the basis of the extinction coefficients, the β-form has a higher enol content than that of the α-form. The fact that the extinction coefficient of the β-form remains fairly constant over a wide concentration range may be due to the existence of the β-form in a stable configuration.

Acknowledgments.—The authors gratefully acknowledge the help of Mr. Richard E. Dagle who made the infrared absorption spectral measurements and of Mrs. Barbara B. Martin who made the ultraviolet absorption spectral measurements. The authors are indebted to the Union Carbide Chemicals Co. for supplying the acetylacetone and to Dr. Joseph A. Dixon for supplying the 1,10-dibromodecane.

UNIVERSITY PARK, PENNA.

[CONTRIBUTION FROM THE INSTITUTE OF ORGANIC CHEMISTRY, THE UNIVERSITY OF CHICAGO]

The Mechanism of the Prins Reaction[1]

BY N. C. YANG, DING-DJUNG H. YANG AND CAMILLA B. ROSS

RECEIVED JULY 31, 1958

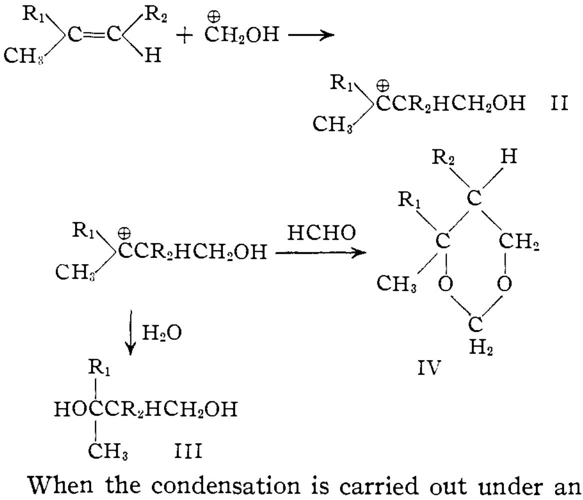
The stannic chloride-catalyzed condensation of some trisubstituted olefins with formaldehyde in chloroform was investigated. The products obtained from 2-methyl-2-butene and from 1-ethoxy-3-methyl-2-butene were 2,3-dimethyl-3-buten-1-ol and 1-ethoxy-2-hydroxymethyl-3-methyl-3-butene, respectively, and their corresponding formals. The structures of these products, established by infrared spectroscopy and chemical degradations, differ from those predicted by a previous mechanism. A mechanism involving general acid catalysis is suggested for the induced condensation of olefins with aldehydes. Catalysts such as anhydrous metal halides and aqueous acids result in different products depending on the solvolytic action of the reaction media.

The condensation of olefins with aldehydes is catalyzed by acids, heat, light and peroxides, and those catalyzed by acids are referred to generally as the Prins reaction. The reaction may be carried out in an aqueous or an anhydrous medium, and the major products consist of a 1,3-dioxane, 1,3-glycol or an unsaturated alcohol depending on the experimental conditions.[2,3] Because of this unusual versatility, the Prins reaction is useful in organic syntheses. It offers a new route to the manufacture of many organic compounds utilizing readily available petroleum products.[4] Despite the fact that the Prins reaction has been employed frequently for synthetic purposes, the condensation in aqueous and anhydrous media was believed to proceed by different mechanisms,[5-7] and different products were derived accordingly. There is some controversy as to the actual mechanism involved and experimental evidence is scarce.[5,6b]

When an olefin is condensed with formaldehyde in an aqueous medium using mineral acids as catalysts, a mixture of a 1,3-dioxane and a 1,3-glycol is produced.[8] If the condensing olefin is trisubstituted, a 1,3-diene is obtained additionally.[9] The acid-catalyzed hydrolysis of a 1,3-dioxane to the corresponding 1,3-glycol and formaldehyde is a reversible process. Since the 1,3-dioxane and the 1,3-glycol are not readily interconvertible under the conditions of the condensation, the two products must be produced independently.[7a] A mechanism (mechanism A) which involves the addition of a protonated formaldehyde molecule to the olefin was postulated.[5] The intermediate adduct II may react with formaldehyde or solvent to give a mixture of the 1,3-dioxane and the 1,3-glycol.

Mechanism A

$$\mathrm{HCHO} + \overset{\oplus}{\mathrm{H_3O}} \rightleftarrows \overset{\oplus}{\mathrm{CH_2OH}} + \mathrm{H_2O}$$



When the condensation is carried out under anhydrous conditions with stannic chloride as a catalyst, an unsaturated alcohol is produced.[10] This alcohol could be dehydrated readily to the corresponding conjugated diene,[7b] and was claimed to have the general formula VI,[10,11] isomeric with that

---

(1) Presented in part at the 133rd Meeting of the American Chemical Society, April, 1958, San Francisco, Calif.

(2) For a review on the Prins reaction, see E. Arundale and L. A. Mikeska, *Chem. Revs.*, **51**, 505 (1952).

(3) A. T. Blomquist, *et al.*, THIS JOURNAL, **79**, 4972 (1957), and later papers.

(4) E. Arundale and L. A. Mikeska, U. S. Patent 2,312,743, *C. A.*, **37**, 4749 (1943); E. Arundale and L. A. Mikeska, U. S. Patent 2,350,-485, *C. A.*, **38**, 4957 (1944); E. Rosen, U. S. Patent 2,335,029, *C. A.*, **38**, 3834 (1944).

(5) C. C. Price, "Mechanisms of Reactions at Carbon–Carbon Double Bonds," Interscience Publishers, Inc., New York, N. Y., 1946, p. 45.

(6) (a) J. W. Baker, *J. Chem. Soc.*, 296 (1944); (b) J. W. Baker, *Nature*, **161**, 171 (1948).

(7) (a) Reference 2, p. 516; (b) p. 539.

(8) H. J. Prins, *Proc. Acad. Sci. Amsterdam*, **22**, 51 (1919); H. J. Prins, *J. Chem. Soc.*, **118**, 42 (1920); ref. 2, p. 507.

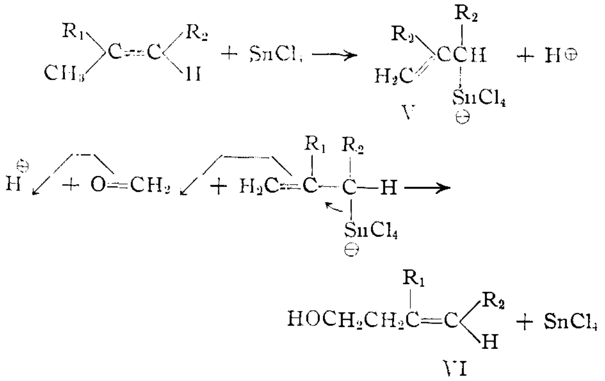
(9) E. Arundale and L. A. Mikeska, U. S. Patent 2,350,485, *C. A.*, **38**, 4957 (1944); R. Rosen and E. Arundale, U. S. Patent 2,368,494, *C. A.*, **39**, 4529 (1945).

(10) L. A. Mikeska and E. Arundale, U. S. Patent 2,308,192, *C. A.*, **37**, 3450 (1943); L. A. Mikeska and E. Arundale, British Patent 545,191, *C. A.*, **36**, 7030 (1942).

(11) L. A. Mikeska and E. Arundale, U. S. Patent 2,253,342, *C. A.*, **35**, 7974 (1941).

predicted by mechanism A. On the basis of this evidence, a different mechanism (mechanism B) which directly involves an "active α-hydrogen" was postulated.[6]

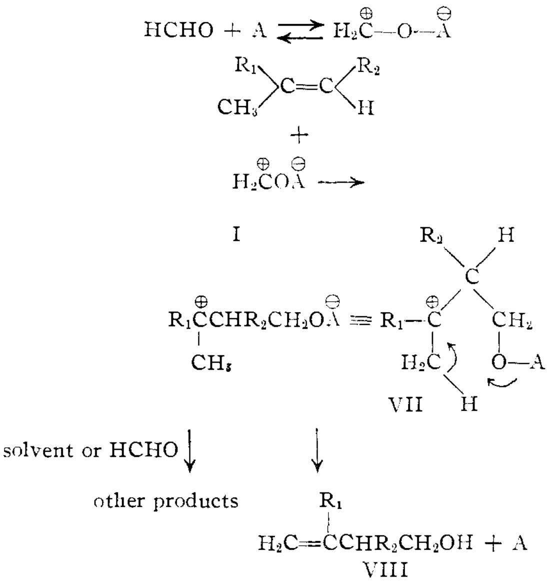
Mechanism B



Other metal halides including aluminum chloride, zinc chloride[12] and boron trifluoride[13] have been employed as catalysts in the Prins reaction. All are Lewis acids and are electrophilic with respect to olefins and carbonyl compounds.[14] The major difference between the two suggested mechanisms may be ascribed to the postulation of an initial association between the proton and the aldehyde or an association between the metal halide and the olefin which induces the condensation. It is unlikely that acids in different media catalyze the condensation by different mechanisms and there is indication that the reaction does proceed by general acid catalysis. Assuming a similar catalytic effect for all acids, we wish to propose a general mechanism (mechanism C) to explain the catalysis by metal halides in anhydrous media. Stannic chloride reacts initially with formaldehyde to form a polarized addition complex. The complex then adds to the olefin in accordance with the Markownikoff rule. Finally, stannic chloride is regenerated by a simultaneous proton transfer through a six-membered ring intermediate[5,15] VII giving rise to the corresponding β,γ-unsaturated alcohol VIII. This mechanism is applicable to the acid-catalyzed condensation of olefins and aldehydes in an aqueous or an aprotic medium.

According to the reaction schemes outlined above, it is apparent that disubstituted olefins of the type $CH_3CR_1{=}CH_2$ will give identical alcohols by mechanisms B and C (VI = VIII if R_2 = H), whereas trisubstituted olefins of the type $CH_3CR_1{=}CHR_2$ will give different alcohols: $R_2CH{=}CR_1CH_2CH_2OH$ (VI) by mechanism B and $CH_2{=}CR_1CHR_2CH_2OH$ (VIII) by mechanism C.[16] Hence, the two mechanisms can be differentiated readily by suitable choice of the reacting olefin and careful investigation of the condensation products. An ordinary kinetic approach was not successful because of the complicated nature of the condensation.[6a]

Mechanism C



where A = $SnCl_4$ or other acids

Although it was claimed that the condensation of formaldehyde with many trisubstituted olefins produced alcohols of formula VI, no experimental proof of the proposed structures was reported. The condensation of formaldehyde with some simple trisubstituted olefins was reinvestigated. In the case of 2-methyl-2-butene (Ia, $R_1 = R_2 = CH_3$), 2,3-dimethyl-3-buten-1-ol (VIIIa, $R_1 = R_2 = CH_3$) was isolated instead of the reported 3-methyl-3-penten-1-ol (VIa, $R_1 = R_2 = CH_3$). While the physical constants of VIIIa are identical to those reported previously for VIa,[10] its infrared spectrum shows a strong absorption at 890 cm.$^{-1}$ and no absorption at 800–840 cm.$^{-1}$ region indicating the presence of a vinylidene unsaturation. The correct structure of this alcohol was confirmed by degradations. Ozonolysis of VIIIa followed by hydrogenation yielded formaldehyde (46–53%) and a C_5-methyl ketone. The C_5-methyl ketone was shown to be β-hydroxyisopropyl methyl ketone by (1) reverse aldol condensation to formaldehyde and 2-butanone, (2) unambiguous synthesis through the aldol condensation of its components and (3) dehydration in acid solution to isopropenyl methyl ketone.

In addition to the unsaturated alcohol VIIIa which constituted the major product (26–29%) of the condensation, there was obtained the formal of VIIIa (19–23%) and no appreciable quantity of the 1,3-dioxane was isolated. The formal X shows a strong infrared absorption at 885 cm.$^{-1}$, indicative of a vinylidine double bond, and at 1040 and 1110 cm.$^{-1}$, indicative of an ether function. On hydrogenation, X absorbed two equivalents of hydrogen to give a saturated formal (XI). When X was subjected to ozonolysis followed by hydrogenation, formaldehyde and a C_{11}-methyl ketone were isolated. The C_{11}-ketone was identified by its bis-2,4-dinitrophenylhydrazone which could be converted

---

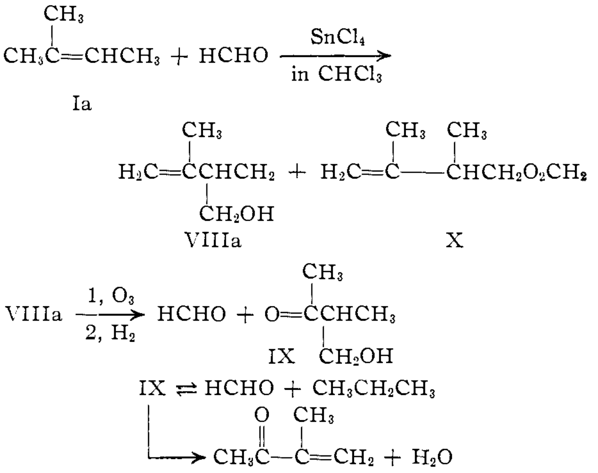
(12) Reference 2, p. 532.

(13) D. J. Loder, U. S. Patent 2,158,031, *C. A.*, **33**, 6343 (1939); D. J. Loder, U. S. Patent 2,289,548, *C. A.*, **37**, 388 (1943).

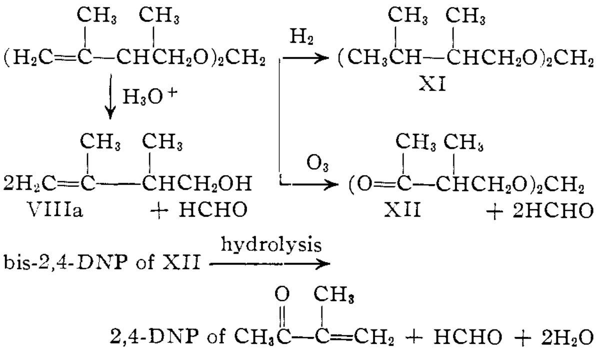
(14) G. W. Wheland, "Advanced Organic Chemistry," John Wiley and Sons, Inc., New York, N. Y., 1949, p. 80.

(15) R. T. Arnold, *Helv. Chim. Acta*, **32**, 134 (1949).

(16) The deprotonization step in mechanisms B and C may involve the methylene group in R_1, depending on the structure of the alkyl substituent. In this case, the general statement remains true, and the predicted alcohols will have different formulas accordingly. This possibility is eliminated if R_1 = CH_3.

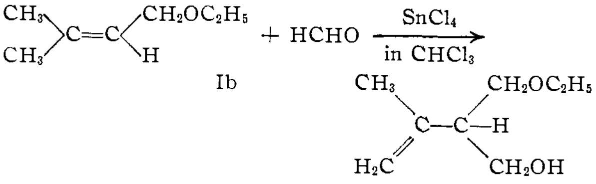


readily to the 2,4-dinitrophenylhydrazone of isopropenyl methyl ketone in the presence of acid. Direct hydrolysis of X in acid gave formaldehyde and alcohol VIIIa, isolated, respectively, as its dimedone derivative and 3,5-dinitrobenzoate and the structure of formal X was thereby confirmed.



where 2,4-DNP = 2,4-dinitrophenylhydrazone

Likewise, the condensation of 1-ethoxy-3-methyl-2-butene (Ib, R_1 = CH_3, R_2 = $CH_2OC_2H_5$) and formaldehyde gave 1-ethoxy-2-hydroxymethyl-3-methyl-3-butene (VIIIb) instead of the reported 5-ethoxy-3-methyl-5-penten-1-ol.[11] Structure VIIIb was assigned to the unsaturated alcohol on the basis of infrared absorption at 890 cm.$^{-1}$ and degradative ozonolysis which gave over 40% of formaldehyde and a methyl hydroxyketone. Because of the instability of this methyl β-hydroxy-β-ethoxy ketone with respect to β-elimination, it was not further characterized.



VIIIb

To avoid effects of small traces of moisture and protolytic solvents on the reaction mechanisms,[6b] the condensation was carried out in absolute chloroform utilizing trioxymethylene and freshly distilled stannic chloride. Under these conditions, the condensation products invariably consisted of the same alcohol with unsaturation at the terminal position, and the corresponding formal. For simple olefins of the type $(CH_3)_2C{=}CHR$, the results appear to be general, and the following conclusions are drawn: The structure of the unsaturated alcohol supports mechanism C. Therefore, the Prins reaction in aqueous and anhydrous media apparently follows a general mechanism which involves an acid-activated formaldehyde intermediate. The observation that only one isomeric unsaturated alcohol is produced during the condensation favors an intramolecular proton transfer in a cyclic manner as suggested above.

Acknowledgment.—The authors wish to thank Mr. William Saschek for the microanalyses. A fellowship from E. I. du Pont de Nemours & Co. to C. B. R. is gratefully acknowledged.

Experimental[17]

The Prins Reaction of 2-Methyl-2-butene (Ia).—To a stirred mixture of 70.1 g. (1.0 mole) of freshly distilled 2-methyl-2-butene and 28.0 g. (0.31 mole) of trioxymethylene in 60 ml. of anhydrous chloroform,[18] a solution of 7.9 g. (0.030 mole) of freshly distilled stannic chloride in 15 ml. of chloroform was added. The mixture was stirred at room temperature for 18 hours. At the end of this period, most of the trioxymethylene was dissolved and the unreacted portion (4–7 g.) was removed by filtration. The filtrate was treated immediately with a mixture of dilute ammonium hydroxide and ice, and the *p*H of the mixture was adjusted to 4. The organic layer, combined with the chloroform extracts of the aqueous layer, was washed thoroughly with 5% aqueous sodium bicarbonate and water, dried, and fractionally distilled through a tantalum spiral column (5 mm. × 60 cm.). After the removal of a fore-run which contained mainly the unreacted olefin and some dissolved formaldehyde, two major fractions were obtained: **Fraction I**, an alcohol (VIIIa) of b.p. 66–66.5° at 31 mm. or 132–133° at 749 mm. (b.p. reported[10] 135–145° at atmospheric pressure), $n^{20}D$ 1.4391, weight 20–23 g. (yield 26–29% based on formaldehyde consumed). The alcohol shows characteristic infrared absorption at 3350, 3060, 1645 and 890 cm^{-1}. Gas chromatography of VIIIa through a G. E. Silicone SF96 on firebrick column (1/4″ × 6 ft.) and a polypropylene glycol on firebrick column (1/4″ × 6 ft.) shows the presence of only a single component.

Anal. Calcd. for $C_6H_{12}O$: C, 71.63; H, 12.04. Found: C, 71.95; H, 12.08.

Fraction II, a formal (X) of b.p. 77–78° at 2 mm., $n^{20}D$ 1.4462, weight 11–13 g. (yield 19–23% based on formaldehyde consumed). The formal shows intense infrared absorption at 3060, 1120, 1050 and 890 cm.$^{-1}$.

Anal. Calcd. for $C_{13}H_{24}O_2$: C, 73.53; H, 11.39; mol. wt., 212. Found: C, 73.50, 73.30; H, 11.60, 11.10; mol. wt., 206.

The Characterization of 2,3-Dimethyl-3-buten-1-ol (VIIIa). a. β-Hydroxyisopropyl Methyl Ketone (IX).—A slow stream of ozone (0.38 millimole per minute) was passed into a solution of 4.3 g. (0.043 mole) of VIIIa in 50 ml. of ethyl acetate at −45°. When the uptake of ozone had subsided, the solution was diluted with an equal volume of 95% ethanol and hydrogenated in the presence of 2% palladium oxide on $CaCO_3$ (0.45 g.). The reaction mixture was filtered and the filtrate was concentrated by distillation at atmospheric pressure. The distillate was collected under the surface of 10 ml. of aqueous methanol (1:1). To the residue, 20 ml. of methanol was added, and the distillation was continued in the same manner. A good yield (53%) of the dimedone derivative of formaldehyde (m.p. 109–191°) could be isolated from aliquots of the distillate mixture.

The residual oil was fractionally distilled through a semi-micro Vigreux column and 2.3 g. (30%) of β-hydroxyisopropyl methyl ketone (IX) was obtained, b.p. 64–66° at 7 mm., $n^{20}D$ 1.4320. The ketone gave a positive iodoform test. Its infrared absorption spectrum was identical to

---

[17] The melting points reported were not corrected, and the molecular weights were determined by cryoscopic measurements in benzene.

[18] Analytical reagent, Fisher Scientific Co.

that of an authentic sample (b.p. 70° at 9 mm., n^{20}_D 1.4318) prepared by the aldol condensation of formaldehyde and 2-butanone.[19]

A 2,4-dinitrophenylhydrazone of the ketone was prepared from a methanolic hydrochloric acid solution, and an 85% yield of red needles was isolated, m.p. 185–186° dec. The derivative was shown to be the 2,4-dinitrophenylhydrazone of the dehydrated isopropenyl methyl ketone by analyses and infrared spectrum.

Anal. Calcd. for $C_{11}H_{12}N_4O_4$: C, 49.99; H, 4.58; N, 21.21. Found: C, 49.97; H, 4.62; N, 21.26.

b. The Reverse Aldol Condensation of IX.—Two grams of IX isolated from the ozonolyses of VIIIa was treated for 20 minutes over a steam-bath with 30 ml. of 3% aqueous potassium bicarbonate. The mixture was steam distilled until 150 ml. of the distillate had been collected. After removal of a small quantity of an immiscible oil, the distillate was treated with a 10% excess of Tollens reagent. The resulting clear solution, separated from the reduced metal by decantation, was neutralized with 6 *N* hydrochloric acid and the precipitated silver chloride was removed by centrifugation. Fractional distillation of the aqueous layer at atmospheric pressure gave a ketone fraction boiling between 80–90°. A 2,4-dinitrophenylhydrazone of the ketone was prepared; weight 0.39 g., corresponding to an over-all yield of 15%. The melting point was not depressed on admixture with an authentic sample of the 2,4-dinitrophenylhydrazone of 2-butanone (m.p. 117–118°).

The Characterization of X, the Formal of 2,3-Dimethyl-3-buten-1-ol. a. Hydrogenation of X.—A solution of 1.09 g. (0.0050 mole) of the unsaturated formal X in 15 ml. of glacial acetic acid was hydrogenated in the presence of platinum oxide and the hydrogenation was complete after two equivalents of hydrogen was absorbed. The reaction mixture was worked up by the usual procedure, and the crude residue, dissolved in a small amount of petroleum ether, was chromatographed through aluminum oxide. The major fraction eluted with petroleum ether was concentrated and the residue was distilled at 20 mm. pressure and an oil-bath temperature of 90–95°. The product showed intense absorption at 1120 and 1050 cm.$^{-1}$ and no absorption in the double bond region; n^{20}_D 1.4401.

Anal. Calcd. for $C_{13}H_{28}O_2$: C, 72.16; H, 13.05; mol. wt., 216. Found: C, 71.79; H, 12.82; mol. wt., 209.

b. The Formal of β-Hydroxyisopropyl Methyl Ketone.—A solution of 1.09 g. (0.0050 mole) of X in 12 ml. of ethyl acetate was subjected to ozonolysis followed by catalytic hydrogenation in the presence of 2% palladium oxide on $CaCO_3$ (0.20 g.) and ethanol (15 ml.). The reaction mixture was concentrated by the method described previously for the isolation of β-hydroxyisopropyl methyl ketone. A good yield of the dimedone derivative of formaldehyde (weight 1.8 g., yield, 60%, m.p. 190–191°) was isolated from the distillate and a diketone (0.37 g., b.p. 75–80° at 0.25 mm.) was isolated from the residue. The diketone gave a positive iodoform test. A bis-2,4-dinitrophenylhydrazone (XII) was prepared at room temperature by treatment with a slight excess of a methanolic 2,4-dinitrophenylhydrazine hydrochloride reagent. Two recrystallizations of the derivative from chloroform–ethanol afforded an analytical sample (m.p. 178–179°), the analyses of which agreed with those required for the bis-2,4-dinitrophenylhydrazone derived from the formal of β-hydroxyisopropyl methyl ketone.

Anal. Calcd. for $C_{23}H_{28}N_8O_{10}$: C, 47.91; H, 4.90; N, 19.44. Found: C, 47.89, 47.92; H, 4.87, 4.95; N, 19.32.

An 80-mg. sample of the bis-2,4-dinitrophenylhydrazone (XII) dissolved in a mixture of 0.20 ml. of concentrated hydrochloric acid, 5 ml. of dioxane and two drops of water was warmed gently on a steam-bath for 25 minutes. After removal of solvents at reduced pressure, the residue was recrystallized from ethyl acetate–ethanol mixture and 25 mg. of fine red needles was obtained. A mixed melting point determination with an authentic sample of the 2,4-dinitrophenylhydrazone of isopropenyl methyl ketone gave no depression (m.p. 184–185°). Its infrared absorption spectrum in KBr was identical with that of an authentic sample.

c. Hydrolysis of X.—A solution of 0.34 g. (0.0017 mole) of X dissolved in 5 ml. of aqueous dioxane was treated with three drops of concentrated hydrochloric acid and the mixture was warmed on a steam-bath for 15 minutes. After neutralization with potassium carbonate, the mixture was divided into two equal portions from which the dimedone derivative of formaldehyde (m.p. 189–191°) and a 3,5-dinitrobenzoate were prepared. Two recrystallizations of the benzoate from aqueous methanol yielded 15 mg. of glittering flakes (m.p. 40–41°) identified as the 3,5-dinitrobenzoate of 2,3-dimethyl-3-buten-1-ol (VIIIa) by mixed melting point determination.

Anal. Calcd. for $C_{13}H_{14}N_2O_6$: C, 53.06; H, 4.80; N, 9.52. Found: C, 53.14; H, 4.99; N, 9.70.

The Prins Reaction of 1-Ethoxy-3-methyl-2-butene (Ib).—A stirred suspension of 17.1 g. (0.19 mole) of trioxymethylene in 51.5 g. (0.45 mole) of Ib[20] and 167 ml. of anhydrous chloroform was treated at room temperature with a solution of 7 ml. of chloroform containing 6.6 g. (0.0245 mole) of freshly distilled stannic chloride. At the end of 20 hours, the unreacted trioxymethylene (3.5 g.) was removed and the reaction mixture was worked up by the regular procedure. The crude product was fractionally distilled through a Vigreux column and there was obtained 14.9 g. (23% based on formaldehyde consumed) of VIIIb (b.p. 66–67° at 2.8 mm.). The product showed infrared absorption maxima at 3420, 3070, 1646, 1115, 1035 and 890 cm.$^{-1}$. A sample was refractionated through a 60-cm. tantalum spiral column for analyses; b.p. 53–53.5° at 1.75 mm. (b.p. reported[11] 89–90° at 1.5 mm.), n^{20}_D 1.4433.

Anal. Calcd. for $C_8H_{16}O_2$: C, 66.62; H, 11.19. Found: C, 66.54; H, 11.06.

A second fraction (5.4 g., b.p. 72–85° at 0.05 mm.) which showed characteristic absorption at 3060, 1646, 1120, 1035 and 890 cm.$^{-1}$, and the high boiling residue (11.0 g.) were not investigated.

The Characterization of 1-Ethoxy-2-hydroxymethyl-3-methyl-3-butene (VIIIb).—A solution of 5.0 g. (0.035 mole) of VIIIb dissolved in 45 ml. of ethyl acetate was treated with ozone at −45°, and hydrogenated in the presence of 0.50 g. of platinum oxide and 45 ml. of 95% ethanol. The mixture was concentrated by distillation at atmospheric pressure according to the procedure described previously for the isolation of β-hydroxyisopropyl methyl ketone, and 4.1 g. (40%) of the dimedone derivative of formaldehyde (m.p. 191–192°) was isolated from the distillate. Fractional distillation of the residue through a semimicro Vigreux column gave 2.4 g. (51%) of a hydroxy ketone (b.p. 78–86° at 14 mm.; $\gamma_{\max}$ at 3440, 1707, 1115 and 1040 cm.$^{-1}$). The ketone gave a positive iodoform test and decomposed readily to a resin on standing. When the ketone was treated with a 2,4-dinitrophenylhydrazine reagent at room temperature, a mixture of 2,4-dinitrophenylhydrazones (m.p. 230–250°) was obtained which could not be purified by recrystallization from common organic solvents or chromatography.

Chicago 37, Ill.

---

[19] C. T. Morgan, N. J. L. Megson and K. L. Peper, *Chemistry & Industry*, **57**, 885 (1938); C. T. Morgan and E. L. Homes, *J. Chem. Soc.*, 2667 (1932).

[20] L. Claisen, *J. prakt. Chem.*, [2] **105**, 80 (1922).