48 g., was observed to have a higher melting point than the starting material.

The relatively high refractive indices and low molecular weights of other fractions indicated that hydrogen compounds were present. Fraction 5 was the largest such fraction; b. p. 42.0 to 45.0°; wt. 3 g.; mol. wt. 234–257; $n^{20}\mathrm{D}$ 1.288; H, 0.21. Hydrogen was determined by the method previously reported.[13]

The compound C_5F_9H has a calculated mol. wt. of 232 and hydrogen content of 0.43%. Other fractions decomposed slowly on storage. The evidence is inconclusive but indicates that cyclic hydrogen-containing fluorocarbons were produced. The virtual absence of hydrogen compounds of intermediate chain lengths (2 to 5 carbon atoms) is particularly evident in this experiment.

Discussion

In all experiments with acylic fluorocarbons the principal products isolated were CF_3H and C_2F_5H; compounds having three or more carbon atoms per molecule were found only in small amounts. The initially formed products are apparently more reactive than the fluorocarbons themselves and react with hydrogen until C_2F_5H and especially CF_3H are formed. This process of carbon–carbon bond cleavage would be expected to yield considerable amounts of CF_2H_2, a product which was actually found only in small amounts. A rough calculation of the amount of CF_2H_2 that could have been formed in the reaction of C_3F_8 to account for the amounts of CF_3H and C_2F_5H isolated gives 19.8 g. of CF_2H_2. The carbon contained in 19.8 g. of CF_2H_2 is 4.5 g., while the carbon formed during the reaction of C_3F_8 with hydrogen weighed 5.5 g. While CF_2H_2 may be quite unreactive under the reaction conditions, the data suggest that the CF_2 group expected to appear in the final products as CF_2H_2 is degraded by some process to carbon and (presumably) hydrogen fluoride.

The high temperature necessary for the reaction of the mixed isomers of C_6F_{12} with hydrogen illustrates the particular stability of cyclic fluorocarbons. Even under the rigorous conditions used the principal reaction observed was the cleavage of side chains, indicating that the parent ring compounds are still more stable. The fact that the recovered C_6F_{12} had a higher melting point than the starting material suggests that cyclic isomers having side chains reacted preferentially, leaving a mixture enriched in $(CF_2)_6$, the highest melting isomer.

Acknowledgment.—This work was done under the sponsorship of the Minnesota Mining & Manufacturing Company, Saint Paul, Minnesota. The assistance of Dr. T. J. Brice during the course of the experiments and in the preparation of the manuscript is gratefully acknowledged.

Summary

Reactions of fluorocarbons with hydrogen at elevated temperatures have been studied. The principal products are those to be expected from the cleavage of carbon–carbon bonds in the presence of hydrogen, CF_3H and similar hydrofluorocarbons. The comparative stability of the cyclic fluorocarbons is demonstrated by their resistance to hydrogenolysis of the ring structure.

STATE COLLEGE, PENNSYLVANIA
RECEIVED SEPTEMBER 10, 1949

---

[13] W. H. Pearlson, T. J. Brice and J. H. Simons, *Ind. Eng. Chem., Anal. Ed.*, **18**, 330 (1946).

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY OF THE UNIVERSITY OF KANSAS]

A Polarographic Study of β,γ- and α,β-Angelica Lactones

BY E. VANCE KIRKLAND,[1] CHARLES A. REYNOLDS AND CALVIN A. VANDERWERF

The marked differences noted[2] in the behavior of β,γ-angelica lactone and α,β-angelica lactone upon catalytic hydrogenation suggested that a polarographic investigation of these unsaturated lactones should be of considerable interest. Such a study was undertaken, and solutions of both lactones were found to give well-defined reduction waves in the *p*H range 8.00–9.66. It soon became apparent, however, that the waves were obtained only for solutions of the lactones which gave positive qualitative tests for peroxides, and also that the magnitude of the diffusion current roughly paralleled the time of exposure to oxygen for any given solution. Hence the direction of the problem shifted to a quantitative study of the relationship between oxygen uptake and polarographic behavior of the lactones.

Experimental

A. Preparation and Purification of Materials.—Levulinic acid, technical grade, was purified by fractional distillation under reduced pressure. The fraction boiling at 101–102° at 3 mm., m. p. 30.3–31.2°, cor., was retained.

β,γ-Angelica lactone was prepared and purified by the procedure of Thiele, Tischbein and Lossow[3]; b. p. 89–90° at 16 mm., $n^{25}\mathrm{D}$ 1.4457.

α,β-Angelica lactone was prepared by isomerization of the β,γ-lactone in the presence of triethylamine according to the method of Thiele, *et al.*[3] Freed from unchanged β,γ-angelica lactone by the method of Wolff,[4] it boiled sharply at 83°; $n^{25}\mathrm{D}$ 1.4532.

2,3-Dihydroxyvalerolactone was prepared by oxidation of α,β-angelica lactone with potassium permanganate according to the procedure of Thiele, *et al.*,[3] m. p. 100.1–101.3°, cor.

A series of buffer solutions was prepared according to Clark and Lubs as described by Kolthoff and Laitinen.[5] In all polarographic measurements for which data are

---

[1] American Chemical Society Pre-doctoral Fellow, 1946–1948. Present address: Pan American Refining Corporation, Texas City, Texas.

[2] Jacobs and Scott, *J. Biol. Chem.*, **87**, 601 (1930).

[3] Thiele, Tischbein and Lossow, *Ann.*, **319**, 180 (1901).

[4] Wolff, *ibid.*, **229**, 249 (1885).

[5] Kolthoff and Laitinen, "*p*H and Electro Titrations," John Wiley and Sons, Inc., New York, N. Y., 2nd ed., 1941, pp. 32–37.

given, unless otherwise specified, the Clark and Lubs buffer of *p*H 9.60 was employed and no additional supporting electrolyte was added. The *p*H in every case was measured by means of a calibrated Beckman *p*H meter.

Tetramethylammonium bromide, Eastman Kodak Company product, was purified by repeated recrystallization from water–alcohol.

Apparatus.—A Sargent model XII Heyrovsky Polarograph was employed. A polarographic cell was constructed entirely of glass in such a manner that it could be connected with a gas buret. A drawing of the cell is shown in Fig. 1.

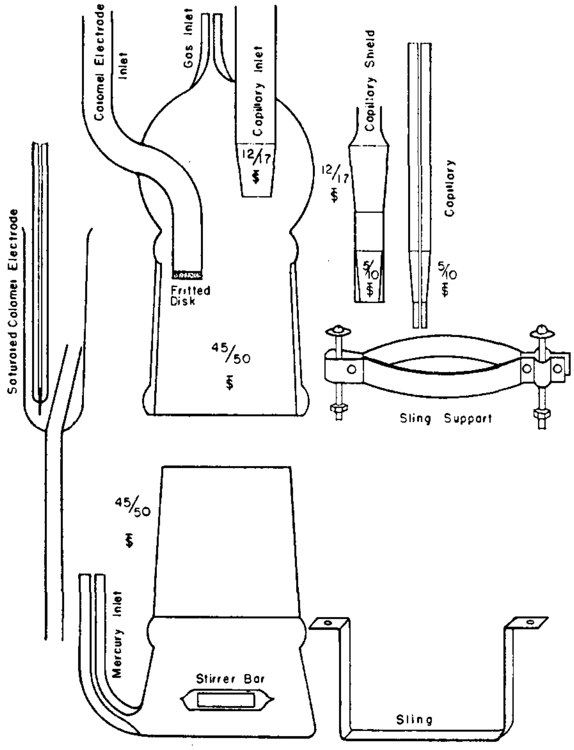


Fig. 1.—Oxygen uptake—diffusion current cell.

Its essential features are an inlet at the bottom for introducing mercury, a capillary inlet at the top for introducing solution and oxygen, and two electrode leads. Introduction of the capillary of the dropping mercury electrode with maintenance of an air-tight system was accomplished by the use of two ground glass joints as shown in Fig. 1. The several capillaries used during the course of the investigation were first ground by hand, then cut off in order to eliminate any possibility that the capillary openings might be contaminated. Constants for the capillaries used for the various runs were as follows: for runs 1, 2, 3 and 4, $m^{2/3}t^{1/6} = 1.40$ at -0.4 volt; for runs 5 and 6, $m^{2/3}t^{1/6} = 1.46$ at -0.4 volt; for runs 7, 8 and 9, $m^{2/3}t^{1/6} = 1.54$ at -0.4 volt.

The second electrode inlet, that from the saturated calomel electrode, was a tube sealed through the side of the cell and ending with a fritted disc. The fritted disc was backed up with agar saturated with potassium chloride so that no solution would pass through the disc. The calomel cell was prepared according to the directions of Kolthoff and Laitinen[6]; its general design is shown in Fig. 1.

The gas buret assembly connected to the polarographic cell is shown in Fig. 2. The gas buret was of 50-ml. capacity and was accurately calibrated to read to ±0.01 ml. The temperature of the water surrounding the buret and polarographic cell was controlled to within 0.4°. Effective stirring was obtained by means of a magnetic stirrer, the stirrer bar resting on the surface of the mercury within the cell.

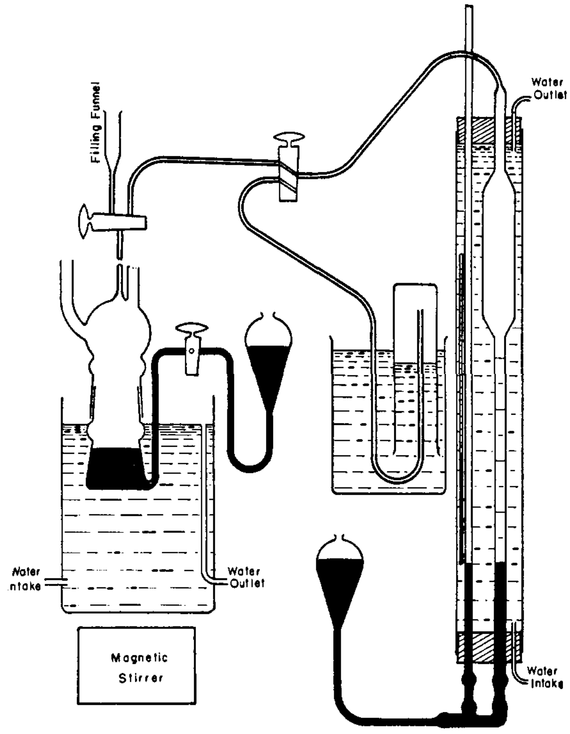


Fig. 2.—Oxygen uptake apparatus.

Procedure.—The following experimental procedure was adopted in correlating the oxygen uptake of each lactone with its polarographic diffusion current. The lactone was distilled and stored in a nitrogen atmosphere. The buffered solvent was heated to boiling and rapidly cooled immediately before use in order to eliminate dissolved oxygen. The solution was then introduced into the polarographic cell with minimum exposure to atmospheric oxygen. A polarogram was obtained before the solution was exposed to the oxygen in the buret in order to determine the amount of oxygen which had been absorbed in the transfer process.

At this point, the cell was filled with oxygen from the buret, the magnetic stirrer was started, and the solution was stirred for a short period, usually five to ten minutes. The stirrer was then stopped, the oxygen uptake measured, and a polarogram obtained before the stirrer was started once more. This procedure was repeated at regular intervals.

The amount of dissolved but unreacted oxygen was determined for each polarogram, along with the diffusion current of the organic compound. Dissolved oxygen gives a well-defined polarographic wave at a lower applied potential than did the compounds studied. The values for the diffusion coefficient of oxygen, in the various buffered solutions employed, as determined by use of the gas buret, were $9.83 \pm 0.08 \times 10^{-6}$ cm.^{2} sec.$^{-1}$ at 0°, and $2.48 \pm 0.08 \times 10^{-5}$ cm.^{2} sec.$^{-1}$ at 25°.

Results

β,γ-Angelica Lactone.—When no precautions were taken to exclude oxygen during the distillation process, an aqueous solution of freshly distilled β,γ-angelica lactone was found to give a polarographic wave with a half-wave potential of 1.32 ± 0.02 volts *vs.* S.C.E. Reduction occurred

---

(6) Ref. 5, pp. 84–85, model III.

only in basic media; there was no change in half-wave potential with *p*H in the basic range. There was no correlation whatsoever between the diffusion current and the lactone concentration. A plot of $\log \frac{(i_d - i)}{i}$ *vs.* E gave a straight line, but the line had a slope of 0.77, indicating irreversibility.

It was further observed that if the lactone was distilled under a nitrogen atmosphere and no oxygen was allowed to come into contact with the polarographic solution, no wave was obtained, and that, after standing in contact with air, solutions of the lactone produced waves with larger diffusion currents, indicating that more oxygen had been absorbed. These facts suggested that the polarographic waves resulted from the reduction, not of β,γ-angelica lactone itself, but, of a peroxide formed spontaneously by the reaction of the lactone with oxygen. This hypothesis was further substantiated by the observation that solutions which gave reduction waves also gave qualitative tests for peroxides and by the failure of levulinic acid, the hydrolysis product of β,γ-angelica lactone, to be reduced polarographically.[7]

A more detailed study of peroxide formation in β,γ-angelica lactone was undertaken by use of the apparatus previously described in which the amounts of oxygen taken up by the lactone could be correlated with the diffusion currents of the polarographic waves. The results of four typical runs on β,γ-angelica lactone at 25° in solutions of *p*H 9.60 are shown graphically in Fig. 3, in which oxygen uptake expressed in millimoles of oxygen per liter of solution is plotted against diffusion current in milliamperes. The lactone concentrations were as follows: run 1, 0.03117 *M*; run 2, 0.03117 *M*; run 3, 0.02865 *M*; run 4, 0.02471 *M*. All runs were made at atmospheric pressure, and the stirring was conducted as uniformly as possible in the four cases. In each run, the polarogram showed that free oxygen was absent from solution until a limiting concentration of peroxide was reached; at this point the peroxide diffusion current remained approximately constant and any decrease in the oxygen volume could be accounted for by an increase in the concentration of free oxygen in solution. If the peroxide may be assumed to be formed by the reaction of one mole of oxygen with one mole of lactone, the fractions of lactone converted to the peroxide at the limiting peroxide concentration, as calculated from the original lactone concentrations and the oxygen uptake, were as follows: run 1, 3.0%; run 2, 1.9%; run 3, 2.7%; run 4, 4.0%. These conversion fractions in all cases correspond to peroxide concentrations in the order of 10^{-3} molar.

Figure 4 shows similar plots of two typical runs made at 0°. The lactone concentrations were 0.02356 and 0.2942 *M*, respectively. Again, no unreacted oxygen remained in solution until the limiting concentration of peroxide was approached. The calculated fractions of conver-

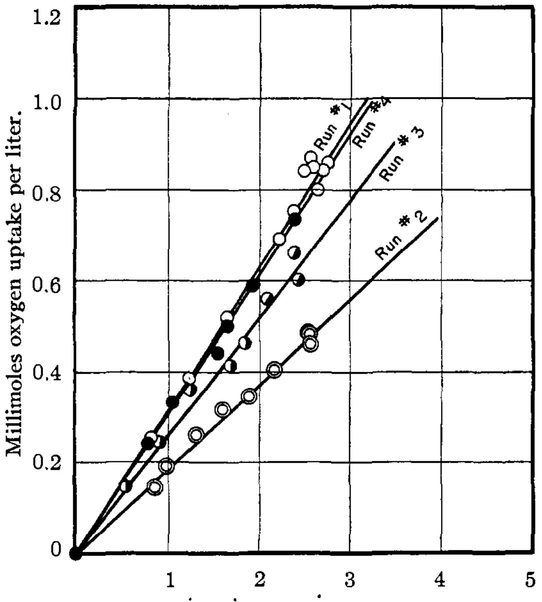


Fig. 3.—Oxygen uptake of β,γ-angelica lactone as a function of diffusion current at 25°.

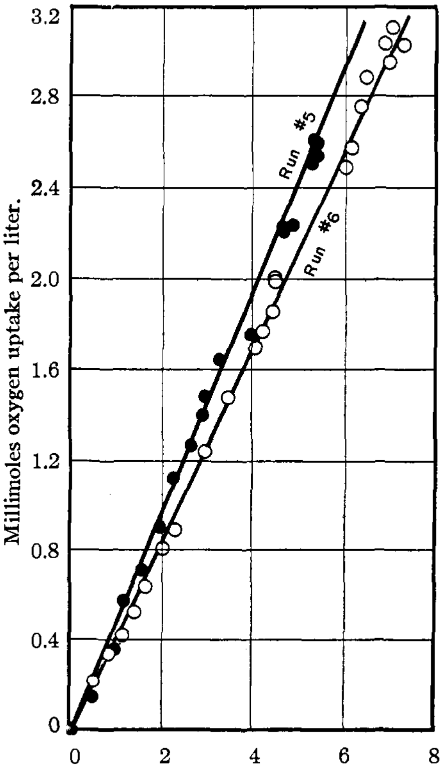


Fig. 4.—Oxygen uptake of β,γ-angelica lactone as a function of diffusion current at 0°.

---

[7] Schwaer, *Coll. Czechoslov. Chem. Commun.*, **7**, 326 (1935), also reported that levulinic acid is non-reducible at the dropping mercury electrode.

sion, 12.1% in run 1, and 11.2% in run 2, were significantly higher than the values for the runs made at 25°.

β,γ-Angelica lactone itself was found to be nonreducible polarographically up to an applied potential of -2.50 volts *vs.* S.C.E.

α,β-Angelica Lactone.—α,β-Angelica lactone was also found to form a peroxide in basic solution which reduced polarographically with a half-wave potential of -1.32 ± 0.02 *vs.* S.C.E. No reduction was observed in neutral or acid media, and the reduction in basic solution was irreversible. 2,3-Dihydroxyvalerolactone, the first oxidation product of α,β-angelica lactone, was found to be non-reducible at the dropping mercury electrode. Plots of oxygen uptake *vs.* diffusion current for three typical runs with α,β-angelica lactone at *p*H 9.60 are shown in Fig. 5. The lactone concentrations were as follows: run 7, 0.02461 *M;* run 8, 0.02271 *M;* run 9, 0.02108 *M* The rate of oxygen uptake for α,β-angelica lactone was considerably slower than that for its β,γ-isomer, and the polarograms revealed that a considerable excess of oxygen remained dissolved in the medium throughout each run. The curves shown in Fig. 5 have been corrected to account for dissolved but unreacted oxygen. The percentage conversions of α,β-angelica lactone to peroxide at the limiting concentrations of peroxide were considerably higher than those for the β,γ-isomer at 25°. The values for the three runs, as calculated from initial lactone concentration and oxygen uptake, were 12.0, 8.8 and 9.2%, respectively.

α,β-Angelica lactone itself was found to be reduced in the absence of oxygen when a solution of 0.1 *M* tetramethylammonium bromide was used as the supporting electrolyte. The reduction proceeded in two steps with half-wave potentials of -1.88 and -1.99 volts *vs.* S.C.E. The wave heights corresponding to these potentials for 0.01 *M* α,β-angelica lactone were approximately 15 and 30 microamp., respectively, when a capillary whose $m^{2/3}t^{1/6}$ value was 2.19 at -1.5 volts was employed. The accuracy of these measurements was no better than ± 0.04 volt because of the close proximity of the waves. There appeared to be a definite correlation between the concentration of the lactone and the wave height, but no diffusion current constant could be obtained.

Discussion of Results

From the variations in the slopes of the plots of oxygen uptake *vs.* diffusion current for β,γ-angelica lactone in Fig. 3, and also for α,β-angelica lactone in Fig. 4, it is obvious that not all of the oxygen taken up is accounted for as reducible peroxide. The formation of peroxide appears to be accompanied by a side reaction or followed by a secondary reaction the rate of which is proportional to the peroxide concentration or is constant for a given run, but which varies somewhat in different runs. If this is the case, the values for the percentage conversions of the lactone to peroxide, as calculated from the oxygen uptake of the lactone, is high in each instance. From the lesser divergence in the slopes of the plots for the runs at 0° as compared with that for the plots at 25°, it appears that this second reaction is not so important a factor at the lower temperature and therefore that it possesses a large temperature coefficient. The ease and extent to which this second reaction takes place are perhaps also closely related to the percentage conversion of lactone to peroxide observable in any given case. From the fact that treatment of either β,γ- or α,β-angelica lactone with oxygen in basic solution results largely in the formation of high boiling and nondistillable materials, it appears likely that this second reaction may be one of polymerization.[8]

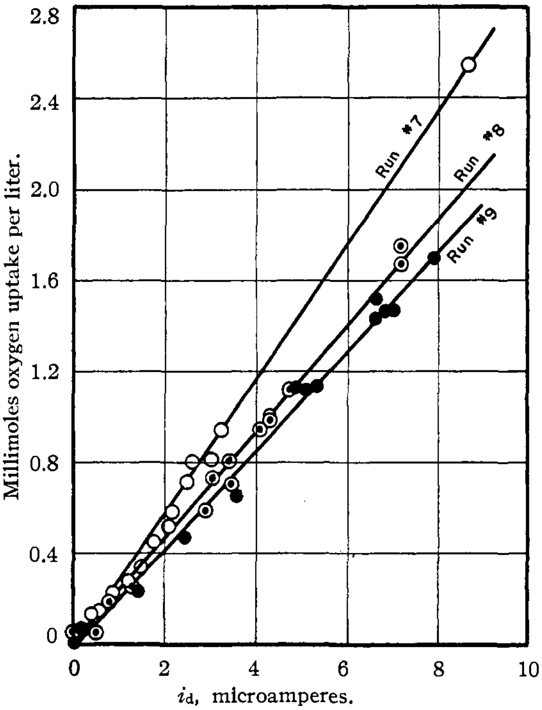


Fig. 5.—Oxygen uptake of α,β-angelica lactone as a function of diffusion current at 25°.

The half-wave potentials for both β,γ- and α,β-angelica lactone peroxides have been found to be the same, namely, -1.32 volts *vs.* S.C.E. Barring an unlikely coincidence, the reducible peroxide formed from β,γ-angelica lactone is identical with that formed from α,β-angelica lactone. The observation that the two lactones form peroxides in basic solution agrees with the findings of Mendez,[9] who attributed the cardiac activity of the lactones to the presence of peroxides. The data of Mendez appear to be consistent with the assumption that the same peroxide is formed from both lactones,

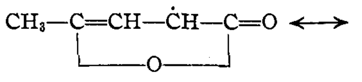
---

[8] Marvel and Levesque, THIS JOURNAL, **61**, 1682 (1939), found that peroxides do not polymerize β,γ-angelica lactone, but their experiments were presumably carried out in a neutral medium.

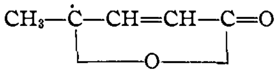
[9] Mendez, *J. Pharmacol. Exp. Therap.*, **81**, 151 (1944).

but much more rapidly in the case of the β,γ-isomer.

If one assumes that the first step in the formation of a peroxide from both β,γ- and α,β-angelica lactone is the removal of an α-methylenic hydrogen atom, the resulting structures, I and II, would be resonance structures of the same radical, and the same peroxide would necessarily be formed in both cases.

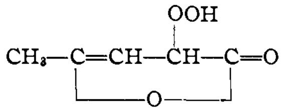


I

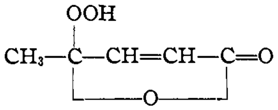


II

This resonance would stabilize the radical and, in all probability, might reduce the activation energy of the primary dehydrogenation process sufficiently to allow the process to occur with reasonable speed at room temperature. Because the conjugated double bond system of α,β-angelica lactone itself is more stable than the isolated system of its β,γ-isomer, it seems likely that the activation energy for the dehydrogenation process should be greater, and hence the rate of reaction slower, in the case of α,β-angelica lactone. Possible structures for the peroxide are III and IV, the latter being the more probable because of its conjugated system of double bonds.

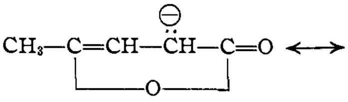


III

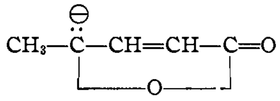


IV

Postulation of the abstraction of a hydrogen atom as the first step in the mechanism of peroxide formation from the lactones does not account for the fact that the peroxide is formed only in basic solution. Hence, an alternative mechanism, which involves the ion (the resonance hybrid represented by structures V and VI) formed by the removal of a proton from either lactone, may be still more plausible. In this mechanism, the free radical (structures I and II) would be formed by the removal of an electron from the ion by an oxygen molecule, which would itself be converted into a superoxide ion.



V



VI

On the basis of such a mechanism, the rate constant for the formation of the peroxide from α,β-angelica lactone should be identical with the rate constant for the acidic ionization of the lactone. Further studies on the mechanism of peroxide formation in these and similar compounds are in progress in this Laboratory.

Summary

1. A study has been made of the behavior of β,γ- and α,β-angelica lactones at the dropping mercury electrode. The β,γ-isomer is non-reducible; the α,β-isomer is reduced in two steps with half-wave potentials of −1.88 and −1.99 volts *vs.* S.C.E.

2. Both β,γ-angelica lactone and α,β-angelica lactone absorb oxygen in basic media with the formation of a peroxide which is reduced irreversibly at the dropping mercury electrode. Inasmuch as the half-wave potential is the same (−1.32 volts *vs.* S.C.E.) for both lactones, it is assumed that the same peroxide is formed in each case. A linear relationship is obtained for each lactone when oxygen up-take is graphed as a function of the diffusion current.

3. Two plausible mechanisms for the formation of the peroxide have been proposed, both of which are consistent with the supposition that the same peroxide is formed from both lactones and with the fact that peroxide formation from β,γ-angelica lactone is much more rapid than that from its α,β-isomer.

Lawrence, Kansas Received July 12, 1949