Summary

Sterols may be isolated and separated as steryl sulfates because of their (1) ease of formation in quantitative yields, (2) insolubility in lipid solvents, (3) inexpensiveness when compared to digitonides, which are commonly employed due to their insolubility in lipid solvents.

Three examples are given. (1) Cholesterol was removed from a reaction mixture, i. e., the thermal decomposition products of calcium and potassium cholesteryl sulfates. (2) Cholesterol was quantitatively separated from its ester, i. e., cholesteryl acetate. (3) Ergosterol was isolated from a natural product, i. e., brewer's yeast.

BROOKLYN, N. Y.   RECEIVED OCTOBER 10, 1941

[CONTRIBUTION No. 256 FROM THE RESEARCH LABORATORY OF ORGANIC CHEMISTRY OF THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY]

The Partial Reduction of Acetylenes to Olefins Using an Iron Catalyst. II. Enyne and Dienyne Reduction[1]

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Not much has been published describing partial hydrogenation of the triple bond in substances containing the conjugated enyne and dienyne systems. Zal'kind and Khudekova[3] reported the formation of 5-methyl-heptadiene-1,3-ol-5 by the addition of one molecule of hydrogen to the corresponding vinylethynylcarbinol, in the presence of a palladium-starch catalyst. Golovchanskaya,[4] by electrolytic reduction of the same vinylethynyl derivative, obtained a very complex mixture of products, with evidence of 1,4 addition, 1,2 addition and isomerization. The production of butadiene by partial reduction of vinylacetylene has been patented.[5] Blomquist and Marvel,[6] have described experiments designed to introduce one molecule of hydrogen into divinylacetylene, using platinum oxide as a hydrogenation catalyst, but they obtained a mixture of products.

Partial hydrogenation of enynes and dienynes is most unpromising unless a catalyst is used which acts selectively on the acetylenic link. Otherwise a complex mixture of hydrocarbons is very likely to result, difficult to separate due to small differences in properties of the component hydrocarbons. Thus, electrolytic reduction as practiced by Golovchanskaya[4] and hydrogenation with most catalysts are likely to give discouraging results. However, palladium and Raney nickel[7] have been shown to exhibit a selective action which makes hydrogen attack on the triple bond proceed virtually to completion before the olefin linkage begins to be reduced. In addition, these catalysts have a further important characteristic; when all acetylenic linkages have been partially reduced, further hydrogenation of the double bonds proceeds at a measurably slower rate. Recently, Paul and Hilly[8] reported the preparation of an iron catalyst which was not only selective but had the valuable property of catalyzing acetylene hydrogenation without being measurably effective in catalyzing reduction of olefins. In the first paper of this series,[1] the properties of this iron catalyst were studied, and Paul and Hilly's results to some extent confirmed. Most interesting was the isolation of isoprene, characterized as its maleic anhydride addition product, from persistent reduction of the corresponding methylvinylacetylene derivative. This result suggested possible application of the iron catalyst for partial reduction of enynes and dienynes now being prepared in connection with synthetic work in progress in this Laboratory.

The hydrogenation of a number of acetylenes, most of them enynes and dienynes, has been studied in the presence of the iron catalyst. It can now definitely be stated that the catalyst is not completely specific for the carbon–carbon triple bond. On the other hand, all the evidence available shows that the substance has the same selective action as palladium and Raney nickel, and that there is a marked decrease in the rate of reduction of the olefin as compared with the acetylene. Moreover, in a number of cases the

(1) First paper of this series: THIS JOURNAL, **62**, 2555 (1940).

(2) From the thesis submitted by E. N. Shaw to the Massachusetts Institute of Technology in partial fulfillment of the requirements for the degree of Bachelor of Science.

(3) Zal'kind and Khudekova, J. Gen. Chem. (U. S. S. R.), **10**, 435 (1940).

(4) Golovchanskaya, ibid., **10**, 521 (1940).

(5) U. S. Patents 1,920,242 and 2,207,070.

(6) Blomquist and Marvel, THIS JOURNAL, **55**, 1655 (1933).

(7) Campbell and O'Connor, ibid., **61**, 2897 (1939). This paper includes numerous references to earlier investigations of partial hydrogenation.

(8) Paul and Hilly, Bull. soc. chim., [5] **6**, 218 (1939).

effect observed by Paul and Hilly, that reduction ceases after the triple bond has been reduced, has been confirmed. The specific action of the catalyst is marked when both triple bonded carbon atoms are substituted, R—C≡C—R. In only one special case, that of tolane, has the hydrogenation of acetylenes of this structure proceeded beyond the olefin stage. On the other hand, true acetylenes, RC≡C—H, behave differently, the olefin is reduced more slowly, but always at an appreciable rate. Curves illustrating the behavior of different types of acetylene derivatives are included in Fig. 1.

Fig. 1.—⊕, 0.300 mole $R_2C(OH)$—C≡CH; ⊙, 0.275 mole RCH=CR—C≡CH. The third curve represents the average of many hydrogenations of compounds RCH=CR'—C≡CR". These substances were always reduced at nearly the same rate as other acetylene derivatives and no hydrogen was ever introduced beyond the amount equivalent to one double bond. The curve thus represents the behavior of these substances.

Since acetylenes of structure R—C≡C—R seem to be specifically affected by the catalyst, the possibility arises of studying the course of reduction of enynes (R—C≡C—CR=CHR) and dienynes. Three enynes of the above structure were hydrogenated with the iron catalyst and the products isolated. It was interesting to note that all these products formed constant boiling mixtures with the alcohol used as solvent for the

reductions, so that this always had to be removed by washing with water. Although hydrogenation was always allowed to run until no more gas was absorbed, the products in every case contained two double bonds, as evidenced by their consumption of hydrogen with platinum oxide. The structures of the products were indicated to be 1,3-butadienes, since the exaltation of molecular refraction in every case corresponded to that of a 1,3 conjugated system. Further, each of the compounds reacted with maleic anhydride to form amorphous acid products of polymeric character. The tendency of highly substituted butadienes to yield polymeric products with maleic anhydride is well known;[9] however, since these products were acids and maleic anhydride itself yields no polymer under these conditions, it may be inferred that addition took place, and that these reduction products are conjugated olefins and not allenes.

This evidence indicates that hydrogen, in the presence of this iron catalyst, attacks the triple bond of the enyne to yield a 1,2-addition product, since the allene formed by 1,4-addition to the enyne system would be expected to have properties quite different from those actually found. Moreover, isomerization of such an allene would not normally yield a butadiene; allenes in general produce acetylenes rather than conjugated dienes on isomerization.

In contrast, hydrogenation of two divinylacetylene derivatives, in the presence of the iron catalyst, seemed to take a different course. The reductions stopped at a point equivalent to addition of one molecule of hydrogen; the products appeared homogeneous and analyzed for three double bonds. The reduction products did not have the properties of conjugated triolefins; they showed normal molecular refraction values, and were surprisingly stable, showing no tendency to oxidize or polymerize, although the parent divinylacetylene derivatives would set to jelly in a few days. Attempts are in progress to settle the question of their structures more definitely, but at present they are assigned the structures of allenes, formed by 1,4-addition of hydrogen across one of the conjugated systems of double and triple bonds

$$RCH=\overset{\overset{\displaystyle R}{|}}{C}-C\equiv C-\overset{\overset{\displaystyle R}{|}}{C}=CHR \longrightarrow$$

$$RCH_2-\overset{\overset{\displaystyle R}{|}}{C}=C=CH-\overset{\overset{\displaystyle R}{|}}{C}=CHR$$

(9) Bacon and Farmer. J. Chem. Soc., 1065 (1937).

This represents the course of hydrogen addition to dienynes as the same as that of chlorine and hydrogen chloride as investigated by Carothers,[10] who obtained allene derivatives with the arrangement of double bonds shown above, which were not isomerized to conjugated trienes, in contrast to the behavior of corresponding 1,4-addition products obtained from enynes, which readily rearranged. Also, allenes of this structure were shown by Carothers[10] to exhibit no exaltation of molecular refraction.

Work is in progress to establish the mechanism of hydrogenation of enynes and dienynes with this catalyst, which, it is felt, is an exceptionally well adapted tool for the purpose. Study of its action on conjugated systems, other than those containing only carbon atoms, is also in progress.

Experimental

The active iron catalyst was prepared from an iron–aluminum alloy as previously described.[1] It should be noted that the time necessary for complete reaction of the alloy is often much greater than stated by Paul and Hilly,[8] and as long as twenty-four hours at 80° may be required. Numerous samples of catalyst were prepared, and wide differences in activity of different samples, prepared as nearly as possible in the same way, were observed. However, every sample prepared was an active hydrogenation catalyst, and no important difference in the selective action of the catalyst, made in different batches, was ever observed.

Hydrogenation of Diisopropylethynylcarbinol.—This substance was chosen as a typical R—$C{\equiv}C$—H compound of the kind needed to be studied in connection with other work in this Laboratory. Preliminary experiments indicated that reduction did not stop at the olefin stage. Accordingly, measurements were made of the rate of reduction at 100° with an initial pressure of 1,000 lb., in alcohol solution. The rate was followed by the change in pressure in a calibrated apparatus. In each case it was found that reduction was slower after one molecule of hydrogen was introduced, but that it did continue at about one-fourth of the average value for the first stage of reduction. Typical results are included in Fig. 1. The selective action of the catalyst was demonstrated by a number of experiments when the reduction was stopped at the theoretical half-way point. The unsaturated carbinol, when isolated, gave no silver test for acetylenic hydrogen, under conditions which had been demonstrated to give a precipitate if 5% of acetylenic carbinol was present.

$$R$$
$$|$$
Hydrogenation of $RCH{=}C$—$C{\equiv}CH$ Vinylacetylene Derivatives.—The only hydrocarbon of this type which had been investigated was 2-methylbutene-1-yne-3, which was found[1] to yield isoprene after twenty-four hours of

reduction with the iron catalyst. Two additional vinylacetylenes were tested, 3-ethylpentyne-1-ene-3 and 3-n-propylhexyne-1-ene-3. These substances were prepared from the corresponding acetylenic tertiary carbinols by a modification of the procedure described by Thompson, Burr and Shaw.[11] The carbinol was slowly dropped into boiling acetic anhydride, containing 5% of p-toluenesulfonic acid, the mixture being well stirred, and the carbinol added at such a rate that the vinylacetylene derivative distilled out smoothly. Under these conditions, the vinylacetylene derivatives were obtained in 50–60% yield in a number of runs: 3-ethylpentyne-1-ene-3, $CH_3CH{=}$
C—$C{\equiv}CH$, b. p. 96.5° C., $n^{25}D$ 1.4338, $d^{25}{}_{4^\circ}$ 0.7886;
$|$
C_2H_5
　　　　　　　　　　　　　　　　　C_3H_7
　　　　　　　　　　　　　　　　　$|$
3-n-propylhexyne-1-ene-3, C_2H_5—$CH{=}C$—$C{\equiv}CH$, b. p. 136-7° C., $n^{25}D$ 1.4432, $d^{25}{}_{4^\circ}$ 0.7799. The di-n-propylethynylcarbinol used as intermediate was obtained by condensation of sodium acetylide with di-n-propyl ketone in liquid ammonia, according to Campbell.[12] The yield of this fragrant carbinol was 64%, boiling at 169–172°.

Hydrogenation of the two enynes showed that accumulation of alkyl groups about the unsaturated system facilitated the reduction. In contrast to the behavior of 2-methylbutene-1-yne-3, which was scarcely attacked by the catalyst after one molecule of hydrogen had been absorbed, these two vinylacetylenes showed only a relatively slight decrease in rate of hydrogen uptake after one molecule of hydrogen had been absorbed, the hydrogenation continuing at about 40% of the former rate (Fig. 1).

$$R$$
$$|$$
Hydrogenation of $RCH{=}C$—$C{\equiv}C$—R Vinylacetylene Derivatives.—Three hexyne derivatives were prepared for these experiments by condensing hexynylmagnesium bromide with the appropriate ketone, and dehydrating the resulting acetylenic carbinol over alumina at 230°.[11] These three vinylacetylene derivatives were then shaken with hydrogen at 100° and 1,000 lb. pressure with about 5 g. of the iron catalyst until no more hydrogen was absorbed. In every case the rate of reduction, as measured by the drop in pressure, was negligible after one molecule of hydrogen had been absorbed. The diolefins so formed were isolated by pouring the filtered alcoholic solution into water, washing the organic layer, drying with calcium chloride and distilling. The water treatment was made necessary by the fact that all these unsaturated hydrocarbons form constant boiling mixtures with ethyl alcohol. Careful fractionation indicated the hydrogenated product was homogeneous in each case. Quantitative hydrogenation with platinum oxide indicated 1.90–2.00 double bond for each of the unsaturated hydrocarbons. The properties of these hydrocarbons are included in Table I.

Tests for conjugated diene were applied to these unsaturated compounds as follows. The compounds were heated in sealed tubes at 130° for twelve hours with the theoretical amount of maleic anhydride. The maleic anhydride was purified by distillation from phosphorus pentoxide in vacuo, and was very reactive with such dienes as isoprene and 2,3-dimethylbutadiene. On working up, amorphous products were obtained, which dissolved in

(10a) Carothers, Berchet and Collins, THIS JOURNAL, **55**, 2040 (1933).

(10b) Coffman, Nieuwland and Carothers, ibid., **55**, 2048 (1933).
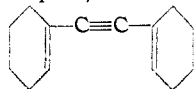
(11) Thompson, Burr and Shaw, ibid., **63**, 188 (1941).

(12) Campbell, Campbell and Eby, ibid., **60**, 2884 (1938).

Table I

	CH_2 Enyne CH_3—CH=C—C≡CC$_4$H$_9$	CH_4 $C_2H_5CH=C$—C≡CC$_4$H$_9$	CH_3 $C_4H_9CH=C$—C≡CC$_4$H$_9$
Diene	CH_3 $CH_2CH=C$—CH=CHC$_4$H$_9$	CH_3 $C_2H_5CH=C$—CH=CHC$_4$H$_9$	CH_4 $C_4H_9CH=C$—CH=CHC$_4$H$_9$
B. p., °C. (at 5 mm.)	38–40	48–50	74–75
d^{25}_4	0.7648	0.7720	0.7718
n^{25}D	1.4475	1.4518	1.4450
M_R (Found)	48.26	53.10	62.08
M_R (Calcd.)	47.30	51.90	61.10
Exaltation	0.94	1.20	0.98

organic solvents, but refused to crystallize. They could be titrated with alkali. Milder condensing conditions yielded no condensation product. The evidence pointed to polymeric condensation products, as found by other workers for α,δ substituted butadienes.[9]

Hydrogenation of Divinylacetylene Derivatives.—Two known divinylacetylenes were used for these experiments, 2,5-dimethylhexadien-1,5-yne-3, prepared according to Dupont,[13] and the corresponding cyclohexyl derivative,

prepared according to Blomquist and Marvel.[6] These two enynes were shaken with hydrogen in the presence of the iron catalyst until no more hydrogen was absorbed. Usually the apparatus was allowed to shake overnight after absorption ceased. The compounds were quite resistant to reduction, so that a temperature of

Table II

	CH_3 CH_3 Dienyne......$CH_2=C$—C≡C—C=CH$_2$	
	CH_5 CH_3 Triene.......CH_3—C=C=CH—C=CH$_2$	
d^{25}_4	0.7966	0.9641
n^{25}D	1.4705	1.5350
M_R (Calcd. for above formula)	37.70	61.10
M_R (Found)	37.86	60.85
Double bonds (cat. H$_2$)	2.91	2.77

(13) Dupont, *Ann. chim. phys.*, [8] **30**, 514 (1913).

130° and pressures up to 1700 lb. per sq. in. had to be used to introduce even one mole of hydrogen. The hydrocarbons were isolated as described in the preceding section. The properties of the partially reduced dienynes are included in Table II.

Attempts were made to locate the positions of the double bonds by ozonization of 1–2 g. samples of these trienes in ethyl acetate. The ozonides were decomposed with hydrogen peroxide[6] and attempts were made to isolate derivatives of the acids which should be present. Complex mixtures of derivatives were obtained which gave little promise of yielding pure compounds with these small amounts of material. Experiments are in progress to prepare and study these trienes on a larger scale.
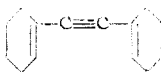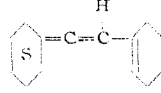
Summary

The properties of the iron hydrogenation catalyst of Paul and Hilly have been studied using compounds containing the enyne and dienyne systems of multiple linkages. It has been shown that some alkynes R—C≡C—H yield alkenes and eventually alkanes on hydrogenation with this catalyst. On the other hand, alkynes RC≡C—R' seem to yield only alkenes in the cases studied, which included enynes and dienynes. The possible application of the catalyst in studying the mechanism of reduction of enyne and dienyne systems is therefore suggested, and preliminary experiments for this object are described.