Perchloric Acid Isomerization of Oleic Acid

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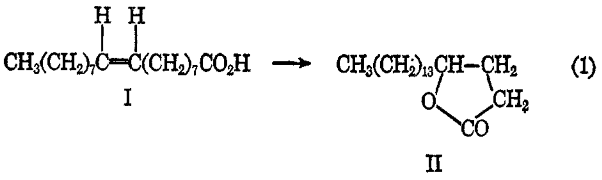
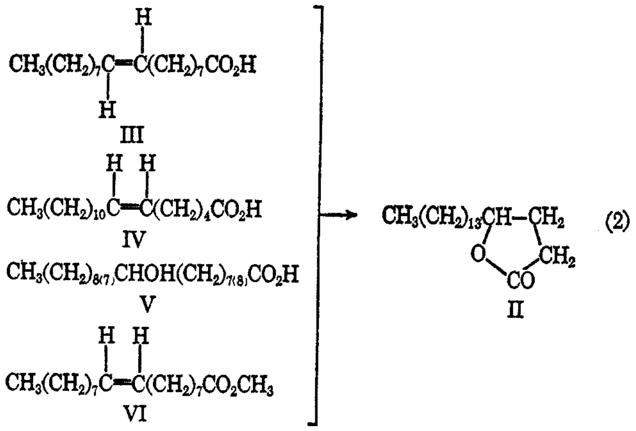
γ-Stearolactone was prepared from oleic acid using 70% perchloric acid in place of the concentrated sulfuric acid customarily used. Improved yields were obtained and the crude reaction product was easier to purify. Isomerization, addition, and polymerization reactions were all found to be important in this process. The procedure is applicable to other olefinic acids, monohydroxy acids, and the methyl esters of olefinic acids. δ-Stearolactone and di- and triestolides were the important intermediates in the production of γ-stearolactone. Other compounds isolated from the final product were the cyclic ketones, 2-tridecyl-2-cyclopentenone and 2-dodecyl-2-cyclohexenone, methyl branched C_{18} γ-lactones, produced by isomerization of the hydrocarbon chain prior to lactone formation, and δ-stearolactone.

The sulfuric acid catalyzed isomerization of oleic acid, I, to 4-tetradecyl-5-butyrolactone (γ-stearolactone), II, shown in eq 1 was first discovered by Zhukov and Shestakov in 1903,[2a] and was later studied in 1924.[2b] Although the yield is low and the isolation procedure laborious, this has remained the simplest and most direct route to γ-stearolactone. More recently, the reaction, using shorter chain monounsaturated acids as starting materials, has been restudied by Ansell and Palmer.[3,4]



Our studies show that 70% perchloric acid is superior to sulfuric and methanesulfonic acids in the isomerization of oleic acid; higher yields of γ-stearolactone are obtained and the recovery of the pure γ-lactone from the crude reaction product is much easier. Preliminary studies indicate that other C_{18}-monounsaturated acids can be readily converted into γ-lactone. Examples are elaidic acid (III) and petroselinic acid (IV, *cis*-6-octadecenoic acid). The hydration product of oleic acid, 9(10)-monohydroxystearic acid (V), yields the lactone smoothly, as does methyl oleate (VI) (eq 2). Yields of γ-stearolactone under optimum isomerization conditions are essentially identical for elaidic, petroselinic, and 9(10)-monohydroxystearic acid; the yield from methyl oleate is lower because of the slow hydrolysis of the methyl ester under the reaction conditions.



Perchloric acid–oleic acid mixtures were heterogeneous under all the conditions studied in this work. Optimum conditions for the production of γ-stearolactone were determined by studying the reaction variables: temperature, perchloric acid–oleic acid mole ratio, perchloric acid concentration, rate of stirring, and reaction time.

Effect of Temperature.—At 30° (24 hr, 1:1 perchloric–oleic acid mole ratio), little γ-lactone (0.8%) was formed; the crude reaction product consisted essentially of estolides. The effect of varying the temperature (24 hr, 1:1 perchloric–oleic acid mole ratio) is illustrated in Figure 1. L, E, and A in Figure 1 stand, respectively, for the characteristic γ-lactone band at 1780, ester band at 1740, and acid band at 1710 cm^{-1}.[5] Figure 1 illustrates the decrease in γ-lactone yield with increasing temperature, the γ-lactone having essentially disappeared at 115°. The highest yield of γ-lactone was obtained at 85°, the order being 85 > 100 > 115°.

Effect of Reaction Time.—Maximum yields (decreasing order for 1:1 perchloric–oleic acid mole ratio) are 85°, 10 hr; 100°, 3 hr; 115°, 1 hr. The yield of γ-stearolactone as a function of the reaction time is shown in Figure 2.

Effect of Perchloric Acid–Oleic Acid Mole Ratio.—In the reaction mixture, the organic and inorganic layers are saturated with respect to one another. A 1:1 mole ratio of perchloric acid to oleic acid was found suitable for studies of the optimum synthetic conditions. The importance of the perchloric acid–oleic acid mole ratio is illustrated in Figure 3.

The 1:100 mole ratio produces estolide but no γ-lactone; with the 1:10 ratio, γ-lactone is produced and the intermediate estolide decreases. In the 1:1 mole ratio the estolide completely disappears and degradation reactions now become important. Since the 1:1 mole ratio gives acceptable yields, it was felt that use of higher mole ratios needlessly increases the potential hazard inherent in the use of perchloric acid. Safety shields should be used even at the 1:1 mole ratio.[6]

Effect of Stirring.—Because oleic acid and aqueous 70% perchloric acid are immiscible throughout the

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(2) (a) A. A. Zhukov and P. I. Shestakov, *J. Russ. Phys. Chem. Soc.*, **35**, 1 (1903); *ibid.*, **40**, 830 (1908); (b) P. W. Clutterbuck, *J. Chem. Soc.*, **125**, 2330 (1924).

(3) M. F. Ansell and M. H. Palmer, *J. Chem. Soc.*, 2640 (1963).

(4) M. F. Ansell and M. H. Palmer, *Quart. Rev.* (London), **18**, 211 (1964).

(5) L. J. Bellamy, "The Infrared Spectra of Complex Molecules," 2nd ed, John Wiley and Sons, Inc., New York, N. Y., 1958.

(6) E. Levens in "Perchlorates, Their Properties, Manufacture, and Uses," J. C. Shumacher, Ed., Reinhold Publishing Corp., New York, N. Y., 1960, Chapter 11.

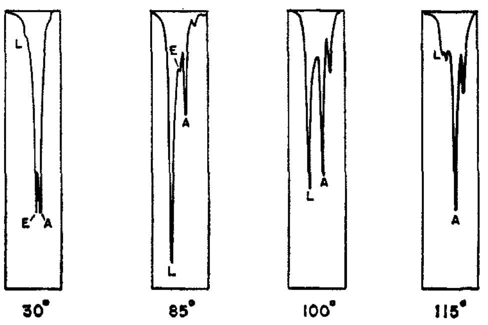


Figure 1.—The effect of temperature on the yield of γ-stearolactone in a 24-hr, 1:1 mole ratio reaction.

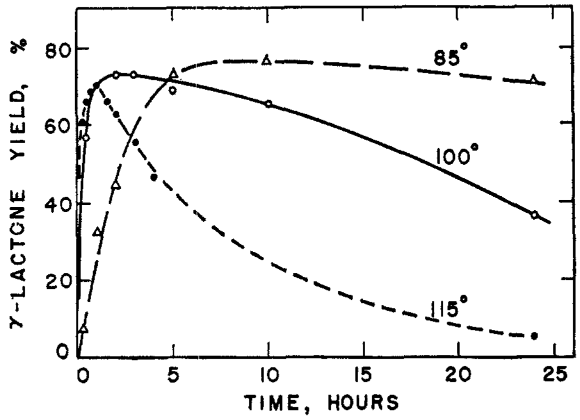


Figure 2.—The effect of reaction time on the yield of γ-stearolactone at three temperatures (1:1 mole ratio).

range of $HClO_4$–oleic acid mole ratios from 1:1 to 1:100, the rate of reaction will be influenced by the rate of stirring. The difference in behavior (85°, 5 hr, 1:1 mole ratio) between the stirred and nonstirred system is shown in Figure 4. The difference indicates that the extent of reaction is limited by the rate of diffusion of a reactant across the interface to the bulk of one of the two phases and does not occur principally at the interface, or reaction is occurring at the interface but does not have adequate surface area.

To distinguish between these possibilities, the reaction was carried out with the more intense mixing provided by a Vibromixer. No increase either in rate or yield was observed over that stirred with a magnetic stirrer. This strongly suggests that the reaction occurs in the bulk of one of the two phases. Furthermore, a reaction mixture containing only a catalytic amount of $HClO_4$ (1:100 mole ratio, 5 hr, 85°), mixed by the Vibromixer, showed substantially no reaction.

These facts, along with the knowledge that the extent of the reaction is influenced by the perchloric acid–oleic acid mole ratio, indicate that the principal reaction occurs in the perchloric acid phase; the reaction at the interface does not make any significant contribution.

Interactions of Variables.—Experimental conditions chosen finally as most satisfactory for a laboratory procedure represented a compromise among all the possible interactions. These are 100° for 3 hr with a 1:1 perchloric–oleic acid mole ratio.

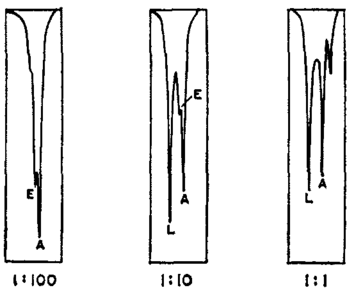


Figure 3.—The effect of perchloric–oleic acid mole ratio in 24-hr reactions at 100°.

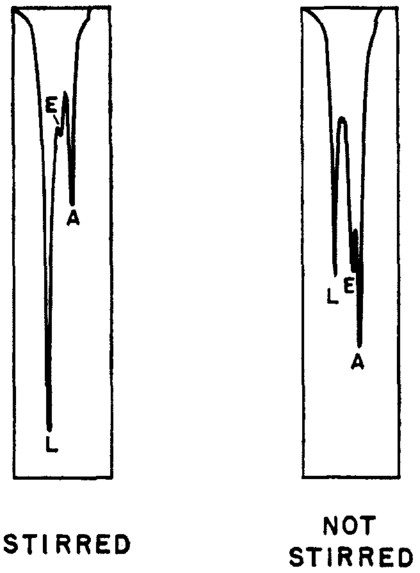


Figure 4.—The effect of stirring on γ-stearolactone yield in 5-hr, 1:1 mole ratio reactions at 85°.

Intermediates.—The intermediates in the perchloric acid catalyzed isomerization were studied by isolating and identifying the products formed during a 1-hr reaction at 85° with a 1:1 perchloric acid–oleic acid mole ratio; this reaction time is considerably less than required for maximum conversion to γ-stearolactone. The analytical data (expressed in milliequivalents per gram) show the extent of reaction at 1 and at 10 hr, respectively: acid equivalent 1.38 and 0.56; hydrogenation equivalent 1.13 and 0.39; ester equivalent 1.70 and 3.48.[7]

The relatively large ester value after 10 hr, coupled with the extensive consumption of carboxyl and olefin functions, indicates a high conversion into lactone. In the 1-hr reaction, however, the ester value is lower, and the acid and hydrogenation values higher, indicating only a partial conversion into final product, γ-lactone. The infrared spectrum of the 1-hr reaction product has a characteristic absorption at 968 cm^{-1} due to *trans*-1,2-disubstituted olefins.

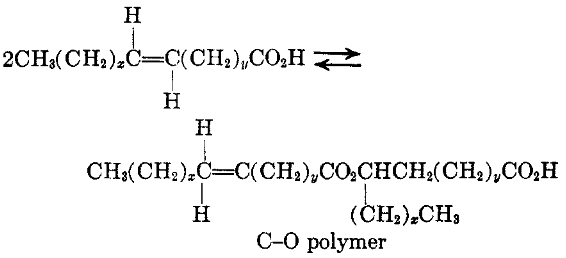
The 1-hr reaction product was methylated with freshly prepared diazomethane and separated into five major components, by partitioning in a Craig countercurrent distribution apparatus; a total of 700 transfers was performed by the single withdrawal procedure. Figure 5 shows a plot of weight against transfer number for the distribution.

Compounds corresponding to peaks A, C, D, and E are methyl esters of carboxylic acids present in the original reaction mixture; peak B corresponds to neutral materials.

Fraction A (1.1%) is a complex mixture of methyl esters of monomeric and polymeric monohydroxycar-

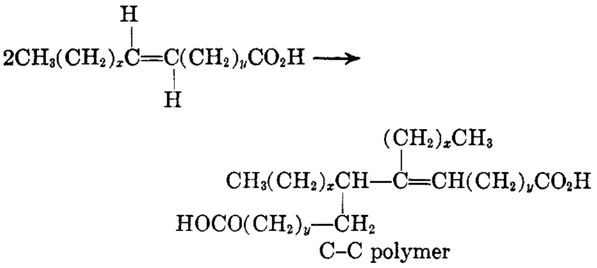
[7] J. S. Showell, *J. Amer. Oil Chemists' Soc.*, **36**, 343 (1959).

boxylic acids. Fraction C (20.2%) is a complex mixture of geometrical and positional isomers of octadecenoic acid. The double bond of the octadeceonic acids was located from $\Delta^{4,5}$ to $\Delta^{15,16}$ with a slightly higher proportion of isomers with the double bond at the center of the chain. Fractions D (33.7%) and E (5.9%) are dimers and trimers, respectively, of 9-octadecenoic acid. Detailed studies show that these exist as two distinct types "C–O polymer" and the "C–C polymer." The former class, the C–O polymers (eq 3),



$$2\mathrm{CH_3(CH_2)_x}\overset{\mathrm{H}}{\overset{|}{\mathrm{C}}}=\underset{\underset{\mathrm{H}}{|}}{\mathrm{C}}\mathrm{(CH_2)_yCO_2H} \rightleftarrows \mathrm{CH_3(CH_2)_x}\overset{\mathrm{H}}{\overset{|}{\underset{\underset{\mathrm{H}}{|}}{\mathrm{C}}}}=\mathrm{C(CH_2)_yCO_2}\underset{\underset{\mathrm{(CH_2)_xCH_3}}{|}}{\mathrm{C}}\mathrm{HCH_2(CH_2)_yCO_2H} \qquad (3)$$

C–O polymer



$$2\mathrm{CH_3(CH_2)_x}\overset{\mathrm{H}}{\overset{|}{\mathrm{C}}}=\underset{\underset{\mathrm{H}}{|}}{\mathrm{C}}\mathrm{(CH_2)_yCO_2H} \longrightarrow \mathrm{CH_3(CH_2)_x}\underset{\underset{\mathrm{HOCO(CH_2)_y—CH_2}}{|}}{\mathrm{CH}}—\overset{\mathrm{(CH_2)_xCH_3}}{\overset{|}{\mathrm{C}}}=\mathrm{CH(CH_2)_yCO_2H} \qquad (4)$$

C–C polymer

are esters that are formed by the intermolecular addition of the carboxyl of one octadecenoic acid molecule to the double bond of another, with the formation of a C–O–C linkage of the typical ester (estolide). The latter class, the C–C polymers (eq 4), is formed by the addition of a carbonium ion (or its functional equivalent) to a double bond of another molecule, producing a C–C linkage forming a branched carbon skeleton double the original chain length. The C–O polymers are reversibly formed while C–C polymers are irreversibly formed in the reaction mixture. Other studies have shown that as the reaction time is increased the per cent of C–C polymer increases and forms an irreversible drain of the material from the pool of reactive intermediates in the reaction. The dimer fraction (peak D) could be partially converted into γ-lactone under the conditions of the isomerization procedure but could not be completely converted because of C–C polymer.

The neutral fraction B (nonacidic in the original crude reaction mixture) is a mixture of γ-stearolactone (74.7%) (infrared, 1780 $\mathrm{cm^{-1}}$) and δ-stearolactone (25.3%) (1740 $\mathrm{cm^{-1}}$). No other C=O bands were observed nor were conjugated carbonyl groups detected in the ultraviolet spectrum. Only one molecular ion peak at m/e 282 was observed under conditions of low ionization in a mass spectrometer. The mass spectrum of the mixture had its two most intense peaks at m/e 85 and 99 which correspond, respectively, to lactone ring fragments resulting from the cleavage of the side chains from a γ- and δ-lactone. Studies with the pure γ- and δ-lactones confirmed these observations.[8]

A low-intensity peak was observed at m/e 113, corresponding to a ring fragment remaining when the side chain was cleaved from an ε-lactone. However, the extreme weakness of this peak plus a failure to detect any compound by glpc and tlc make the existence of the ε-stearolactone questionable. The δ-lactone is probably an intermediate in the production of the γ-lactone as is shown by the fact that the proportion of the δ- to γ-lactone (25.3:74.7) is much higher in fraction B than in a reaction carried out under the preparative conditions (1.8:98.2).

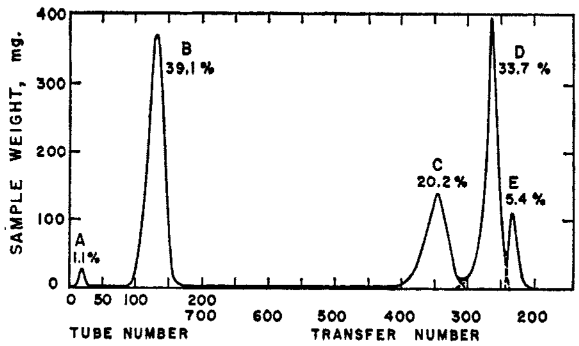


Figure 5.—Countercurrent distribution of the esterified reaction product (85°, 1 hr, 1:1 mole ratio).

Competing Reactions.—The method of isolation permitted the essentially quantitative (≥99%) recovery of the organic material from the reaction mixture. The neutral fraction was shown to consist of the normal chain γ-stearolactone, branched chain C_{18} γ-lactones, δ-stearolactone, 2-tridecyl-2-cyclopentenone, and 2-dodecyl-2-cyclohexenone, representing 74.7% of the original crude product; the balance of the crude product consisted of the acidic fraction (isomeric octadecenoic acids, dimers, and trimers). The normal chain γ-lactone is 64.5% of the total crude product, while the branched chain γ-lactones are 6.6%. The δ-stearolactone represents 1.2% while the substituted cyclopentenone and substituted cyclohexenone are 2.3 and 1.7%, respectively.

Crystallization of the original crude neutral fraction from acetone cleanly produces a solid precipitate consisting of the normal chain γ-lactone and a small amount of δ-lactone as the principal impurity; the liquid filtrate contains little normal chain γ-lactone. Two recrystallizations of the precipitate yield a solid whose physical properties are essentially identical with the material in the filtrate from the final crystallization.

The branched chain γ-lactones are an isomeric mixture resulting from the replacement of the normal tetradecyl side chain of the γ-stearolactone by a methyl tridecyl side chain. The branched chain γ-lactones show a relatively broad peak of shorter retention time than the normal γ-lactone in the glpc. This decrease in retention time is characteristic of branched chain compounds compared to normal chain isomers,[9] the breadth of the curve reflects the multiplicity of branched isomers present.

Integration of the nmr spectra indicates that the average number of methyl groups is two per molecule. Fusion of the branched γ-lactones with the molten KOH leads to the production of a mixture of branched acids *via* the dehydrogenation of the hydroxy acids to keto acids and the subsequent base-catalyzed cleavage of the

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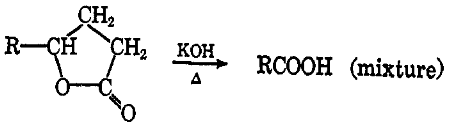
[8] W. H. McFadden, E. A. Day, and M. J. Diamond, *Anal. Chem.*, **37**, 89 (1965).

[9] J. W. Farquhar, W. Insull, Jr., P. Rosen, W. Stoffel, and E. H. Ahrens, Jr., *Nutr. Rev. Suppl.*, **17**, 1 (1959).



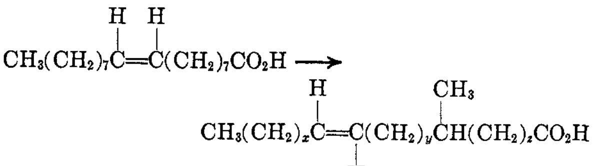
(5)

keto acids (eq 5). Glpc of the methyl esters of the acids revealed at least seven compounds with retention times greater than undecanoate and less than pentadecanoate, corresponding to none of the normal chain methyl esters. The straight chain γ-lactone produced only the straight chain pentadecanoic acid under identical conditions.[10] This behavior is to be expected when a single methyl group is randomly distributed on the chain. The mass spectra of the branched γ-lactones exhibit fragmentation patterns which differ principally from the normal chain isomer in having two series of peaks corresponding to $P - (15 + 14N)$ and $P - [15 + 14(N - 2)]$, where $N = 5\text{-}12$. This is the pattern of behavior expected for the random distribution of a single methyl group in the tridecyl side chain.[11] Under the preparative conditions the ratio of the normal chain γ-lactone (64.5%) to the branched chain lactones (6.6%) is approximately 10:1. There was no evidence for a methyl group located on the γ-lactone ring.

The δ-stearolactone, XI, was isolated in small yield and showed the characteristic ester carbonyl band at 1740 cm^{-1} in the ir region. Fusion of the δ-stearolactone with molten KOH caused cleavage of the δ-lactone analogous to that shown in eq 5. Glpc of the methyl ester of the fusion product showed only the tetradecanoic acid corresponding to normal chain δ-lactone.

The small amounts of substituted cyclic ketones, XVIIa and XVIIb, were characterized principally by means of their spectral properties. 2-Dodecyl-2-cyclohexenone, XVIIb, showed an infrared band at 1680 cm^{-1} and an ultraviolet band at 230 mμ characteristic of an α,β-conjugated cyclohexenone.[12,13] 2-Tridecyl-2-cyclopentenone, XVIIa, showed infrared bands at 1710 and 1640 cm^{-1}, characteristic of an α,β-unsaturated carbonyl group and a conjugated double bond, respectively.[5] The ultraviolet spectrum had a maximum at 223 mμ.[13,14] No attempt was made to show that the alkyl group of XVIIa and XVIIb were branched.

The reactions leading to the formation of the materials in both the neutral and acidic fractions can be formally broken into three classes: addition (inter- and intramolecular), isomerization, and polymerization. Hydration of the double bond to form hydroxy acids corresponds to intermolecular and cyclization to γ- and δ-lactones and to the cyclic ketones corresponds to intramolecular addition. Isomerization reactions are represented by three classes: *cis–trans* and positional isomerization of the double bond, and the chain branching reaction (eq 6) leading to the formation of the methyl side chains. The polymers formed are of two types: C–O polymers which contain an olefinic double bond, an ester, and a carboxyl function (eq 3); C–C polymers which contain an olefinic double bond and two carboxyl groups (eq 4).



$$\mathrm{CH_3(CH_2)_7\overset{H}{C}{=}\overset{H}{C}(CH_2)_7CO_2H} \longrightarrow \mathrm{CH_3(CH_2)_x\overset{H}{C}{=}\underset{H}{C}(CH_2)_y\overset{CH_3}{C}H(CH_2)_zCO_2H} \quad (6)$$

$$x + y + z = 12$$

From the nature of the reagents that form the γ-lactone (perchloric acid, sulfuric acid, methanesulfonic acid, microreticular resins), a carbonium ion intermediate must be formed. The variety of products and the types of reaction (addition, isomerization, and polymerization) are characteristic of carbonium ion reactions in general.

Occurrence of the principal reaction in the perchloric acid phase is consistent with the formation of a charged intermediate. The reaction of oleic acid (I) with a proton occurs *via* the rearrangement into a carbonium ion (VII) of the complex of the partially hydrated oxonium ion with the π electrons of the double bond. The resulting carbonium ion (VII) can then undergo a variety of reactions. These are represented schematically in Figure 6. *cis–trans* isomerization results from loss of the proton from the original addition point after rotation about the new single bond. A carbonium ion can accept an anion (or the formal equivalent, an electron pair) to form a neutral adduct such as a hydroxy acid. Thus it was found that 9(10)-monohydroxystearic acid (V) readily forms γ-stearolactone under the reaction conditions. This indicates that the reverse process, the protonation of the hydroxyl and the subsequent loss of water, is also a rapid, easily reversible one. The carbonium ion can undergo polymerization reactions whose easy reversibility to form a γ-lactone was demonstrated. On the other hand, the carbonium ion can alkylate the octadecenoic acid (II or IX) to form a C–C polymer (eq 4). This reaction, however, is an irreversible process under the reaction conditions. The carbonium ion (VII), the product of the protonation of the original double bond of oleic acid, can lose a proton to form VIII, an isomeric octadecenoic acid which by a repetitive sequence of proton addition and elimination reactions can form a mixture of isomeric octadecenoic acids, IX. Protonation of the octadecenoic acids, of general structure IX, will lead to the general carbonium ion X.

Although the rearrangement of the initial carbonium ion (VII) is visualized in Figure 6 as occurring through sequence of repetitive addition and proton elimination reactions, it is possible that the reactions occur by an intramolecular path. The present work provides no evidence on this point. Unpublished work strongly suggests the existence of both inter- and intramolecular paths.[15] The carbonium ion X is written in such a manner as to suggest that intramolecular processes can occur when x and y have suitable values. The work has quite clearly shown that δ-stearolactone XI ($x = 12$, $y = 2$) is formed in the reaction and probably acts as an intermediate in the subsequent formation of γ-stearolactone, II ($x = 13$, $y = 1$). The γ-stearolactone (II) forms a small amount of the isomeric octadecenoic acids (IX) under the conditions of the isomerization reaction. The isomerization of the carbon skeleton to

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[10] R. G. Ackman, P. Linstead, B. J. Wakefield, and B. C. L. Weedon, *Tetrahedron*, **8**, 221 (1960).

[11] K. Biemann, "Mass Spectrometry; Organic Chemical Applications," McGraw-Hill Book Co., Inc., New York, N. Y., 1962.

[12] H. Born, R. Pappo, and J. Szmuszkovicz, *J. Chem. Soc.*, 1779 (1953).

[13] M. F. Ansell and S. S. Brown, *ibid.*, 2955 (1958).

[14] H. S. French, *J. Amer. Chem. Soc.*, **74**, 514 (1952).

[15] J. S. Showell and I. S. Shepherd, unpublished work.

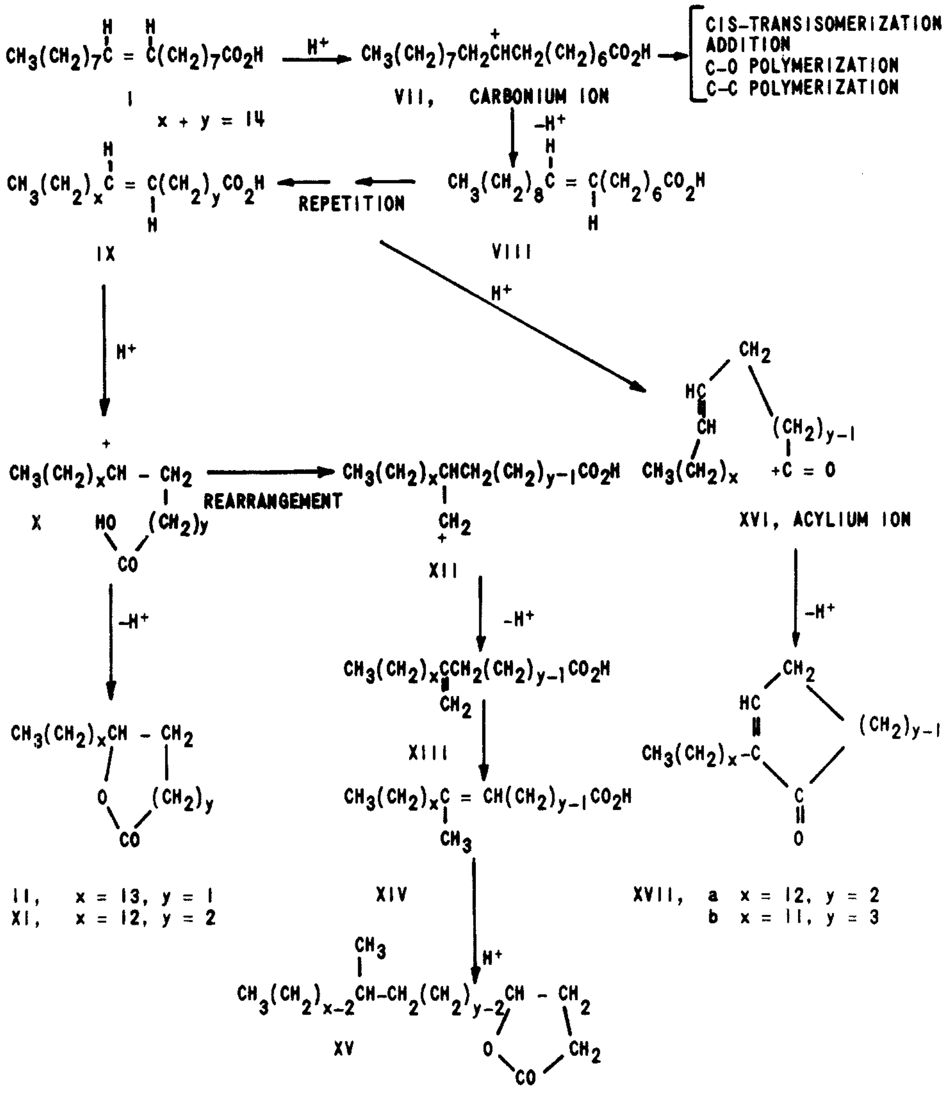

Figure 6.—Schematic representation of the reaction path.

the methyl branched γ-lactone is an irreversible process. This is visualized as taking place *via* carbonium ion X which rearranges from a secondary to a primary carbonium ion XII; carbonium ion XII can then undergo proton elimination to give the branched olefinic acid XIII; this would isomerize under the reaction conditions to the more stable isomer XIV. This branched octadecenoic acid (XIV) could then isomerize to a methyl branched γ-lactone (XV) by a process paralleling the formation of the straight chain γ-lactone. However, it is surprising that the branching reaction is as efficient as it appears to be. The observed ratio of the unbranched γ-lactone to the branched chain γ-lactone is approximately 10. The rearrangement of the secondary to the primary carbonium ion is energetically running up hill by at least 26 kcal mol.[16] The existence of such a large energy difference strongly suggests that another path may be an important one. The reaction path for the branched γ-lactone may be *via* an insertion reaction to form a cyclopropane which can be visualized as rearranging under these conditions,[17] or *via* a protonated cyclopropane intermediate of the type visualized in the protonation of the cyclopropane.[18a] Unpublished work from this laboratory has shown that a cyclopropane acid under these conditions will lead to γ-lactone.[18b]

The formation of the substituted cyclic ketones XVIIa ($x = 12, y = 2$) and XVIIb ($x = 11, y = 3$) is a different reaction involving protonation of the carboxyl group of the octadecenoic acid IX to form an acylium XVI which then undergoes an intramolecular cyclization.

Other acids beside perchloric acid were also investigated as reagents for the isomerization but none was as effective. These were sulfuric acid (96.5%), methanesulfonic acid, glacial phosphoric acid (84.2% H_3PO_4), and the sulfonic acid resin, Amberlyst 15.[19]

Sulfuric acid gave lower yields of γ-lactone and the work-up was complicated. Methanesulfonic acid caused isomerization but subsequent condensation reactions were significant and the resulting yield of lactone was poor. Glacial phosphoric acid was without action on oleic acid under extreme conditions of temper-

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[16] F. H. Field and J. L. Franklin, "Electron Impact Phenomena and the Properties of Gaseous Ions," Academic Press Inc., New York, N. Y., 1957.

[17] J. Bayless, L. Friedman, J. A. Smith, F. B. Cook, and H. Shechter, *J. Amer. Chem. Soc.*, **87**, 661 (1965).

[18] (a) R. L. Baird and A. A. Aboderin, *ibid.*, **86**, 252 (1964); (b) J. S. Showell and W. R. Noble, unpublished work.

[19] Mention of products or companies does not constitute an endorsement by the Department of Agriculture over others of a similar nature not mentioned.

ature and time (130°, 24 hr). The sulfonic acid resin, Amberlyst 15, gave low yields of lactone; polymerization seemed to be the predominating reaction.

Other long chain monoolefinic acids were also investigated briefly. Undecylenic acid (10-hendecenoic acid) and erucic acid (13-docosenoic acid) were also isomerized under the optimum conditions used for oleic acid. Under these conditions γ-undecalactone was obtained in 48% yield as a colorless liquid, while γ-erucalactone was obtained in 46% yield as a white solid (mp 63°).

Experimental Section

General Procedure for Perchloric Acid Isomerization Reactions.—Oleic acid (99.5 mol %, 2.00 g, 7.08 mmol) and a quantity of 70% perchloric acid (exact $HClO_4$ content determined by titration) chosen to give the required $HClO_4$–oleic mole ratio were allowed to react in a jacketed flask concentrated to a constant-temperature bath. Maintainance of a positive nitrogen pressure prevented autoxidation by atmospheric oxygen; intimate mixing of the two phases was ensured by magnetic stirring. After a specified time interval, the reaction was quenched by pouring the hot mixture into cold water contained in a liquid-liquid extractor. Any residue remaining in the reaction flask was rinsed into the extractor with hydrocarbon solvent. The organic material was quantitatively recovered by extracting with distilled hexane. The γ-stearolactone content of the crude reaction product recovered from the hydrocarbon extract was estimated from the intensity of the infrared absorption at 1780 cm^{-1} (5 g/l., CS_2 solution).

Pure γ-stearolactone was treated with an equimolar amount of perchloric acid (70.0%) at 100° for 3 hr, the large-scale preparative conditions. The reaction mixture was worked up according to the standard procedure and the recovery of organic material was essentially quantitative. The crude residue consisted of 91% γ-lactone and the balance consisted principally of unsaturated polymeric acids. In studies at 85° for 10 hr and at 115° for 1.5 hr, recovery of the γ-lactone was 93 and 77%, respectively.

Large-Scale Preparation of γ-Stearolactone.—Large quantities of γ-stearolactone were prepared using the same procedure but with 200-g charges of oleic acid (99.2 mol %). They were a mole ratio of 1:1, steam-bath temperature, and a reaction time of 3 hr.

The crude reaction product isolated by liquid–liquid extraction was purified by chromatography and crystallization. The first purification step consisted of column chromatography, eluting with benzene on a short wide column of Florisil (6 g of adsorbent/g of sample). This step removed all acidic materials and the more highly colored impurities. The material recovered from the benzene eluate was crystallized at −32° from acetone (10 ml/g). Most of the impurities were removed by the first crystallization from which a liquid filtrate fraction (amounting to 12.6% of the quantity crystallized) was obtained. The principal impurity in the solid was the isomeric δ-lactone; two more crystallizations yielded pure γ-lactone. All subsequent filtrate fractions amounted to only 1% and were solids. The yield of pure γ-stearolactone (mp 51–52°) was 60–65%.

Countercurrent Distribution Studies.—Reaction conditions were chosen to give relatively low conversion to γ-stearolactone and a relatively high conversion to intermediates in the reaction: 85°, 1:1 mole ratio of oleic acid to perchloric acid, and a 1-hr reaction time (maximum yield is obtained at 10 hr). The reaction and extraction procedures were identical with those described in preceding sections; however, to ensure a sample as free of autoxidation products as possible, the extraction was performed under a nitrogen atmosphere using water and hexane which had been saturated with nitrogen. The crude reaction product was esterified with diazomethane.

The sample (28 g) was divided into five parts and placed in the first five tubes of a 200-tube Craig countercurrent distribution apparatus. It was then partitioned between acetonitrile (40 ml) and *n*-hexane (10 ml). The apparatus was allowed to run for 700 transfers while a single withdrawal procedure was followed.[20] A fundamental weight curve (Figure 5) was drawn of the material remaining in the apparatus and the single withdrawal fractions.

Each fraction was subjected to analysis by gas–liquid partition and thin layer chromatography and infrared spectroscopy. In addition, fraction B (the lactone fraction) was analyzed by mass spectrometry (Consolidated Electrodynamics Corp. 103-C mass spectrometer), ionization voltage 80 eV.

The glpc data were obtained at 214° with an 8 ft × 0.25 in. i.d. column packed with 20% ethylene glycol succinate on 60–80 mesh Chromosorb W. Infrared spectra were obtained with a Perkin-Elmer Infracord Model 137 using CS_2 solutions (5 g/l.). Thin layer chromatography data were obtained from silica gel G plates developed with petroleum ether (bp 80–90)–diethyl ether–glacial acetic acid (180:20:4).

Fraction A, 1.1% of the charge, was not characterized. The glpc data (long retention times), tlc data ($R_f = 0$), and the location in the countercurrent distribution (partition coefficient, 0.011) suggest a very polar material. The infrared spectrum showed a typical hydroxyl envelope at 3300–3500 cm^{-1}.

Fraction B (Lactones).—Fraction B, 39.1% of the charge and partition coefficient, 0.91, was analyzed by mass spectrometry. A molecular ion peak was observed at *m/e* 282, while strong fragment ion peaks were observed at *m/e* 85 and 99.[8,21] The infrared spectrum had two carbonyl absorptions: 1780 (γ-lactone) and 1740 cm^{-1} (δ-lactone). Two glpc peaks were observed, one with the same retention time as γ-stearolactone; the other, with a longer retention time, was δ-stearolactone. The relative amounts of the two lactones, determined by integration of the glpc curve, were γ-stearolactone (74.7%) and δ-stearolactone (25.3%).

Two spots were observed on a tlc plate, one with an R_f value identical with that of pure γ-stearolactone; the other spot, with a smaller R_f value, was δ-stearolactone.

Anal. Calcd for $C_{18}H_{34}O_2$: ester equiv, 282.5. Found: ester equiv, 280.6.

Fraction C (Methyl Octadecenoates).—Fraction C, 20.2% of the charge and partition coefficient, 5.5, on glpc yielded one large peak with the same retention time as methyl oleate. A number of much smaller peaks were observed but not identified. *trans* double bond absorption at 968 cm^{-1} in the infrared spectrum was observed. Positional isomerization was determined by oxidative cleavage.[22] The cleavage products were esterified with BF_3–CH_3OH and compared by glpc to standard methyl ester mixtures ranging from C_8 to C_{15}. The results showed that the double bond was distributed from $\Delta^{4,5}$ to $\Delta^{15,16}$ with slightly more double bond at the center of the chain.

Anal. Calcd for $C_{19}H_{36}O_2$: ester equiv, 296.5; hydrogen no., 296.5; mol wt, 296.5. Found: ester equiv, 329; hydrogen no., 318; mol wt, 296 (mass spectrometry).

Fraction D (Methyl Ester Dimer).—Fraction D, 33.7% of the charge and partition coefficient, 17, had an ester carbonyl absorption at 1730 cm^{-1} and a *trans* double bond absorption at 968 cm^{-1}. The sample was completely retained when injected on either polyester or silicone rubber glpc columns.

Anal. Calcd for $C_{37}H_{70}O_4$: mol wt, 579. Found: mol wt, 647.

Fraction E (Methyl Ester Trimer).—Fraction E, 5.9% of the charge and partition coefficient, 33, also had an ester carbonyl absorption at 1730 cm^{-1} and a *trans* double bond absorption at 968 cm^{-1} (less intense than fraction D). This sample was also completely retained by glpc columns.

Anal. Calcd for $C_{55}H_{104}O_6$: mol wt, 861. Found: mol wt, 826.

Conversion of the Dimer Fraction (Fraction D) into γ-Stearolactone.—The dimer fraction was allowed to react with 70% perchloric acid; mole ratio of $HClO_4$ to methyl ester dimer was 2:1 at 85° for 24 hr. The infrared spectrum of the crude reaction product showed that although some of the ester configuration has been retained most (67%) of the dimer had been converted into γ-lactone. This indicates that part of the dimer is in a reversible pool leading to γ-lactone.

Isolation of Polymeric Compounds from a Typical Reaction Product.—A reaction product (85°, 24 hr, 1:1 perchloric acid–oleic acid mole ratio), typical of those with a high γ-stearolactone

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[20] L. C. Craig and D. Craig in "Technique of Organic Chemistry," Vol. III, Part 1, A. Weissberger, Ed., 2nd ed, Interscience Publishers, Inc., New York, N. Y., 1956, p 149.

[21] E. Honkanen, T. Moisio, and P. Karvonen, *Acta. Chem. Scand.*, **19**, 370 (1965).

[22] M. R. Subbaram, and C. G. Youngs, *J. Amer. Oil Chemists' Soc.*, **41**, 150 (1964).

yield, was chromatographed on 100 mesh reagent grade silicic acid. The first fractions, all monomeric, were eluted from the column with 4% diethyl ether in redistilled hexane. They were, in order, octadecenoic acids and C_{18} γ- and δ-lactones. The octadecenoic acids (6.0%) had a typical fatty acid envelope and a *trans* double bond absorption at 968 cm^{-1}. The γ-lactones amounted to 71.0% of the reaction product. The δ-lactones were not obtained in sufficient purity to estimate their precentage accurately. The last fractions, eluted from the column with increasing percentages of ether, were polymeric. With one exception, the polymeric fractions had two carbonyl absorption bands in he infrared spectrum. One fraction, corresponding to the C–O type of polymer, had ester (1740 cm^{-1}) and acid (1710 cm^{-1}) carbonyl absorptions. Polymers of the C–C type were represented by two fractions: one with only an acid (1710 cm^{-1}) carbonyl absorption, the other with acid and γ-lactone (1780 cm^{-1}) carbonyl absorptions. Tlc definitely showed that the fractions with two carbonyl absorptions were not physical mixtures of two different, monomeric, carbonyl-containing compounds. When these fractions were spotted, developed, and visualized on a tlc plate, only one spot was observed per fraction. The R_f values were less than those of the monomeric C_{18} compounds eluted earlier in the chromatography, *e.g.*, the octadecenoic acids and the γ- and δ-lactones. The exception already noted, the fraction with only an acid carbonyl band in the infrared spectrum, was also considered polymeric. When analyzed by tlc, only one spot was observed with an R_f value much lower than that of the octadecenoic acids.

Isolation and Characterization of By-products from the Oleic Acid Isomerization.—Essentially all of the by-products were isolated from the first filtrate fraction in the purification of a large-scale γ-stearolactone preparation.

The filtrate fraction was chromatographed on a column (21 × 2.5 in.) packed with silicic acid (325 mesh, reagent grade). Development was started with redistilled hexane. Nothing was eluted with hexane. The remainder of the chromatography was performed with 4% diethyl ether in hexane except for the last fractions which were eluted with increasing amounts of diethyl ether. Four types of compounds were eluted from the column in the following order: a substituted cyclohexenone, a substituted cyclopentenone, C_{18} branched chain γ-lactones (all eluted with 4% ether), and δ-stearolactone. None of these compounds was isolated completely pure.

A. **2-Dodecyl-2-cyclohexenone Fraction.**—This fraction was rechromatographed on silicic acid using benzene–hexane. The substituted cyclohexenone was eluted with 4–6% benzene. Following the chromatography, the ketone was distilled twice under vacuum. After purification, infrared analysis showed one large peak at 1680 cm^{-1} due to the carbonyl absorption of the conjugated cyclohexenone, with shoulders at 1640 and at 1710 cm^{-1} due to the conjugated double bond and carbonyl, respectively, of the conjugated cyclopentenone. Glpc data (silicone gum rubber column) paralleled the ir spectrum; there was one large peak and two smaller peaks. The rechromatography and distillations, while not completely purifying the sample, removed all lactonic material and substantially reduced the amount of the isomeric cyclopentenone.

Anal. Calcd for $C_{18}H_{32}O$: C, 81.75; H, 12.20; mol wt, 264. Found: C, 81.12; H, 11.99; mol wt, 260.

The $\nu_{max}^{CS_2}$ 1680 cm^{-1} (carbonyl) and the ultraviolet peak at 230 mμ (log ϵ 3.99, isooctane) are consistent with literature values for 2-alkyl-2-cyclohexenones.[5,12,13]

B. **2-Tridecyl-2-cyclopentenone Fraction.**—This fraction was twice distilled in a microstill. The distillate still contained a substantial amount of the isomeric cyclohexenone both by the ir band at 1680 cm^{-1} and by glpc. The intense characteristic ir band of the α,β-unsaturated carbonyl group at 1710 cm^{-1} and the conjugated double bond at 1640 cm^{-1} are typical of a conjugated cyclopentenone.[5] The ultraviolet spectra showed a maximum at 223 mμ (isooctane) (log ϵ 3.98).[13,14]

Anal. Calcd for $C_{18}H_{32}O$; C, 81.75; H, 12.20; mol wt, 264. Found: C, 80.63; H, 12.05; mol wt, 256.

C. **Branched γ-Lactones Fractions.**—The lactone fraction was fractionally distilled under reduced pressure, yielding four fractions which had strong ir absorption bands of γ-lactones at 1780 cm^{-1} and very weak shoulders at 1740–1750 and 1710–1720 cm^{-1} owing to traces of the substituted cyclic ketones. Glpc curves substantiated these conclusions.

Anal. Calcd for $C_{18}H_{34}O_2$: C, 76.54; H, 12.13; ester equiv, 282. Found for fraction I: C, 76.52; H, 12.06; ester equiv, 283. Found for fraction II: C, 76.73; H, 12.03; ester equiv, 280. Found for fraction III: C, 76.55; H, 12.03; ester equiv, 281. Found for fraction IV: C, 76.47; H, 12.03; ester equiv, 282.

The mass spectra of the four fractions were quite similar and the glpc curves were also similar but differed in relative shape. Both the mass and the glpc spectra were different from those of the normal chain γ-stearolactone, the latter showing a less complex fragmentation pattern and having a greater retention time. The mass spectra of the branched chain lactones, like that of the straight chain isomer, had their most intense peak at *m/e* 85, the fragment corresponding empirically to the lactone ring.

The integrated nmr spectra (Varian HR-60) of the branched γ-lactones indicated 1.83 ± 0.11 methyl groups per molecule.

A sample of branched γ-lactones was fused with molten KOH for 1 hr at 320° in a nickel pot fitted with a nickel stirrer and nitrogen inlet and outlet tubes for maintainance of an inert atmosphere.[10] The fusion reaction was stopped by immersing the pot in cold water. Cleavage products and excess KOH were washed from the pot and acidified with concentrated sulfuric acid. The products were recovered by ether extraction, washed to remove mineral acid, dried, and esterified with BF_3–CH_3OH. The methyl esters were then analyzed by glpc.

D. **δ-Lactone Fraction.**—The δ-lactone was vacuum distilled from the polymer and then saponified. The basic solution was extracted with hexane to remove unsaponifiables and treated with decolorizing carbon after acidification. Two successive uses of preparative thin layer chromatography with silica gel G (250-μ layer), developed with petroleum ether–diethyl ether–glacial acetic acid (140:60:4), enabled the δ-lactone to be purified. It showed a characteristic carbonyl band at 1740 cm^{-1} and a moderately intense band at 1240 cm^{-1}.

Anal. Calcd for $C_{18}H_{34}O_2$: C, 76.54; H, 12.13; ester equiv, 282. Found: C, 76.50; H, 12.03; ester equiv, 285.

The alkali fusion technique was also applied to the purified δ-stearolactone. Glpc of the esterified cleavage products showed two peaks. The first peak had the same retention time as methyl tetradecanoate, the normal cleavage product of 5-hydroxyoctadecanoic acid. The second peak, which did not have a retention time equal to any normal straight chain ester, probably was methyl 3-methylhexadecanoate. Under similar conditions, Dytham and Weedon reported that 3-methylpentadecanoic acid was a major rearrangement product of 5-oxoheptadecanoic acid and that the cleavage products of keto and hydroxy acids are identical.[23]

γ-Erucalactone.—Erucic acid (2.47 g, 7.29 mmol) and perchloric acid (70.2%, 1.04 g 6.96 mmol) were heated at 85° for 10 hr. The work-up procedure was identical with that for oleic acid except that crystallization from acetone (20 ml/g, −30°) was preceded by treatment with decolorizing carbon to yield an easily crystallizable product. The erucalactone (1.13 g, 46% yield) had mp 62.5–63.5° and an ir band at $\nu_{max}^{CS_2}$ 1780 cm^{-1} (carbonyl).

Anal. Calcd for $C_{22}H_{42}O_2$: C, 78.04; H, 12.15; ester equiv, 339. Found: C, 78.18; H, 12.44; ester equiv, 342.

4-Hydroxyoctadecanoic Acid.—γ-Stearolactone (1.50 g, 5.32 mmol) and KOH (85.3%, 0.32 g, 13.0 mmol) were refluxed in 50% aqueous ethanol (100 ml) for 4 hr. The free acid was obtained by dropwise addition of the soap solution to a stirred mixture of dilute HCl (10% excess) and ice, followed by ether extraction. The ether extract was washed with aqueous Na_2SO_4 until neutral and dried over anhydrous Na_2SO_4. The ether was removed in a stream of N_2 and the residue recrystallized from tetrahydrofuran (15 ml) at −25°. The resulting 4-hydroxyoctadecanoic acid melted at 86.2–87.2°.[24]

Anal. Calcd for $C_{18}H_{36}O_3$: C, 71.95; H, 11.99. Found: C, 72.32; H, 12.08.

Reaction between Perchloric Acid and Octadecenoic Acid Derivatives.—The reaction between equimolar quantities of perchloric acid (70.6%) and 9(10)-monohydroxystearic acid was carried out using the optimum conditions for oleic acid (85°, 10 hr; 100°, 3 hr; 115°, 1 hr) and a similar work-up procedure.

The reaction between equimolar quantities of perchloric acid and petroselinic acid (*cis*-6-octadecenoic acid) was carried out using the optimum conditions for oleic acid and the standard work-up procedure. Yields were 10% higher than those from

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[23] R. A. Dytham and B. C. L. Weedon, *Tetrahedron*, **8**, 246 (1960).

[24] S. Bergström, G. Aulin-Erdtman, B. Rolander, E. Stenhagen, and S. Ostling, *Acta Chem. Scand.*, **6**, 1157 (1952).

oleic acid, the side reactions being less important. Reaction of elaidic acid under the optimum conditions was essentially similar to that of oleic acid.

Reaction between Perchloric Acid and Undecylenic Acid.—Undecylenic acid (49.3 g, 268 mmol) and perchloric acid (70.2%, 37.9 g, 261 mmol) were heated at 100° for 3 hr and worked up using procedures similar to those for oleic acid. The acid fraction of the reaction product was polymeric, as indicated by its complete retention on glpc columns. The total residue contained 2.8% of α,β-conjugated carbonyl-containing compounds (λ_{max} at 230 mμ), 2-alkyl-substituted 2-cyclopentenone and 2-cyclohexenone. Fractional distillation of the neutral residue through a spinning-band column gave the colorless γ-undecalactone (bp 146° at 4.5 mm) in 48% yield.

Anal. Calcd for $C_{11}H_{20}O_2$: C, 71.69; H, 10.94. Found: C, 71.43; H, 10.76.

Registry No.—I, 112-80-1; II, 502-26-1; XI, 16317-08-1; γ-erucalactone, 16317-09-2; 4-hydroxyoctadecanoic acid, 2858-39-1; γ-undecalactone, 104-67-6; perchloric acid, 7616-81-1.

The Electrochemical Oxidation of Epimeric β-Hydroxycycloalkylacetic Acids[1]

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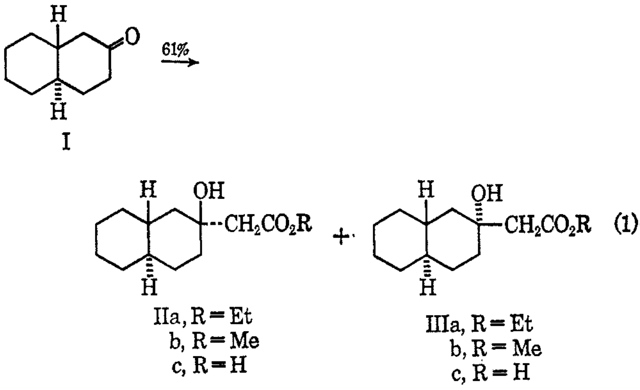
Chemical and spectral evidence for the configurations of the epimeric Reformatsky products from *trans*-2-decalone and cholestanone is presented. Electrochemical oxidation–decarboxylation of each of the epimeric β-hydroxycarboxylic acids derived from *trans*-2-decalone gave products *via* both radical and carbonium ion intermediates. No significant product differences attributable to the different configurations of the acids were found. Methyl substitution α to the carboxyl led to no specific bond migration in the rearrangement of the carbonium ion leading to homologated ketones.

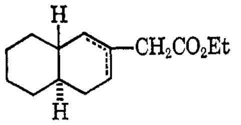
In order to ascertain the possible effect of configurational differences on product distribution in the Kolbe electrosynthesis reaction, a study of the electrooxidation of epimeric β-hydroxycycloalkylacetic acids was undertaken. This reaction, which gives rise to ring homologated ketones *via* carbonium ion intermediates, was briefly described by Corey and his coworkers[2] in 1960. It seemed reasonable that steric differences might bear upon the electrode absorptivity requirements for the electrode processes leading to intermediates and possibly to the products as well. This report deals with the preparation and characterization of isomeric Reformatsky products from *trans*-2-decalone and cholestanone and the electrolysis of the pair of epimeric acids derived from the former.

Results and Discussion

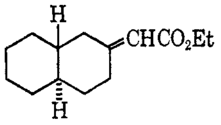
The Reformatsky reaction of *trans*-2-decalone with ethyl bromoacetate and zinc in tetrahydrofuran gave a 61% yield of the two epimeric hydroxy esters, IIa and IIIa, in a 1:1 ratio after column chromatography (eq 1). The isomer that was eluted first (IIa) was assigned the axial (β) hydroxyl configuration. Chemical evidence for the hydroxyl configurations was obtained by dehydration of the hydroxy esters with pyridine–phosphoryl chloride.[3] The α isomer (IIIa), with an equatorial hydroxyl, gave as the major product an exocyclic olefin (V), while the β isomer gave an endocyclic olefin (IV).

The nmr spectra of the two epimers in dimethyl sulfoxide showed a chemical-shift difference of 0.23 ppm for the hydroxyl protons, the equatorial OH in IIIa resonating at a lower field in agreement with the observations of Chapman and King[4] (Table I).





IV



V

TABLE I

NMR SPECTRA (δ) OF EPIMERS IIa AND IIIa (IN PARENTHESES)[a]

DMSO-d_6	$CDCl_3$	Benzene	Pyridine
1.09 (1.10)	1.27 (1.30)	0.34 (0.34)	0.57 (0.46) (ester CH_3, three protons, T, J = 7 cps)
2.25 (2.37)	2.40 (2.59)	1.68 (1.89)	1.90 (2.06) ($-CH_2CO-$, two protons, S)
4.13 (4.36)	3.62 (3.16)	2.73	4.36 (4.65) (OH, one proton)
3.99 (3.99)	4.16 (4.22)	3.34 (3.37)	3.48 (3.50) ($-OCH_2-$, two protons, Q, J = 7 cps)

[a] T = triplet; S = singlet; Q = quartet.

The nmr spectra of these epimeric esters exhibited two interesting features. One was the singlet resonance of the geminal methylene protons of the acetic ester side chain instead of an AB quartet, even though the adjacent ring carbon is asymmetric. The other feature was that the axial methylene in IIIa resonated at a lower field than the equatorial one although one might expect the reverse because of C–C bond anisotropies. Surprisingly, these methylene resonances were reversed in the nmr spectra of the corresponding car-

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[1] (a) Presented in part at the 154th National Meeting of the American Chemical Society, Chicago, Ill., Sept 1967. (b) Supported by the Michigan Cancer Foundation.

[2] E. J. Corey, N. L. Bauld, R. T. LaLonde, and J. Casanova, Jr., *J. Amer. Chem. Soc.*, **82**, 2645 (1960).

[3] D. H. R. Barton, A. da S. Campos-Neves, and R. C. Cookson, *J. Chem. Soc.*, 3500 (1956); J. L. Beton, T. G. Halsak, E. R. H. Jones, and P. C. Phillips, *ibid.*, 753 (1957).

[4] O. L. Chapman and R. W. King, *J. Amer. Chem. Soc.*, **86**, 125 (1964).