m.p. 95–96°, and 228 mg. (0.001 mole) of periodic acid in 10 ml. of water plus sufficient dioxane to effect solution of the reactants was stirred for 1 hr. and then treated with 1 g. of barium carbonate. The mixture was filtered into a solution of 396 mg. (0.002 mole) of 2,4-dinitrophenylhydrazine and 0.1 ml. of concentrated hydrochloric acid in 50 ml. of boiling ethanol. The solution was boiled and filtered while hot to separate 240 mg. (80%) of acetophenone 2,4-dinitrophenylhydrazone, m.p. 245–246°. The cold filtrate deposited 150 mg. (54%) of ethyl glyoxylate 2,4-dinitrophenylhydrazone, m.p. 123–124°. Similarly, 224 mg. (0.001 mole) of the diol, m.p. 43–45°, gave 230 mg. (77%) of acetophenone 2,4-dinitrophenylhydrazone and 120 mg. (43%) of ethyl glyoxylate 2,4-dinitrophenylhydrazone. In all cases the products were shown to be identical with authentic samples by mixed melting-point determinations and comparison of infrared spectra.

An authentic sample of ethyl glyoxylate 2,4-dinitrophenylhydrazone was obtained by the cleavage of 206 mg. (0.001 mole) of diethyl tartrate with periodic acid as previously described. The pure derivative crystallized from an ether-petroleum ether mixture as orange needles, m.p. 124–125° (lit.[27] 124°). The infrared spectrum[11] of the derivative has a broad band at 1725 cm.$^{-1}$ (ester C=O).

Sodium β-Methyl-β-phenylglycidate.—The reaction of 20.6 g. (0.1 mole) of ethyl β-methyl-β-phenylglycidate with sodium ethoxide, prepared from 30 ml. of ethanol and 2.3 g. (0.1 gram-atom) of sodium, and 1.8 g. (0.1 mole) of water by the procedure previously described[28] except that a reaction time of only 30 min. was employed yielded 19.9 g. (99%) of the crude sodium salt, m.p. 221° dec. The infrared spectrum[29] has a broad band at 1615 cm.$^{-1}$ (carboxylate anion) and no other band in the 6 μ region attributable to a carbonyl function. Fractional crystallization of the sodium salt from aqueous ethanol afforded one diastereoisomer of the sodium salt as white prisms, m.p. 256° dec. (lit.[28] 255–256° dec.), yield 4.5 g. (23%). Evaporation of the mother liquor under reduced pressure left the second crude diastereoisomer, m.p. 221–224° dec. The infrared spectra[29] of both fractions exhibit a 1610 cm.$^{-1}$ (carboxylate anion) and no other band in the 6 μ region attributable to a carbonyl function. The infrared spectra of the two fractions differ in the fingerprint region. In particular, the less soluble salt, m.p. 256 dec.°, has bands at 935 and 855 cm.$^{-1}$ which are present only as very weak bands in the spectrum of the crude, more soluble salt, m.p. 221–224° dec.

A mixture of 1 g. (0.005 mole) of less soluble sodium salt, m.p. 256 dec., and 1.39 g. (0.005 mole) of *p*-bromophenacyl bromide in 15 ml. of water plus sufficient ethanol to effect solution was boiled under reflux for 1 hr. The cold solution deposited 1.40 g. (78%) of the crude *p*-bromophenacyl ester, m.p. 75–90°. Recrystallization from ethanol gave 0.70 g. (40%) of the pure **p-bromophenacyl ester of β-methyl-β-phenylglycidic acid** as colorless plates, m.p. 97–98°. The infrared spectrum[6] of the ester has bands at 1765 cm.$^{-1}$ with a shoulder at 1750 cm.$^{-1}$ (ester C=O) and at 1710 cm.$^{-1}$ (conj. C=O) and no bands in the 3 μ region attributable to a hydroxyl function.

Anal. Calcd. for $C_{18}H_{15}BrO_4$: C, 57.61; H, 4.02; Br, 21.30. Found: C, 57.38; H, 4.15; Br, 21.26.

Reaction of 1 g. (0.005 mole) of the crude, more soluble sodium salt, m.p. 221–224° dec., with *p*-bromophenacyl bromide as previously described yielded the **p-bromophenacyl ester of β-methyl-β-phenylglycidic acid** as colorless needles from ethanol, m.p. 129–130°, yield 0.90 g. (47%). The infrared spectrum[6] has bands at 1765 cm.$^{-1}$ with a shoulder at 1750 cm.$^{-1}$ (ester C=O) and at 1710 cm.$^{-1}$ (conj. C=O) and has no band in the 3 μ region attributable to a hydroxyl function.

Anal. Calcd. for $C_{18}H_{15}BrO_4$: C, 57.61; H, 4.02; Br, 21.30. Found: C, 57.43; H, 4.10; Br, 21.12.

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[25] G. Darzens, *Compt. rend.*, **203**, 1374 (1936).

[26] Measured as a 2% solution in carbon tetrachloride with both sodium chloride and calcium fluoride optics.

[27] C. W. Crane, J. Forrest, O. Stephenson and W. A. Waters, *J. Chem. Soc.*, 827 (1946).

[28] C. F. H. Allen and J. Van Allan, "Organic Syntheses," Coll. Vol. 3, John Wiley and Sons, Inc., New York, N. Y., 1955, p. 723.

[29] Determined as a suspension in a potassium bromide pellet.

A solution of 10 g. (0.05 mole) of crude sodium β-methyl-β-phenylglycidate in 50 ml. of water, cooled to 0°, was made just acid to litmus with cold, 10% aqueous sulfuric acid. The resulting mixture was extracted with four 10-ml. portions of ether and the combined extracts were washed with water, dried over magnesium sulfate and concentrated. Distillation of the residue afforded 3.90 g. (59%) of α-phenylpropionaldehyde, b.p. 60° (1 mm.), n^{29}D 1.5138 [lit.[28] 73-76° (4 mm.)]. The 2,4-dinitrophenylhydrazone of the product crystallized from a methanol-ethyl acetate mixture as yellow prisms, m.p. 137-138° (lit.[30] 136-137°). The vapor-phase chromatogram of the aldehyde indicated the presence of less than 2% acetophenone. The infrared spectrum[11] of the aldehyde has bands at 2710 and 2815 cm.$^{-1}$ (C-H of aldehyde) and at 1720 (C=O) as well as a very weak band at 1682 cm.$^{-1}$ (conj. C=O of acetophenone).

A sample of the aldehyde, b.p. 89-95° (11 mm.), n^{29}D 1.5160, was prepared in 48% yield by the procedure of Newman and Closson.[16] The vapor-phase chromatogram of the crude product indicated the presence of 32% of acetophenone. The infrared spectrum[6] of the crude product had the same peaks present in the spectrum of the aldehyde sample previously described. However, the band at 1682 cm.$^{-1}$ (conj. C=O of acetophenone) was much more intense.

A solution (pH ~ 9) of 1 g. (0.005 mole) of crude sodium β-methyl-β-phenylglycidate in 10 ml. of water was heated to 80° for 1 hr., cooled and extracted with ether. The extract was dried, concentrated and treated with 2,4-dinitrophenylhydrazine in boiling ethanol. The cold, ethanolic solution deposited 0.16 g. (12%) of acetophenone 2,4-dinitrophenylhydrazone, m.p. 246-247°, identified by a mixed melting point determination with an authentic sample. Reaction of the aqueous layer with p-bromophenacyl bromide yielded the p-bromophenacyl ester of β-methyl-β-phenylglycidic acid, m.p. 128.5-130°, previously described, yield 0.80 g. (42%).

A 0.50-g. (0.0025 mole) sample of the less soluble sodium β-methyl-β-phenylglycidate, m.p. 256° dec., was converted to the crude, insoluble silver salt, m.p. 154-155° dec., by treatment with aqueous silver nitrate. The crude silver salt was stirred with excess ethyl iodide at room temperature for 30 min. The resulting mixture was diluted with ether and filtered. After the filtrate had been dried over magnesium sulfate and concentrated, the infrared spectrum[6] of the crude residue (350 mg.) was examined. The spectrum has all of the bands present in the spectrum of the original glycidic ester plus a new, strong band at 915 cm.$^{-1}$. The ultraviolet spectrum of the crude residue has a maximum at 239 mμ (ε 4200). Since attempts to separate the components of the crude re-esterified product by fractional distillation resulted in decomposition of the entire sample, a 300-mg. portion of the crude product was hydrolyzed with aqueous sulfuric acid as previously described. The only crystalline product which could be isolated was the lower-melting isomer of ethyl 2,3-dihydroxy-3-phenylbutyrate, m.p. 42.5-44°, yield 55 mg., which was identified by a mixed melting point determination with the diol sample previously described.

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[30] F. Ramirez and A. F. Kirby, THIS JOURNAL, **75**, 6026 (1953).

[CONTRIBUTION FROM THE ROHM & HAAS CO., REDSTONE ARSENAL RESEARCH DIVISION]

A Re-examination of the Peroxyacid Cleavage of Ketones. I. Relative Migratory Aptitudes

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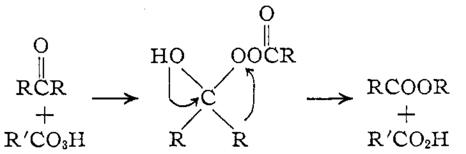
Relative migratory aptitudes of various groups in the cleavage of unsymmetrical ketones with trifluoroperoxyacetic acid have been measured. The results are compared with those of similar studies with other peroxyacids. Among alkyl groups, the usual sequence prim. < sec. < tert. is observed. The 1-apocamphyl group has nearly as high a migratory aptitude as does t-butyl. Among aryl groups, migratory aptitude is decreased by electron-attracting substituents on the aromatic nucleus. Migration aptitudes are significantly different in the reactions of ketones with trifluoroperoxyacetic acid and with peroxyacetic acid; the latter reagent is the more selective of the pair. Mechanistic implications are discussed.

The mechanism of the oxidation of ketones to esters by peroxyacids[2] has received considerable study during recent years. Criegee[3] proposed the mechanism shown in eq. 1. The intermediate, A, will be referred to as the "Criegee intermediate."



A

(1)

Friess[4] and co-workers studied the kinetics of the reaction of various ketones with peroxybenzoic acid and concluded that the reaction was general acid catalyzed and that formation of A was the rate-determining step.

Turner[5] and Mislow and Brenner[6] proved that optically active alkyl groups migrated with complete retention of configuration. The product-determining step of the Baeyer-Villiger reaction thus appears to be related to the well known Lossen,[7] Curtius[8] and Schmidt[9] reactions as the Criegee mechanism would predict.

Doering and Speers[10] carried out a thorough product study of the reaction of unsymmetrical ketones with peroxyacetic acid. From this work and also from the work of Friess[11] it was concluded that the order of increasing migratory aptitudes of alkyl groups is generally prim. < sec. < tert. Similarly, it was shown[10] that aryl groups with electron-releasing substituents displayed enhanced migratory ability.

More recently, Doering and Dorfman[12] have shown, by O^{18}-labeling of the ketone carbonyl, that the oxygen of the carbonyl group of the ester formed in the reaction comes from the ketone. This extremely important result at once ruled out

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[1] Presented at the Sixth Reaction Mechanisms Conference, Swarthmore, Pa., September, 1956.

[2] This general reaction will be referred to as the Baeyer-Villiger reaction throughout this and the succeeding papers of this series [A. v. Baeyer and V. Villiger, *Ber.*, **32**, 3625 (1899)].

[3] R. Criegee, *Ann.*, **560**, 127 (1948).

[4] S. L. Friess and A. H. Soloway, THIS JOURNAL, **73**, 3968 (1951).

[5] R. B. Turner, *ibid.*, **72**, 878 (1952).

[6] K. Mislow and J. Brenner, *ibid.*, **75**, 2318 (1953).

[7] E. S. Wallis and R. D. Dripps, *ibid.*, **55**, 1701 (1933).

[8] L. W. Jones and E. S. Wallis, *ibid.*, **48**, 169 (1926).

[9] J. V. Brown and E. Friehmelt, *Ber.*, **66**, 684 (1933).

[10] W. v. E. Doering and L. Speers, THIS JOURNAL, **72**, 5515 (1950).

[11] S. L. Friess and N. Farnham, *ibid.*, **72**, 5518 (1950).

[12] W. v. E. Doering and E. Dorfman, *ibid.*, **75**, 5595 (1953).