1-(3-Bromomercuri-2-methoxypropyl)-biuret was similarly prepared; it melted at 180–182° after recrystallization from water. *Anal.* Calcd. for $C_6H_{12}BrN_3O_3Hg$: N, 9.24. Found: N, 9.45.

Compound VII.—A suspension of 15.9 g. (0.05 mole) of mercuric acetate and 13.6 g. (0.05 mole) of mercuric chloride in 150 ml. of methanol was added to a boiling solution of 14.3 g. (0.1 mole) of 1-allylbiuret in 100 ml. of methanol. A solid separated directly but redissolved when the mixture was heated to reflux temperature. The boiling solution, which had been clear for about 1 hr., began to deposit a crystalline product. The mixture was refluxed for a tota of 3 hr., cooled and filtered. The air-dried solid weighed 44 g. (100% yield), m.p. 172–174° dec. One recrystallization from water gave 29 g. (67% yield) of **1-(3-chloromercuri-2-methoxypropyl)-biuret**, m.p. 175–177° dec. alone or mixed with the sample of preparation described above. The aqueous filtrate from the above recrystallization slowly deposited a crystalline solid. This was filtered and air-dried; it weighed 7 g. (16% yield), m.p. 144° dec. Recrystallization from acetonitrile gave **1-(2-chloromercuri-3-methoxypropyl)-biuret**, m.p. 153–155° dec. A mixed m.p. (equal portions) of the two isomers was 150–165° dec. *Anal.* Calcd. for $C_6H_{12}ClN_3O_3Hg$: N, 10.24; Cl, 8.64. Found: N, 10.66; Cl, 8.42.

NEW BRUNSWICK, N. J.

[CONTRIBUTION FROM APPLIED SCIENCE DEPARTMENT, UNIVERSITY OF CINCINNATI]

The Selenium Catalyzed *cis–trans* Isomerization of 9-Octadecenoic (Oleic–Elaidic) Acids

BY J. D. FITZPATRICK[1] AND MILTON ORCHIN

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The selenium-catalyzed elaidinization of oleic acid proceeds *via* π-complex formation between oleic acid and selenium, resulting in the solution of the selenium. At reaction temperature, this complex undergoes isomerization, but concomitantly there is a further reaction to a different species in which the selenium is catalytically inactive and in which the substrate has combined irreversibly with selenium in some type of different σ-complex or compound. At any particular initial concentration of selenium, the pseudo first-order rate equation for a reversible reaction holds. The full rate equation is most accurately expressed as rate $= k_1[\text{Oleic}][\text{Se}_0]^{1/4} - k_2[\text{Elaidic}][\text{Se}_0]^{1/3}$. The mechanism for the isomerization is proposed as given in the text. The rate of the reverse isomerization of elaidic to oleic acid is slower than the elaidinization. The requirement of having a particular species of selenium is demonstrated. The high temperatures are probably required for the dissociation of polyatomic selenium. The generality of π- and σ-complexing with unsaturated compounds is established and the analogy between the reaction of selenium and that of oxygen with olefinic compounds is suggested.

Introduction

One of the most simple and effective methods to achieve the isomerization of oleic acid to its *trans* isomer, elaidic acid, is to treat it at elevated temperatures in the presence of elemental selenium, a reaction first described by Bertram.[2] Accordingly, when a sample of elaidic acid was required in this Laboratory, a commercial (90%) oleic acid was treated by the selenium procedure. After isolation of the elaidic acid, it was noted that during its distillation, some reverse isomerization to oleic acid occurred. This chance observation led us to suspect that a soluble form of selenium might have been responsible for the original isomerization as well and that the selenium-catalyzed isomerization is in reality a rare and hitherto unrecognized example of homogeneous catalysis.

In an elaboration of the reaction, Bertram[3] had studied its kinetics and concluded that the conversion was termolecular. Aside from the dubious validity of the kinetic treatment,[4] the facts that neither the dependence on catalyst concentration nor the fate of the catalyst had been studied further prompted us to re-investigate the reaction.

Experimental

Preparation of Pure Acids. Oleic Acid.—Approximately 6.6 liters of a virgin olive oil was transesterified with methanol and the methyl esters carefully fractionated. About 2.8 liters of esters, b.p. 197–199° (9.5 mm.), was collected and saponified, and the recovered crude oleic acid was further purified by two low temperature crystallizations from acetone containing 10 volume per cent. of water.[5] The final product (1900 g.) was estimated to be better than 99% pure oleic acid (iodine no., neut. equiv., m.p.). The acid was sealed *in vacuo* in small, Pyrex, low-actinic bottles.

Elaidic Acid. Oleic–elaidic acid mixtures secured from various experiments with selenium were combined and crystallized from acetone containing 10 volume per cent. of water. A second crystallization combined with carbon treatment gave pure elaidic acid, m.p. 44.0–44.8°. Heating a sample of this material at 200° for 1 hr. under nitrogen did not change its melting point.

Analytical Procedure.—A satisfactorily accurate method for analyzing 1-ml. samples of the acid mixture from a 100-g. charge was developed which involved a micro-modification of the Cc12-41 AOCS Official Titre or freezing-point method.

In place of the standard titer tube which contains approximately 20 ml. of material, a small 3″ × $^3/_8$″ test-tube was employed. Into this small test-tube there was fitted a copper–constantan thermocouple and a small stirrer. The thermocouple wires led to a cold junction (ice-water) and thence to a d.c. millivoltmeter having a range of 0 to 1.0 millivolt with a scale that made readings to 0.001 m.v. possible.

For the determination, a 1-ml. sample is placed in the sample tube and the bath temperature adjusted to about 10° below the expected titer point. The sample is stirred with the wire loop stirrer until clouding appears. At this point, stirring is discontinued. The needle of the millivoltmeter rises along the scale as solidification proceeds and finally reaches a maximum and then begins to drop. The maximum is the microtiter in millivolts. The readings are reproducible to within 0.002 millivolt corresponding to 0.1 to 0.2°. The composition of the mixture can be read from a plot of microtiter *versus* composition, Fig. 1, which was constructed from the determination of the titer points of samples of known composition using the pure oleic acid as prepared above and a sample of pure elaidic acid (courtesy Eastern Regional Laboratory, Department of Agriculture).

Isomerization Experiments. Apparatus.—The apparatus employed for the isomerization reactions consisted of a 1-l. 3-neck flask mounted with a condenser, stirrer and thermometer. A capillary tube was sealed onto the flask near the center neck. This permitted the insertion of a hypodermic

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[1] Taken in part from this author's Ph.D. thesis.

[2] S. H. Bertram, *Chem. Weekblad*, **33**, 3 (1936).

[3] S. H. Bertram, *ibid.*, **33**, 637 (1936).

[4] J. Stuurman, *ibid.*, **33**, 700 (1936).

[5] J. B. Brown and G. J. Shinowara, THIS JOURNAL, **59**, 6 (1937).

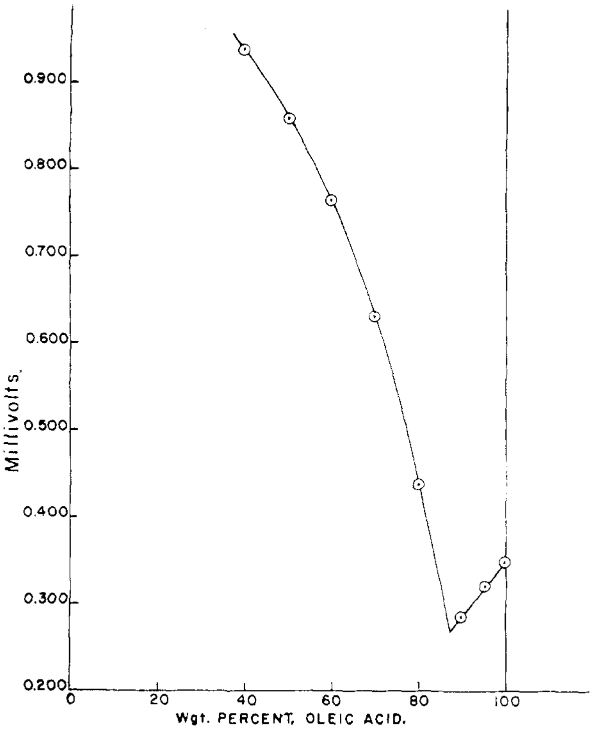

Fig. 1.—Microtiter (m.v.) *vs.* composition of oleic-elaidic acid mixtures.

needle for syringing the 1-ml. samples. Heat was supplied by a mantle connected through a variac to a thermocap relay which in turn was connected to the thermometer by a metal clip. With experience it is possible to control the temperature to ±1° in the temperature range 190–210°. An atmosphere of inert gas is maintained by means of a mercury valve on top of the condenser.

Procedure.—The isomerization experiments were all carried out in essentially the same manner. A typical experiment will be given in detail.

To the reaction flask containing 100.00 g. of oleic acid at 200 ± 1° under helium, there was added with stirring a fragile glass boat containing 0.1000 g. of powdered selenium. The boat was dropped through the condenser opening after momentarily removing the condenser while passing helium through the capillary sampling tube. Timing was begun at the moment the selenium sample was dropped into the reactor. Samples were removed with a 2-ml. syringe after 3, 7, 12, 25, 45, 60 and 90 min. intervals. The samples were cooled immediately by forcing the syringe contents into a small sample vial cooled in ice-water. The samples up to and including the 25-min. sample usually precipitated red selenium on cooling. These samples were filtered while warm through a porcelain microfilter prior to the determination of their titer points.

Results

The results of the rate studies at various temperatures and various initial selenium concentrations are shown in Table I. As typical examples, the data for the experiments at 200° are shown in Fig. 2. At least two important facts are immediately apparent from these curves: (1) the rate of the isomerization increases with increasing initial selenium concentration, and (2) with less than 0.2% selenium, it is not possible to reach the theoretical equilibrium concentration of 66% elaidic acid[6] in a reasonable time. Accordingly, (1) the selenium concentration must enter somehow into the rate equation, and (2) some type of catalyst inactivation reaction is occurring concomitantly with the isomerization.

Table I

Results of Rate Studies with Oleic Acid

Time, min.	190°		200°			210°	
Se, wt. %	0.10	0.20	0.05	0.10	0.20	0.10	0.20
	Percentage elaidic acid						
3	2.0	4.0	7.0	13.9	13.7	21.0	22.8
6							39.8
7	9.0	13.6	21.8	26.5	28.3	40.7	
9							52.0
12	19.7	24.8	32.0	38.0	42.7	54.0	59.5
18	29.3	34.0	40.5	49.4	54.2	60.1	65.7
25	38.0	43.5	46.3	55.0	62.0	62.0	
45	53.8	60.5	50.5	61.0	67.0	64.6	
60	58.8	66.0	51.7	62.0	67.0	65.5	
90	62.0		53.0			67.0	
95		67.0		64.0	67.0		

Dependence of Rate on Concentration of Oleic Acid.—The isomerization of oleic to elaidic acid is a reversible equilibrium reaction

$$A \underset{k_r}{\overset{k_f}{\rightleftarrows}} B$$

The rate of approach to equilibrium for the forward reaction is given by the differential equation

$$-\mathrm{d}A/\mathrm{d}t = k_f[A] - k_r[B]$$

which on integration gives

$$\ln \frac{A_0 - A_e}{A - A_e} = (k_f + k_r)t$$

where A_0 is the initial concentration of A, A_e is the concentration of A at equilibrium and A is the concentration of A at any time, t. In the oleic acid isomerization $A_0 = 100\%$, $A_e = 33\%$ and using $k' = k_f + k_r$ the rate equation becomes

$$\log (\%\ \text{Oleic} - 33) = \frac{-k't}{2.303} + \log 67$$

This is the equation of a straight line, the slope of which gives the value of k', the pseudo first-order rate constant. When the data of Table I are plotted according to the equation above, satisfactory straight lines are obtained in all experiments, especially during the first 70–80% of the isomerization. As a typical example, the data secured at 200° with 0.2% initial selenium are shown in Fig. 3. The values of the pseudo first-order rate constants for the reactions at various temperatures and selenium concentrations are shown in Table II.

Table II

Pseudo First-order Rate Constants (k', Min.$^{-1}$) for the Selenium-catalyzed Isomerization of Oleic Acid

Se concn., wt. %	Temperature, °C. 190	200	210
0.05		0.056	
.10	0.035	.069	0.137
.20	.043	.085	.166

The least square method was applied to the linear portion of the semi-log plots (70–80% of the reaction).

Dependence of Rate on Selenium Concentration.—The pseudo first-order rate constants apply to the rate equation

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[6] H. N. Griffiths and T. P. Hilditch, *J. Chem. Soc.*, 2315 (1932).

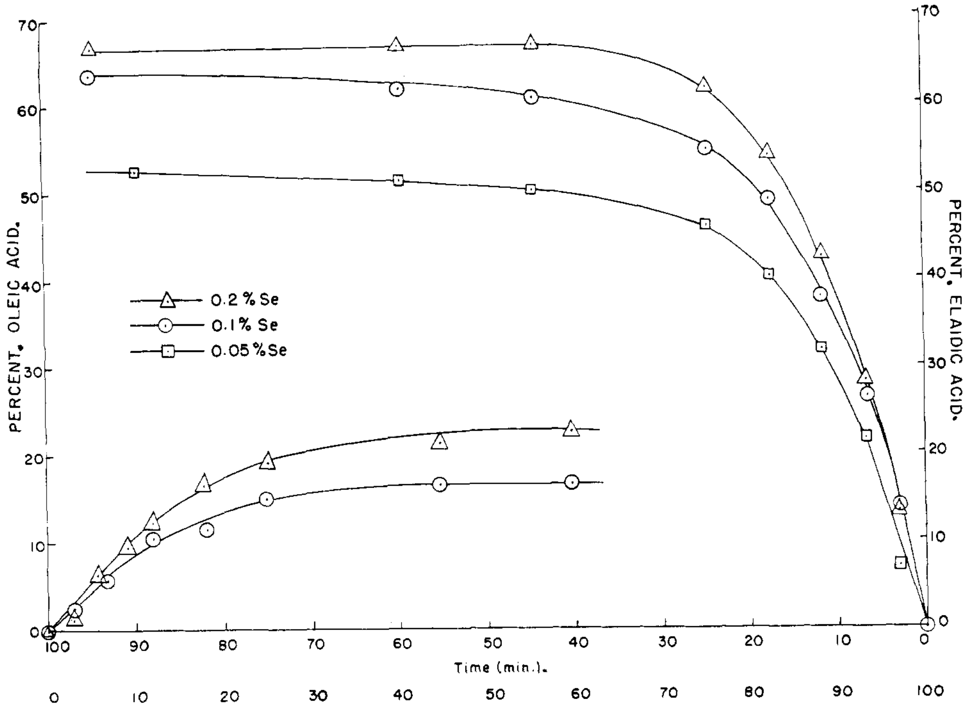

Fig. 2.—Rate curves for isomerization of pure oleic and elaidic acids at 200°.

$$\frac{-\mathrm{d}[\text{Oleic}]}{\mathrm{d}t} = k'_1[\text{Oleic}] - k_2'[\text{Elaidic}]$$

where the k'_1 and k'_2 include the initial concentration of selenium. The true rate equation is therefore

$$\frac{-\mathrm{d}[\text{Oleic}]}{\mathrm{d}t} = k_1[\text{Oleic}][\mathrm{Se}_0]^{1/n} - k_2[\text{Elaidic}][[\mathrm{Se}_0]^{1/n}$$

where $[\mathrm{Se}_0]$ is the initial concentration and n is some integer. It is apparent from these equations that

$$k'_1 + k'_2 = (k_1 + k_2)[\mathrm{Se}_0]^{1/n} \text{ or } k' = k[\mathrm{Se}_0]^{1/n}$$

where $k' = k'_1 + k'_2$ and $k = k_1 + k_2$. Now, since k' the pseudo first-order rate constants were found experimentally and $[\mathrm{Se}_0]$ was measured, it is of importance to learn what value of the exponent gives a constant value for the true over-all rate constant k.

The value of this exponent can be calculated in the following manner: Since

$$k' = k[\mathrm{Se}_0]^{1/n}$$

taking the log of both sides gives

$$\log k' = \frac{1}{n} \log [\mathrm{Se}_0] + \log k$$

from which it is apparent that a plot of log k' *vs.* log $[\mathrm{Se}_0]$ is a straight line whose slope is $1/n$. Figure 4 shows such a plot for data at 200°. The value of n calculated from the slope of the straight line is 3.3. Similar calculations from data at 190 and 210° give values of n = 3.4 and 3.6, respectively. The best integral value for n thus appears to be either 3 or 4. The value of n = 3 appears attractive for reasons which will become apparent later.

Isomerization of Elaidic Acid.—Rate studies of the isomerization of elaidic to oleic acid were made at 200° with selenium concentrations of 0.1 and 0.2 weight per cent. For analysis, the samples collected during the rate studies were diluted with known weights of pure oleic acid so that the composition would lie on a portion of the titer–composi-

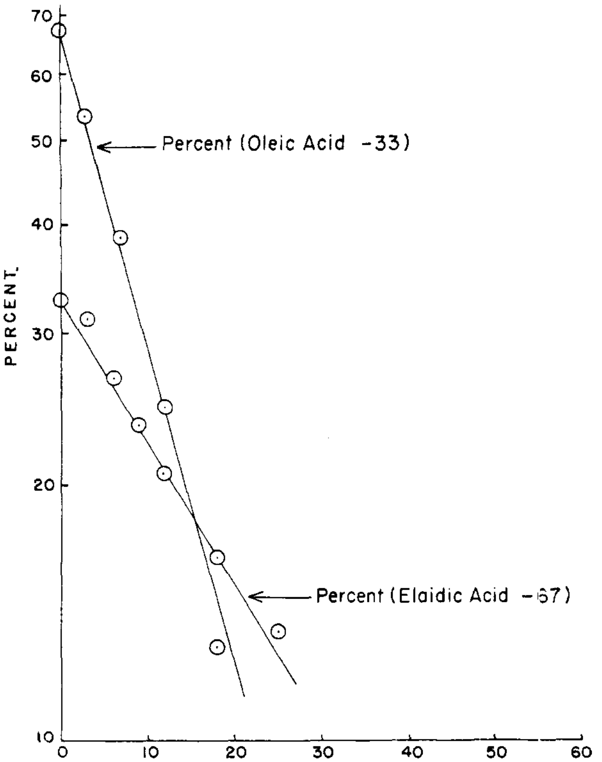

Fig. 3.—Semi-log plot for isomerization of pure oleic and elaidic acids; 200° and 0.2% selenium.

tion curve (Fig. 1) more suitable for analysis. The data secured in the two experiments are plotted in Fig. 2; these curves illustrate the dependence of rate upon the initial selenium concentration and also demonstrate that a catalyst inactivation is occurring. As a matter of fact, the disappearance of catalyst is much more rapid with elaidic acid than with oleic acid since even at 0.2% initial concentration, after 60 minutes only about 23% of the possible 33% elaidic was isomerized, whereas under comparable conditions but starting with oleic acid, equilibrium concentrations (66% elaidic) were obtained.

The semi-log plot (Fig. 3) of the data in Fig. 2 again shows the pseudo first-order rate dependence on substrate. The pseudo first-order rate constants for comparable reactions starting with oleic and elaidic acids are shown in Table III. The exponential value for the selenium concentration in the rate equation has a value of almost exactly $^1/_3$ and is thus approximately equal to that found for the oleic acid substrate.

Table III

Comparison of Pseudo First-order Rate Constants, k' (Min.$^{-1}$), 200°

Se_0 concn., wt. %	Elaidic acid	Oleic acid	Ratio
0.10	0.031	0.069	2.2
.20	.038	.085	2.2

Energy of Activation.—When the pseudo first-order rate constants shown in Table II are plotted against the reciprocal of the absolute temperature, straight lines are secured, as shown in Fig. 5. The slope of these lines gives the activation energy (Arrhenius equation). It is apparent that the slopes at the two catalyst concentrations are identical; both give a value for the activation energy of 30 kcal.

Discussion of Results

The Role of Selenium and Its Fate in the Reaction. π-Complexes.—When 0.05 to 0.2% black, crystalline, selenium is added to oleic acid at 200°, the selenium gradually goes into "solution." On cooling during the early stages of the reaction, a red form of selenium precipitates. With continued heating the selenium no longer precipitates on cooling and at this stage the catalyst is no longer effective in achieving additional isomerization; in other words some type of catalyst inactivation has occurred.

The precipitated red selenium is indeed pure elemental selenium as established by chemical analysis. Its activity as a catalyst for the isomerization is identical with the black form. At no time during the reaction does any form of selenium appear in the vapor phase in detectable amounts.

The selenium which has "dissolved" *irreversibly* in either oleic or elaidic acid appears to be chemically bound to the substrate since dilution with petroleum ether does not cause any precipitation. Heating such "solutions" of selenium in oleic acid at 250° causes the selenium to become active again for isomerization. Conceivably double bond migration is also occurring at this temperature, but this possibility was not investigated.

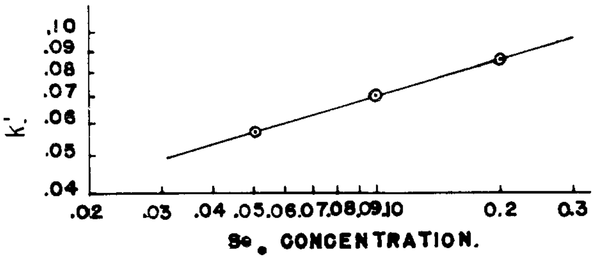

Fig. 4.—Log-log plot of K' against initial selenium concentration, 200°.

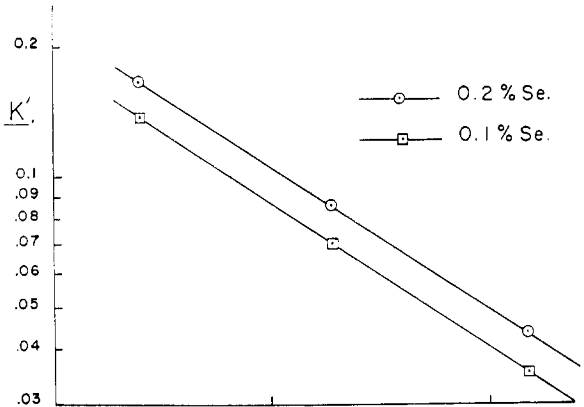

Fig. 5.—Dependence of rate constant on temperature.

Although black selenium does not go into "solution" rapidly in oleic acid, relatively large quantities can be made to disappear irreversibly from the solid phase. Thus after heating about 6 g. of selenium with 300 g. of commercial oleic acid, a "solution" containing about 1.8% of selenium was secured. This "solution" on further treatment "dissolved" additional selenium slowly.

The initial reaction of selenium with oleic or elaidic acid appears almost certainly to be due to the formation of some type of reversible complex which involves bonding between the double bond of the substrate and selenium. This complex apparently forms at elevated temperature; on cooling, the complex dissociates into its constituents. This complex will hereafter be called a "π-complex" since the complex formation involves the π-electrons of the double bond contained in the substrate. Several such π-donor–acceptor complexes have been discovered in recent years; the more common ones are olefin–silver ion and aromatic–iodine complexes. That the double bond is involved in the complexes with oleic and elaidic acids was shown by the failure of stearic acid to dissolve selenium. That the acid function in the unsaturated acids was not involved was shown by positive complexing of selenium with methyl oleate, oleyl alcohol[7] and the mixture of unsaturated hydrocarbons secured by decarboxylation of oleic acid. A list of compounds and their ability to form π-complexes is shown in Table IV. The presence of π-electrons which are not too highly delocalized by conjugation (negative results with diethyl maleate) appears to

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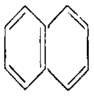
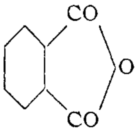
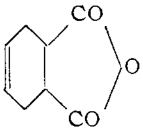
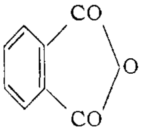
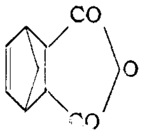
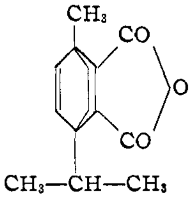
(7) D. Swern, E. F. Jordan and H. B. Knight, This Journal, **68**, 1673 (1946).

TABLE IV

BEHAVIOR OF SELENIUM WITH CERTAIN ORGANIC COMPOUNDS AT 200°

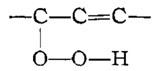
Compound	Formula	Forms[a] π-complex	Forms[a] σ-complex
Stearic acid	$CH_3(CH_2)_{16}CO_2H$	No	No
Methyl oleate	$CH_3(CH_2)_7CH{=}CH(CH_2)_7CO_2CH_3$	Yes	Yes
Undecylenic acid	$CH_2{=}CH(CH_2)_8CO_2H$	Yes	Yes
Cinnamic acid	$C_6H_5CH{=}CHCO_2H$	Yes	No
Diethyl maleate	$C_2H_5O_2CCH{=}CHCO_2C_2H_5$	No	No
Stilbene	$C_6H_5CH{=}CHC_6H_5$	Yes	No
Biphenyl	$C_6H_5{-}C_6H_5$	Yes	No
Naphthalene		Yes	No
Hexahydrophthalic anhydride		No	No
Tetrahydrophthalic anhydride		Yes	Yes
Phthalic anhydride		No	No
Bicyclo[2.2.1]-5-heptene-2,3-dicarboxylic anhydride		Yes	Yes
1-Methyl-4-isopropylbicyclo-[2.2.2]5-octene-2,3-dicarboxylic anhydride		Yes	No

[a] A π-complex is assumed if Se "dissolves" in the substrate at 200°; if the Se does not reappear on cooling, the formation of σ-complex is assumed.

be essential for the π-complex. Complexing with aromatic hydrocarbons was to be expected on the basis of analogous behavior of such hydrocarbons with other acceptors such as iodine, silver ion or Lewis acids like aluminum chloride.

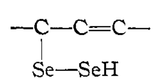
σ-Complexes.—Heating small quantities of selenium with oleic acid at 200° results in the gradual disappearance of the solid phase. If the heating is interrupted in the early stages, red selenium precipitates, but if the heating is continued, cooling no longer results in the precipitation of selenium. Apparently, the π-complex which initially forms is converted to another species in which the selenium is tied up more completely at 200°. This new species very likely is some compound in which the selenium is attached to a particular carbon atom rather than being complexed at the double bond. Because the bonding between the carbon atom and selenium involves σ-bonds, this type of compound or complex will be called a σ-complex. The π–σ nomenclature thus has essentially the same significance as when these terms are used to describe catalytic effects in electrophilic substitution.[8]

The exact nature of the σ-complex has not been established. It is of interest to recall that the attack of oxygen on an unsaturated acid is presumed to occur initially at the double bond. This initial complex is then thought to rearrange, and one of the isolable[9] rearrangement products is a hydroperoxide of the structure



$$\begin{array}{l}—\underset{\displaystyle |}{C}—C{=}C— \\ \;\;O—O—H\end{array}$$

It is conceivable that the π-complex with selenium rearranges to a compound analogous to the hydroperoxide, *viz.*,



$$\begin{array}{l}—\underset{\displaystyle |}{C}—C{=}C— \\ \;\;Se—SeH\end{array}$$

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[8] H. C. Brown, in "Chemistry of Petroleum Hydrocarbons," Vol. III, edited by B. T. Brooks, C. E. Boord, S. S. Kurtz and L. Schmerling, Reinhold Publishing Corp., New York, N. Y., 1955.

[9] F. D. Gunstone and T. P. Hilditch, *J. Chem. Soc.*, 1022 (1946).

Such a "hydroperselenide" might be unstable at high temperatures just as hydroperoxides are known to be unstable. The catalytic reactivation of selenium at 250° probably is due to the decomposition of this σ-complex. As a matter of fact, the solubility of this complex in oleic and elaidic acid and its decomposition at 250° is the explanation for the original observation which prompted this investigation.

It is of more than casual interest to report that as a result of some preliminary experiments it was deduced that the rate at which linoleic acid forms a σ-complex with selenium is about 20 times as great as with oleic acid. The relative rates of oxidation of methyl oleate, linoleate and linolenate at 20° are 1:12:25.[10]

If the σ-complex is in reality an unstable hydroperselenide, then its formation requires the presence of at least one hydrogen atom in the carbon atom alpha to the double bond. The results shown in Table IV demonstrate that only those compounds forming a π-complex that have an α-hydrogen atom can form a σ-complex.

The Molecular Aggregation of Selenium.—The selenium employed was a commercially available black powder (Fisher Scientific Co., reagent grade). Microscopic examination indicated that it had an average particle size of about 10 μ. X-Ray analysis showed it to be crystalline (hexagonal).

In order to eliminate the possibility that the selenium contained impurities that might affect the catalytic activity, a sample of a special high purity selenium was secured from the American Smelting and Refining Co. This pure material came in pelleted form and on arrival was ground in an agate mortar in a helium atmosphere to a particle size of about 10 μ. Isomerization experiments with this material showed it to be almost completely inactive!

It was noted during this isomerization experiment that the selenium had agglomerated into a single lump, owing to softening and flow of the selenium at 200°. This behavior is characteristic of the vitreous or glassy form of selenium, and indeed when some of the regular black crystalline selenium was fused under nitrogen and then plunged into water, a vitreous form of selenium, also catalytically inactive, was secured.

Some of the specially pure, pelleted selenium was converted to the crystalline form by sealing a few pellets in an evacuated tube and heating at 150° for 48 hr. The pellets first softened, agglomerated slightly and then hardened to the crystalline form, m.p. 217.4°. This converted selenium was pulverized to approximately 10-μ size in a helium atmosphere and an isomerization experiment with oleic acid performed. The pseudo first-order rate constant calculated from the data secured in this experiment was 0.069 min.$^{-1}$ compared to the identical value secured with the commercial crystalline variety.

Vitreous selenium is a polymeric form of selenium made up of linear chains randomly crosslinked[11] and in this respect is similar to plastic sulfur. Other forms of solid elemental selenium are hexagonal (gray or black crystalline), red amorphous and two forms of red crystalline, both of which are assumed to consist of eight-membered rings. In the red amorphous as well as the gray crystalline, the linear structure is assumed.

Selenium in solution has been reported to be anywhere from one to ten atomic. Eight atomic selenium is reported to exist in a number of solvents, such as biphenyl, on the basis of ebullioscopic measurements.[12]

In the vapor state, the equilibrium

$$Se_6 \rightleftarrows 3Se_2$$

exists even at temperatures as low as 200–250°. Increasing the temperature increases the dissociation. Also Se_8 has been reported to exist in the vapor state[13]; this dissociates as

$$\begin{tikzcd}
Se_8 \arrow[r, shift left] & Se_6 \arrow[l, shift left] \arrow[d, shift right] + Se_2 \\
 & 3Se_2 \arrow[u, shift right]
\end{tikzcd}$$

In the isomerization reactions at 200°, the rate has been shown to be proportional to the initial selenium concentration taken to the $^1/_3$ power. This fractional exponent dependence becomes reasonable in terms of the above dissociation of Se_6, and the fact that the exponent best fitting the kinetic data was slightly less than $^1/_3$ may be explained by contributions from the dissociation of an Se_8 structure. Although one would expect π-complexes to be more stable at low rather than high temperatures, the existence of the oleic (or elaidic)–selenium π-complex only at high temperature may be due to the fact that such temperatures are required for the dissociation of the polyatomic selenium.

The Mechanism of the Reaction.—Any mechanism proposed for the elaidinization reaction must not only be consistent with the pseudo first-order rate behavior expressed as rate = k'_1[Oleic] − k'_2[Elaidic] but must also be consistent with the full rate expression

$$\text{rate} = k_1[\text{Oleic}][Se_0]^{1/3} - k_2[\text{Elaidic}][Se_0]^{1/3}$$

Furthermore, the mechanism also must be consistent with the fact that the over-all rate of the elaidic to oleic isomerization is not equal to but considerably less (1:2.2) than the elaidinization of oleic acid. The inequality of the over-all forward and reverse reactions possibly may be due to a more rapid "inactivation" or σ-complexing of the elaidic acid with selenium, but experimental evidence for this assumption is lacking.

The following mechanism is proposed

$$Se_6 \overset{\text{fast}}{\rightleftarrows} 3Se_2$$

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[10] F. D. Gunstone and T. P. Hilditch, *J. Chem. Soc.*, 836 (1945).

[11] W. Hückel, "Structural Chemistry of Inorganic Compounds," Vol. II, Elsevier Publishing Co., New York, N. Y., 1951, p. 795.

[12] Gmelin, *Handbuch anorg. Chem.*, **10**, 150 (1953).

[13] Yost and Russell, "Systematic Inorganic Chemistry," Prentice-Hill, Inc., New York, N. Y., 1944, p. 284.

$$\begin{tikzcd}
\text{Oleic} + Se_2 \arrow[r, shift left, "\text{(fast)}"] & \text{Oleic}\cdot Se_2(\pi) \arrow[l, shift left] \arrow[r] \arrow[d, shift left, "\text{(slow)}"] & \text{Oleic}\cdot Se_2(\sigma) \\
\text{Elaidic} + Se_2 \arrow[r, shift left] & \text{Elaidic}\cdot Se_2\ (\pi) \arrow[l, shift left, "\text{(fast)}"] \arrow[r] \arrow[u, shift left] & \text{Elaidic}\cdot Se_2\ (\sigma)
\end{tikzcd}$$

The pseudo first-order rate dependence on substrate means that the active catalytic species is remaining essentially constant at any particular initial concentration of selenium during the major portion of the isomerization reaction. The dissociation of selenium and the establishment of the equilibrium concentration of complexed selenium must be fast. The rate-determining isomerization of one π-complex to the other continues until the selenium is consumed by conversion to the σ-complex. The essential constancy of concentration of complexed selenium at any particular initial concentration of selenium can be determined experimentally and such work is in progress.

The complete rate equation shows the selenium dependence. The known occurrence of an Se_6 species and its dissociation to Se_2 lend credence to the fractional exponent in the rate equation. Also the specificity of the crystalline modification of selenium indicates the necessity of having a special form of selenium available. The increase in rate with increasing concentration of initial selenium is explained by the increased concentration of the π-complex which is essential in order to satisfy the equilibrium constant for the π-complex.

The above "mechanism" does not detail the exact nature of the bonding either in the π- or the σ-complex. The π-complex possibly involves the π-orbital of the olefin and the anti-bonding π-orbital of selenium, but this is conjecture and until further evidence is available it is felt that discussion of the exact bonding in the complexes would not be fruitful.

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CINCINNATI 21, OHIO

[CONTRIBUTION FROM THE ORGANIC CHEMICAL RESEARCH DEPARTMENT, RESEARCH DIVISION, AMERICAN CYANAMID CO.]

Synthesis of Certain 3-Hydroxy-3-phenylpropylsulfonium Salts. Sulfonium Analogs of Artane (Trihexyphenidyl) and Pathilon (Tridihexethyl Iodide)

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Sulfonium analogs (I) of the antispasmodic Artane (trihexyphenidyl) and the gastric secretion inhibitor Pathilon (tridihexethyl iodide) have been prepared by condensation of several 3-alkylmercapto-1-phenylpropan-1-ols (IV) with methyl, ethyl, allyl, propargyl and benzyl halides. 1-Cyclohexyl-3-methylmercapto-1-phenylpropan-1-ol (V), which reacts "normally" with the above halides, unexpectedly gave (3-cyclohexyl-3-hydroxy-3-phenylpropyl)-dimethylsulfonium iodide (VIa) when treated with propyl, butyl or amyl iodide. Other anomalous results are reported. The antispasmodic and gastric secretion inhibitory activities are given.

In the search for more useful pharmaceutical agents, sulfonium salts are interesting as analogs of pharmacologically active ammonium derivatives. Sulfonium salts are not only analogs of the quaternary ammonium compounds, but they also may be considered analogs of the tertiary amines, insofar as the pharmacological activity of the amines is mediated by their protonated derivatives, the tertiary ammonium salts. Various sulfonium analogs of pharmacologically active ammonium compounds and amines have been reported. These include analogs of the muscle contracting agent, tetramethylammonium iodide,[1,2] of acetylcholine,[3,4] of the curare-like succinylcholine[5] and decamethonium (decamethylene bistrimethylammonium iodide),[6a] of the hypotensive agents pentamethonium (pentamethylene bistrimethylammonium iodide)[6a] and hexamethonium (hexamethylene bistrimethylammonium iodide),[6b] of the antispasmodics Trasentine[6c] (β-diethylaminoethyl diphenylacetate hydrochloride)[7,8a] and Pavatrine[8b] (β-diethylaminoethyl fluorene-9-carboxylate),[7,8a] of the antihistaminic Benadryl[8c] [dimethyl-(2-benzhydroloxyethyl)-amine][9] and of the sympathomimetic β-hydroxy-β-phenylethylamines.[10,11]

We wish to report the preparation of sulfonium compounds of the type represented by structure I. These compounds are analogs of the gastric

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