the first 60 ml. of effluent, in an amount of 103 mg. (11.2%), m.p. and mixed m.p. with an authentic sample prepared by the reaction of thionyl chloride in pyridine with D-isomannide (I),[26] 67°.

Reaction of 2,5-Diamino-2,5-dideoxy-1,4:3,6-dianhydro-D-glucitol (XII) with Nitrosyl Chloride.—The deamination was carried out in a manner similar to the one described above. Chromatography of the product yielded 87 mg. of XXI from 0.72 g. of XII; the yield was 9.5%.

CAMBRIDGE, MASSACHUSETTS

[CONTRIBUTION NO. 1338 FROM STERLING CHEMISTRY LABORATORY, YALE UNIVERSITY]

Chromate Esters. II. Reactions of Di-2-methylfenchyl Chromate[1,2]

BY HAROLD H. ZEISS[3] AND DWIGHT A. PEASE, JR.

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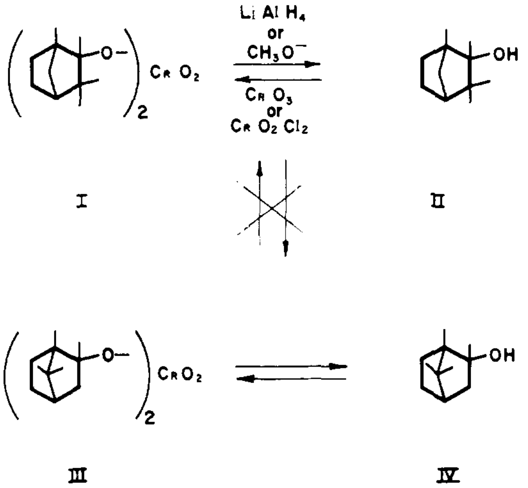
The behavior of the chromate ester of 2-methylfenchol under varied solvolytic conditions has been examined. These results, together with those obtained from the chromic acid oxidation of 2-methylfenchol itself and of a mixture of 1-methylcamphene and 1-methyl-α-fenchene, are used to delineate the path by which tertiary alcohols are oxidized and tertiary chromates react as oxidizing agents.

In the first paper of this series[4] the formation and solvolysis of an aliphatic tertiary chromate ester are demonstrated to occur with retention of configuration at the tertiary carbon atom. In the present paper we describe the chemical properties of a very stable bicyclic tertiary chromate ester in order to delineate as closely as possible the path by which tertiary alcohols are oxidized. As a corollary to these studies the function of tertiary chromate esters as oxidizing agents is adduced.

The first chromate ester to be isolated by Wienhaus, di-2-methylfenchyl chromate (I), was prepared by the usual methods[5] and also by the use of chromyl chloride[4] from 2-methylfenchol (II). Since our preparation commenced with almost racemic α-fenchone, the chromate ester with which we worked was a mixture of *exo* and *endo* isomers.[19,20] However, the stereoisomeric composition of the ester is quite reproducible as are the results, kinetic[9] and chemical, obtained with it. By analogy with the isoborneol–borneol system it may be anticipated that the *exo* (C-2 methyl) forms of the diester will rearrange more rapidly than the *endo* forms during reaction. However, both types of esters should decompose to the same products, albeit in different ratios, and thus produce no difficulties in the interpretation of the results.

Reduction of this red, crystalline ester with lithium aluminum hydride provided structurally pure II, spectroscopically similar in the infrared region to that purified *via* the half phthalate ester and subsequent reduction with the same reagent. This reaction cycle ensures the absence of rearrangement of the fenchyl structure to that of bornyl and establishes the fact that it resides intact in the chromate ester. Further, it confirms the stereochemical evidence for the observed maintenance of asymmetric identity in optically active 2,4-dimethyl-4-hexanol throughout a similar cycle.[4] The structural isomer of II, 2-methylborneol (IV), likewise failed to undergo rearrangement under equivalent circumstances. Then also, the action of methoxide ion on I regenerated II without rearrangement.



The diester I was solvolyzed in methanol at 25, 46 and 65°, and, although the products were the same regardless of the temperature, at 25° less than 20% of I had reacted after 4 days. At 46° reaction was substantially complete in this period of time, and at 65° methanolysis time was less than 24 hours. The products from a sealed tube reaction at 65° were the parent alcohol II, a mixture of 1-methylcamphene (V) and 1-methyl-α-fenchene (VI), an apparent mixture of the methyl ethers of II and IV, formaldehyde and an insoluble organochromium compound analyzing for trimethoxychromium. The presence of methyl ether is indicated by comparison of the 8.5–9.5 μ infrared region of the product with that of an authentic sample of the methyl ether of II; and it is inferred that a mixture of the ethers of II and IV is present on the basis of the reasonable mechanism proposed below. The main product was 2-methylfenchol (61%) unaccompanied by IV. In the incomplete run at 25° the recovered ester I contained none of III. It is concluded, therefore, that the decomposition of I is irreversible with respect to any process involving the reformation of I subsequent to or during the

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(1) This work was supported in large part by Contract No. DA-19-059-ORD-849 between the Office of Ordnance Research, U. S. Army, and Yale University.

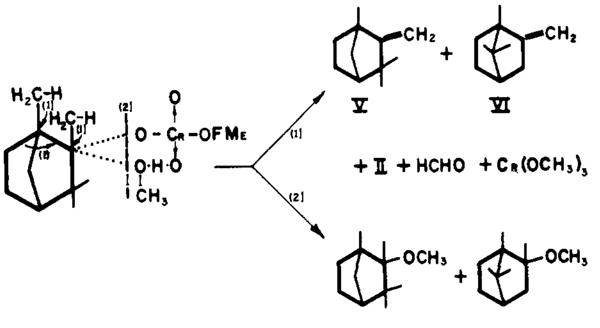
(2) Taken from the Ph.D. dissertation of D. A. Pease, Jr., Yale University, 1954, and presented in part at Los Angeles, Calif., March 18, 1953, *Abstr., 123rd Meeting, Am. Chem. Soc.*, p. 30M.

(3) Monsanto Chemical Co., Dayton 7, Ohio.

(4) H. H. Zeiss and C. N. Matthews, THIS JOURNAL, **78**, 1694 (1956).

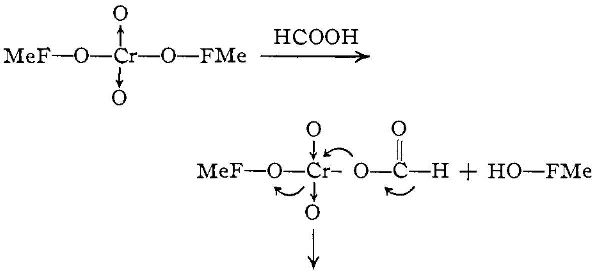
(5) H. Wienhaus, *Ber.*, **47**, 322 (1914).

rearrangement to the bornyl structure (VI and the methyl ether of IV). Inherent in this conclusion is the assumption of the separation of tertiary carbon–oxygen bonds with consequent (1) elimination to a mixture of olefins or (2) methanolysis to a mixture of the methyl ethers of II and IV.



The incursion of a second major process is shown clearly by the formation of formaldehyde in considerable yield by the oxidation of the solvent (no camphor or fenchone present). This may be formulated reasonably as a two-step sequence comprising transesterification and intramolecular oxidation–reduction, the process experimentally supported recently on the basis of stereochemical evidence[4] and proposed by Leo and Westheimer[6] for the behavior of di-*t*-butyl chromate as an oxidizing agent. The operation of the major processes of elimination, transesterification and oxidation–reduction provides for the experimentally observed predominant yield of the parent, unrearranged alcohol.

In a second solvolytic and also oxidizable medium, formic acid, the same processes for the decomposition of I .are indicated by the observed products: the formate esters of II and IV, *carbon dioxide*, and a blue chromium formate. The action of formic acid on II and on a mixture of V and VI[7] in control experiments led in each case to the same mixture of esters. The essential difference between the formolysis and the methanolysis lies in transformylation replacing transesterification.



$$\mathrm{MeF{-}O{-}\overset{\overset{O}{\uparrow}}{\underset{\underset{O}{\downarrow}}{Cr}}{-}O{-}FMe} \xrightarrow{\mathrm{HCOOH}}$$

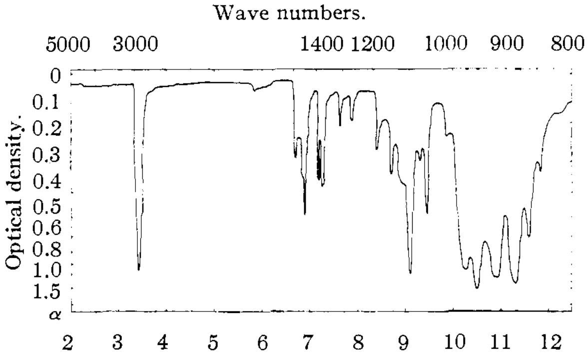
$$\mathrm{MeF{-}O{-}\overset{\overset{O}{\downarrow}}{\underset{\underset{O}{\downarrow}}{Cr}}{-}\ O{-}\overset{\overset{O}{\|}}{C}{-}H + HO{-}FMe}$$

$$\downarrow$$

$$\mathrm{MeF{-}OH + CrO_2 + CO_2}$$

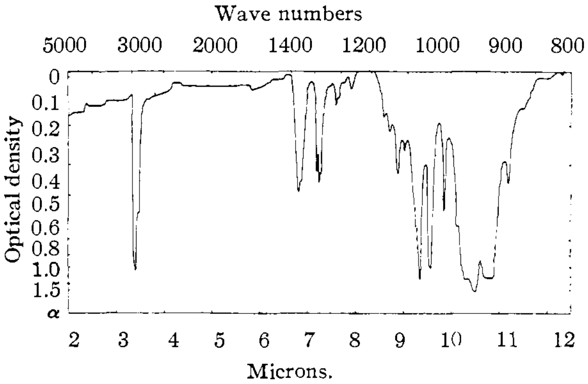
By contrast, the hydrogen phthalate of II after 7 days in methanol was recovered in about 40% yield together with an olefinic mixture of V and VI and an apparent mixture of the methyl ethers of II and IV. No 2-methylfenchol was detected.

The methanolysis of di-2-methylbornyl chromate (III) paralleled that of I in that the products were formaldehyde, 2-methylborneol (IV), a mixture of V and VI, an apparent mixture of the methyl ethers of II and IV and the insoluble organochromium compound. However, the yield of IV was only 41% as compared to 61% of II above, and the amount of V and VI rose from 18% in the methanolysis of I to 24% in the present case. This indicates, perhaps, that the decomposition of III by alkyl–oxygen fission is a more favorable reaction path than of I.



0.125 *M* Di-2-methylbornyl chromate ($CHCl_3$) microns.
Fig. 1.

In inert solvents the self-destruction of I proceeded at rates relative to the polarity of the environment. Thus, the decomposition of the diester in acetic acid or acetonitrile at 65° was comparable in speed to its methanolysis, but in carbon tetrachloride reaction was only 60% completed after 56 days. The products from these reactions (no carbon dioxide detected) consisted of the mixed olefins V and VI accompanied by neutral carbonyl material containing camphor and fenchone, minor amounts of II, and, from the acetolysis, also an acid fraction consisting of the isomeric camphane- and fenchane-2-carboxylic acids.[8] The survival of olefin at the end of the reaction is due, of course, to the limited quantity of hexavalent chromium initially present in I. Whereas the elimination reaction resulting in the formation of V and VI must involve the loss of β-hydrogen atoms, C-2 methyl groups are lost (carbon–carbon bond cleavage) in



0.125 *M* di-2-methylfenchyl chromate ($CHCl_3$).
Fig. 2.

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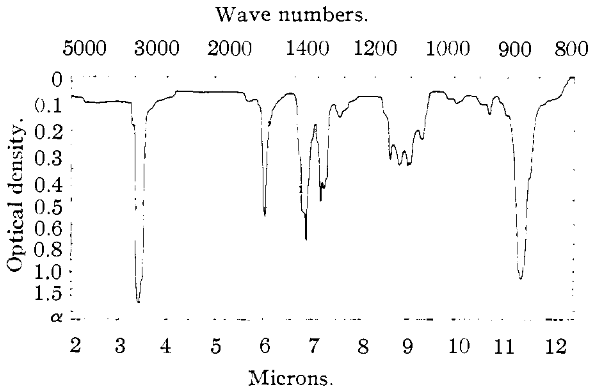
[6] A. Leo and F. H. Westheimer, This Journal, **74**, 4384 (1952).

[7] *Cf.* the hydration of santene with formic acid: F. Semmler and K. Bartelt, *Ber.*, **41**, 128 (1908).

[8] W. Treibs and H. Schmidt, *ibid.*, **61**, 459 (1928), have described the formation of camphenilanic and fenchenylanic acids, among other products, by the chromic acid oxidation of camphene and α-fenchene, respectively, in acetic acid.



0.5 M 1-methylcamphene + 1-methyl-α-fenchene ($CHCl_3$).

Fig. 3.

the production of camphor and fenchone. In acetic acid terminal oxidation of these methyl groups has occurred also.

The oxidation of 2-methylfenchol (II) in acetic acid with a limited amount of chromic acid gave the same products as those formed when its chromate ester I was decomposed in the same solvent. This result, together with other kinetic data,[9] means that II is first esterified by chromic acid, followed by the decomposition of the ester. However, the *same oxidation products* are produced again when the mixture of V and VI is oxidized in acetic acid with chromic acid. These results permit the hypothesis that the oxidation of II and V and the decomposition of I proceed through a common intermediate.[10]

The nature of the oxidation intermediate is limited somewhat by the following considerations. Since a pentane solution of the olefins V and VI does not extract red chromate color from an aqueous chromic acid solution and since the decomposition of either diester I or III is by no means instantaneous,[11] the common intermediate, if such a species exists, cannot be either I or III. The ease of esterification of II to I likewise renders the parent alcohol an unlikely possibility. If, however, the assumption is made, in spite of the fact that there is little reason to do so, that a *mono*chromate ester, formed either by decomposition of I, by the initial step in the esterification of II or by the direct addition of chromic acid[12] to the double bonds of V and VI, undergoes instantaneous decomposition, then the monochromate ester of II (and IV) qualifies as the intermediate. However, as has been noted, there is no reason *a priori* to assume that monochromate tertiary esters decompose instantaneously.

The presence of olefin in all of these oxidation product studies, excepting that in formic acid for reasons already given, is suggestive of an intimate role which it may play in the oxidative process. Clearly, it is a product to which both I and II or III and IV may decompose prior to oxidation and to which they may go *with rearrangement.* The assumption of elimination to olefin with rearrangement and subsequent oxidation is consistent with this product study. However, the oxidation intermediate is still undefined, and it is not yet possible to say whether it is the olefin itself or yet another unisolated intermediate lying between the olefin and the ketonic and acidic products. Hickinbottom, *et al.*,[13] prefer to assume the initial formation of a complex between olefin and chromic acid but have not been able to obtain direct evidence as yet on the sequence of reactions leading to epoxide formation. Kinetic and further product studies are required before these questions can be answered, and these will be the subject of a forthcoming communication.[9]

Experimental[14]

2-Methylfenchol (II).[15]—The reaction between 108 g. of technical α-fenchone (Eastman Kodak Co.), b.p. 192.5–194.5°, $n^{20.5}_{\mathrm{D}}$ 1.4632, α^{25}_{D} +9.45°, in 165 ml. of ether and methylmagnesium iodide prepared from 133.4 g. of methyl iodide and 22.7 g. of magnesium in 325 ml. of ether was completed at reflux for 3 hours, and the product was then hydrolyzed with cold, saturated ammonium chloride solution and its ether solution washed with aqueous sodium thiosulfate. Removal of ether left 84 g. (70%) of crude 2-methylfenchol, m.p. 52–66°, contaminated with fenchone (infrared). This alcohol (8.4 g.) was converted to its potassium salt and then reacted with phthalic anhydride according to procedure previously described in detail.[16] Crystallization of the 9.1 g. of crude half ester obtained from this reaction gave 6.7 g. (42%) of the *hydrogen phthalate* of II, m.p. 140.5–141.5° (dec., uncor.). Recrystallization from benzene did not alter this m.p.

Anal. Calcd. for $C_{19}H_{24}O_4$: C, 72.12; H, 7.65. Found: C, 72.06; H, 7.88.

A solution of the half ester (3.7 g.) in 120 ml. of ether was reduced with 2.0 g. of lithium aluminum hydride in 100 ml. of the same solvent.[16] 2-Methylfenchol, now free of carbonyl impurity (infrared) was sublimed from the product mixture of the tertiary alcohol and phthalyl alcohol: 1 g. (51%), m.p. 56.5–65.0°, $[\alpha]^{24.5}_{\mathrm{D}}$ +0.88° (α 0.15°, *c* 17.1).

Anal. Calcd. for $C_{11}H_{20}O$: C, 78.51; H, 11.98. Found: C, 78.33; H, 12.07.

l-α-Fenchone,[17] $n^{24.5}_{\mathrm{D}}$ 1.4606, α^{27}_{D} −57.39° (10 g.), was treated as just described above with methylmagnesium iodide, from which 11.8 g. (57%) of **hydrogen 2-methylfenchyl-2-phthalate**, m.p. 146–146.5° (dec., uncor.), $[\alpha]^{25.5}_{\mathrm{D}}$ −69.79° (α 0.91°, *c* 1.3), was obtained. Reduction of the half ester as above regenerated 3.4 g. (54%) of *optically active* 2-methylfenchol, m.p. 56.5–61.5°, $[\alpha]^{26}_{\mathrm{D}}$ −4.25° (α 0.15°, *c* 3.53); lit. m.p. 61°,[15a] 51–52°,[15b] 58–59.[15d]

2-Methylborneol (IV).[15c]—From a Grignard reaction between 75 g. of *d*-camphor (Eastman Kodak Co.) and methylmagnesium iodide, prepared from 92 g. of methyl iodide and 14.6 g. of magnesium, 78 g. of impure IV was obtained. Since this crude alcohol was satisfactory for chromate ester preparation, this being in itself a separation process, no purification steps were taken at this stage.

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(9) H. H. Zeiss and F. R. Zwanzig, unpublished results.

(10) The oxidation of IV and VI and the decomposition of III then would be said to proceed through another common, but isomeric, intermediate.

(11) Di-2-methylfenchyl chromate (I) may be crystallized unchanged from acetic acid at room temperature.

(12) The first dissociation constant of chromic acid, K_1 = 1.21, is that of a strong acid: J. Tong and E. L. King, THIS JOURNAL, **75**, 6180 (1953).

(13) W. J. Hickinbottom, D. Peters and (in part) D. G. M. Wood, *J. Chem. Soc.*, 1360 (1955).

(14) All m.p.'s are corrected unless otherwise noted. Rotations were measured in 95% ethanol, 1-dm. tube. Microanalyses were performed by the Schwarzkopf Microanalytical Laboratory, Woodside 77, N. Y.

(15) (a) O. Wallach and H. Wienhaus, *Ann.*, **353**, 224 (1907); (b) N. Zelinski, *Ber.*, **34**, 2883 (1901); (c) L. Ruzicka, *Helv. Chim. Acta*, **1**, 110 (1918); (d) S. Nametkin, *Ann.*, **432**, 215 (1923).

(16) W. von E. Doering and H. H. Zeiss, THIS JOURNAL, **72**, 147 (1950).

(17) This sample was supplied to us by the Hickrill Chemical Foundation, Katonah, N. Y., through the courtesy of Dr. W. von E. Doering.

Di-2-methylfenchyl Chromate (I). (a) **With Chromic Acid.**[18]—2-Methylfenchol (1.0 g.) from technical fenchone was dissolved in 30 ml. of *n*-pentane and shaken for 15 minutes with 30 ml. of an aqueous solution of 3.0 g. of chromium trioxide. The pentane layer, which darkened rapidly to a deep red color, was separated and dried over sodium sulfate. Removal of the solvent *in vacuo* left 1.0 g. of a semi-crystalline residue which, after crystallization from acetone, gave 0.6 g. (48%) of the red chromate ester I, m.p. 107–108° (dec., uncor.). Two recrystallizations of the ester from acetone yielded 0.42 g., m.p. 109.5°, and 0.28 g., m.p. 114.5–115°, of I. All 3 fractions had similar infrared spectra.[19] Optically active II from *l*-α-fenchone gave I, m.p. 129° dec.[20]

Anal. Calcd. for $C_{22}H_{38}O_4Cr$: C, 63.13; H, 9.09; Cr, 12.43. Found[21]: C, 63.10; H, 9.30; Cr, 12.57.

(b) **With Chromyl Chloride.**—Crude 2-methylfenchol (4.0 g.) was dissolved in 100 ml. of carbon tetrachloride and cooled to −30°. To this solution was added with stirring 1.9 g. of freshly prepared chromyl chloride[22] in 50 ml. of the same solvent over a period of 30 minutes. At the end of the addition 2 g. of solid sodium carbonate was added, and the red reaction mixture was allowed to warm to room temperature.[23] After filtration and concentration of this solution the red mass remaining was dissolved in acetone, filtered again and then cooled to 0°. Red needles of I, m.p. 109°, formed overnight, and a second crop, m.p. 102°, was obtained by cooling the acetone mother liquor to −70°, bringing the total yield to 2.7 g. (54%). Both fractions gave infrared spectra which were superimposable on the spectrum of I from the chromic acid method.

Anal. Found: Cr, 12.57.

Di-2-methylbornyl Chromate (III).—Crude 2-methylborneol (25 g.) containing camphor was dissolved in 600 ml. of pentane and shaken for 15 minutes with 33 g. of chromium trioxide in 150 ml. of water. Some of the chromate diester precipitated from the pentane layer, and ether was added to dissolve it. The ether–pentane layer was separated and the solvents were removed *in vacuo* until solid began to precipitate. The solution was warmed to redissolve the solid and then cooled in a Dry Ice–acetone bath. Yellow needles of III, m.p. 98–98.5° (dec., uncor.), weighing 6.0 g. separated from the solution. Concentration of the filtrate to 300 ml. and cooling gave 1.0 g. more, bringing the total yield to 22%.

Anal. Calcd. for $C_{22}H_{38}O_4Cr$: Cr, 12.43. Found: Cr, 12.41.

The infrared spectrum of this ester was quite different from that of di-2-methylfenchyl chromate.

Lithium Aluminum Hydride Reduction of I and III.—The chromate diester of 2-methylfenchol (1.2 g.), m.p. 109°, was reduced in 185 ml. of ether with 1.44 g. of lithium aluminum hydride. The gray reaction mixture turned deep green in color and, after 5 hours reaction time, was hydrolyzed with 18 ml. of water. The clear, supernatant ether solution was decanted from purple, inorganic salt, the ether was evaporated and a total of 0.71 g. of II was isolated and sublimed: m.p. 63.5–66.0°, $[\alpha]^{25}\mathrm{D}$ +1.71° (α 0.21°, *c* 12.25). The identity of this alcohol as 2-methylfenchol was established by comparison of its infrared spectrum with that of II purified *via* the hydrogen phthalate.

Similar reduction of III (0.8 g.) yielded, after sublimation, 0.52 g. (81%) of 2-methylborneol, m.p. 161–163.5°, $[\alpha]^{28}\mathrm{D}$ −14.0° (α 1.71°, *c* 12.2).

Anal. Calcd. for $C_{11}H_{20}O$: C, 78.51; H, 11.98. Found: C, 78.25; H, 12.12.

Reaction of Di-2-methylfenchyl Chromate (I) **with Sodium Methoxide.**—Sodium metal (16.3 g.) was added to 100 ml. of absolute methanol under dry, oxygen-free nitrogen. The chromate ester (1.54 g.), m.p. 109–109.5°, was added next to the solution which immediately took on a red color, changing within several minutes to brown at room temperature. This color changed gradually to green, after which the solution was left to stand overnight. Additional methanol and 40 ml. of water were added, most of the methanol was distilled and the remaining solution was thrice extracted with pentane. The extracts were dried over sodium sulfate and the solvent removed, leaving 1.2 g. of crude II which was purified by sublimation: 0.99 g. (80%), m.p. 65.5–67.5°, $[\alpha]^{25.5}\mathrm{D}$ +1.09° (α 0.135°, *c* 12.4). This substance was identified as 2-methylfenchol (infrared). No other product was isolable.

Solvolysis of I in Absolute Methanol.—The chromate ester (5.0 g.), m.p. 109.5–110°, was placed in a dry, nitrogen-swept tube into which 60 ml. of absolute methanol was distilled. The tube was sealed, maintained at 65° in an oven for 11 days and then cooled to −35° before being opened to an Ascarite absorption train. No carbon dioxide was detected. The reaction mixture was poured now into 400 ml. of cold water, leaving a brown solid on the surface of the aqueous methanol. This mixture was extracted exhaustively with pentane, and the extracts were dried over sodium sulfate. The aqueous methanol solution was filtered, and the brownish-gray solid was dried.

Anal. Calcd. for $(CH_3O)_3Cr$: Cr, 35.84. Found: Cr, 34.17, 34.45.

The filtrate was poured into a saturated, aqueous dimedon (7.37 g.) solution at *p*H 4.6. A precipitate began to form immediately and after 24 hours the formaldehyde-dimedon derivative was filtered and dried: 2.95 g. (42%), m.p. 189.5–191°, mixed m.p. undepressed.

The pentane was removed by atmospheric distillation from the solution above, and the oil, 3.82 g., thus obtained was placed on a column of alumina (80–200 mesh) and chromatographed with pentane and ether. An olefinic mixture was obtained, 0.78 g., sublimed, 0.69 g., m.p. 41–46°, $n^{56.5}\mathrm{D}$ 1.4543, whose infrared spectrum was similar to that of the olefinic mixture obtained from the potassium bisulfate dehydration of 2-methylfenchol except in the 8.5–9.5 μ region. The differences here and the C, H analysis discrepancy are undoubtedly due to the presence of methyl ethers.

Anal. Calcd. for $C_{11}H_{18}$: C, 87.93; H, 12.07. Found: C, 84.76; H, 12.15.

Total elution of the column gave 2.7 g., sublimed, 2.33 g., of 2-methylfenchol, m.p. 66.5–68°, infrared identification.

Solvolysis of I in Formic Acid.—Chromate ester (5.1 g.), a mixture of 109.5–110° (2 g.) and 105–105.5° (3.1 g.) material, was reacted in 40 ml. of formic acid (98–100%) in a sealed tube under nitrogen at 65°. After 14 hours the tube was removed from the oven, cooled to −55° and opened directly into an Ascarite absorption train which trapped 0.28 g. (52%) of carbon dioxide. The reaction mixture was then poured into 200 ml. of water with the precipitation of 1.98 g. of a blue solid.

Anal. Calcd. for $(HCOO)_3Cr$: Cr, 27.80. Found: Cr, 27.84.

The aqueous mixture was extracted 4 times with pentane (two 50-, two 25-ml. portions), the extracts were dried over sodium carbonate and the solvent was then removed by distillation. The residual orange-red oil showed carbonyl absorption at 5.81 μ in the infrared region but no bands which could be attributed to olefin or alcohol. Evaporative distillation of this material at 60° (11 mm.) gave a water-white distillate, 3.55 g., $n^{25}\mathrm{D}$ 1.4670, leaving 0.85 g. of red,

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[18] Modified slightly from the method of Wienhaus, reference 5; see also W. Treibs, Dissertation, Göttingen, 1917.

[19] This Grignard reaction with technical fenchone, theoretically at least, can lead to four alcohols, *d*- and *l*-*exo*, *d*- and *l*-*endo*. This mixture in turn, on esterification with chromic acid, can lead to ten diesters consisting of four pairs, each of which is a diastereoisomer of the other, of enantiomorphs and two diastereoisomeric *meso* forms. It is not surprising, therefore, that fractional crystallization occurs. A series of eleven crystallizations of a sample of I raised the m.p. to 121.5° which could have been improved further.

[20] Wienhaus and Treibs,[18] starting with *d*-α-fenchone, obtained I, m.p. 130° dec. The separation problem in these cases is simplified since *l*-fenchone, for example, can give only two diastereoisomeric alcohols on Grignardization, and these alcohols with chromic acid may produce three diastereoisomeric esters, *l*-*exo*–*exo*, *l*-*endo*–*endo*, *l*-*exo*–*endo*. Constancy of m.p. is reached in two crystallizations.

[21] We are indebted to F. R. Zwanzig for this C,H analysis. Chromium content was obtained by burning the sample and weighing chromium as the sesquioxide.

[22] W. C. Fernelius, "Inorganic Syntheses," Vol. II, John Wiley and Sons, Inc., New York, N. Y., 1939, p. 205.

[23] The reaction proceeded with explosive violence at room temperature; hence the −30° conditions were necessary. If base were not added at the end of the reaction, the trace amount of sulfuric acid remaining in the chromyl chloride after its preparation and/or the hydrogen chloride generated by the reaction caused decomposition of the ester.

polymeric residue in the still. The infrared spectrum of the distillate was identical to that of the formate obtained by the reaction between formic acid and 2-methylfenchol and the mixed olefins, V and VI (see below), *i.e.*, carbonyl and formate absorption at 5.81 and 8.40–8.55 μ, respectively.

2-Methylfenchol (1.0 g.) was dissolved in 42 ml. of formic acid and warmed for 8 hours at 47°. The mixture, progressively darkening to black, was poured into 200 ml. of water and treated exactly as described above. The colorless, liquid formates of II and IV were thrice distilled at 25° (0.5 mm.), 0.61 g. (52%), and were the same mixture as that obtained from the formolysis: n^{25}D 1.4669 (infrared).

Anal. Calcd. for $C_{12}H_{20}O_2$: C, 73.43; H, 10.27. Found: C, 73.00; H, 10.31.

A mixture of 1-methylcamphene (V) and 1-methyl-α-fenchene (VI), 1.14 g., obtained from the dehydration of 2-methylborneol (see below), reacted for 5.5 hours at 65° with 98–100% formic acid. The crude product showed no olefin absorption in the infrared region and gave 0.71 g. of mixed formates, n^{25}D 1.4667, on evaporative distillation at 50° (22 mm.), which were the same as those obtained from the formolysis of I and the esterification of II (infrared).

Dehydration of II and IV.—Crude 2-methylfenchol (5 g.) contaminated with fenchone was dehydrated with 13 g. of fused potassium bisulfate according to the method of Ruzicka.[15c] The liquid product was chromatographed and developed on alumina with petroleum ether to give a semisolid which, after sublimation, amounted to 2.53 g., m.p. 33.5–42.5°, $n^{56.5}$D 1.4529. The infrared spectrum of this mixture of terminal methylenic olefins contained strongly absorbing bands at 6.04 and 11.40 μ.

The dehydration of crude 2-methylborneol (camphor), 15 g., was carried in the same way, from which 3 g. of mixed olefins, m.p. 30.5–41.5°, $n^{56.5}$D 1.4521, was isolated. The spectrum of this material was indistinguishable from the olefinic mixture obtained by the dehydration of II.

Solvolysis of I in Acetic Acid.—The chromate ester (5.0 g.), m.p. 109–10°, was dissolved in 80 ml. of glacial acetic acid under dry, oxygen-free nitrogen and sealed off in a glass tube. After 5 days at 65° the tube was cooled to below −50° and opened into Ascarite (no carbon dioxide). The green reaction mixture was poured into water and extracted with pentane. The pentane solution was extracted with 5% aqueous sodium carbonate, washed, dried over sodium sulfate and then put aside momentarily.

The carbonate extracts were acidified with concentrated hydrochloric acid and extracted thereafter with ether. The ether was removed from the dried solution, leaving a viscous residue which, after evaporative distillation, gave a heavy, clear distillate: 0.21 g., n^{25}D 1.4876, n^{50}D 1.4784. The infrared spectrum of this material was the same as that given by the acidic substances arising from the chromic acid oxidation and 2-methylfenchol and of the olefinic mixture obtained from the dehydration of 2-methylborneol (see below). This acidic product is probably a complex mixture of fenchane- and camphane-2-carboxylic acids.[24]

Anal. Calcd. for $C_{11}H_{18}O_2$: C, 72.49; H, 9.96. Found: C, 72.77; H, 9.78.

The pentane solution of neutral material was freed of its solvent by ordinary distillation, and the residual 2.91 g. of liquid whose infrared spectrum contained hydroxyl absorption at 2.77 μ, carbonyl at 5.77 and 5.86 μ and olefinic at 6.04 and 11.40 μ was chromatographed on a column of silica gel using 2% ether in petroleum ether as the developing agent. The olefinic mixture eluted, 0.81 g., sublimed, 0.74 g., m.p. 37.5–44.5°, $n^{56.5}$D 1.4538, was the same (infrared) as that of the dehydration product of 2-methylfenchol (or of IV).

Further elution yielded 0.18 g. of 2-methylfenchol, m.p. 60.5–64°. Identification was established by the preparation of its chromate ester, 43 mg., m.p. 107.5–108.5° (infrared comparison) and its subsequent reduction with lithium aluminum hydride to 6 mg. of II, m.p. 64–67.5° (infrared).

Total elution of the column gave 0.32 g. of a carbonyl mixture. The presence of camphor and fenchone in the mixture is deduced from infrared absorption at 5.77 μ, corresponding to the carbonyl band of both camphor and α-fenchone, from comparison of this material with that recovered from the chromic acid oxidation of the mixed olefins, V and VI (see below) and from the analogy with the chromic acid oxidation of camphene.[8] The carbonyl absorption at 5.86 μ most probably arose from methyl ketone structure in a degradation product such as methyl 1-methyl-3-isopropenylcyclopentyl ketone. No further characterization was attempted.

The green aqueous acetic acid solution from the original reaction mixture was evaporated to dryness on a steam-bath, leaving 2.4 g. of chromic acetate.

Anal. Calcd. for $(CH_3COO)_3Cr$: Cr, 22.69. Found: Cr, 22.72.

Solvolysis of I in Acetonitrile.—The chromate ester (5.0 g.), m.p. 116.5–117.5°, was dissolved in and reacted with 60 ml. of dry acetonitrile in a tube experiment for 41 days at 65°. The brown, unidentified chromium precipitate was removed by centrifugation, and the acetonitrile solution was poured into 500 ml. of water and extracted with pentane. The oily residue remaining after removal of the solvent was chromatographed on alumina using pentane and ether–pentane as eluting solvents. In this manner the olefinic mixture, V and VI, 1.44 g., m.p. 40.5–49.5°, $n^{56.5}$D 1.4544, similar (infrared) to that obtained from acetolysis, was isolated, as well as a small amount of II and the carbonyl mixture, absorbing at 5.77 and 5.86 μ.

Solvolysis of I in Carbon Tetrachloride.—A solution of 5.0 g. of the chromate ester in 75 ml. of carbon tetrachloride was heated at 65° for 54 days by the sealed tube technique described above. The reaction mixture was centrifuged and decanted from the brown solid found to contain chromium and chlorine but not identified. The clear, red supernatant liquid was analyzed spectrophotometrically for hexavalent chromium in the ultraviolet region[25] and found to contain 40% of the unreacted ester. The red solution was passed through an alumina column to decompose the remaining ester.[26] The carbon tetrachloride was then removed, and the residual oil, 3.86 g., was chromatographed on silica gel using pentane and ether–pentane as developing solvents. Again, mixed olefin, m.p. 41.5–54.5°, $n^{56.5}$D 1.4548, was isolated, then 2-methylfenchol and finally the carbonyl material, 5.77 and 5.86 μ. An attempt was made to separate the carbonyl components with Girard "T" reagent and by fractional crystallization of their 2,4-dinitrophenylhydrazones without success.

Repetition of this experiment with 0.013 mole of I in 60 ml. of carbon tetrachloride containing 0.013 mole of methanol for the same length of time gave the same products. However, differences were that the reaction had proceeded to 92% completion and that the olefinic mixture obtained melted considerably higher, 59–67.5°, although its infrared spectrum was indistinguishable from that of the dehydration product of 2-methylfenchol.

Solvolysis of Di-2-methylbornyl Chromate in Methanol.—The methanolysis of 5.0 g. of III was carried out in a sealed tube under nitrogen at 65° exactly as described in preceding experiments. After 2 weeks the tube was cooled and opened. After centrifugation the solid material was washed with methanol and ligroin, and these washes together with the solvolysis solution were poured into water. The aqueous layer was extracted with ligroin, the ligroin solution was dried over sodium sulfate and then passed through an alumina column, using ligroin and ether for development. An olefinic mixture, 1.32 g. (sublimed, 0.90 g.), m.p. 46–53.5°, $n^{56.5}$D 1.4552, was obtained having an infrared spectrum similar to that obtained from the dehydration of 2-methylborneol in most respects except in the 8.5–9.5 μ region, indicating the presence of methyl ethers in about the same amount as in the case of the products from the methanolysis of I.

Anal. Calcd. for $C_{11}H_{18}$: C, 87.93; H, 12.07. Found: C, 84.38; H, 12.17.

2-Methylborneol, 1.68 g. (sublimed, 1.56 g.), m.p. 158.5–163°, $[\alpha]^{28.5}$D −14.9° (α 1.84°, c 12.3), was also eluted. Its infrared spectrum was the same as that of IV obtained by the lithium aluminum hydride reduction of III.

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[24] The literature lists a m.p. of 45–46° for fenchane-2-carboxylic acid but for camphane-2-carboxylic acid values ranging from 69 to 89° are given.

[25] We are indebted to Dr. C. N. Matthews for this analysis.

[26] In a control experiment it was found that a fresh solution of I in pentane was decolorized in 15 minutes when in contact with alumina. The sole product was 2-methylfenchol.

Formaldehyde was isolated in 30% yield from the aqueous methanol solution above by means of its dimedon derivative.

Oxidation of 2-Methylfenchol with Chromic Acid.—A solution of II in 85 ml. of glacial acetic acid was treated dropwise with a solution of 3.5 g. of chromic anhydride (mole ratio: 0.026/0.035) dissolved in 4 ml. of water and 100 ml. of acetic acid over a period of 100 minutes. At room temperature there was no *visible* reaction after 15 minutes. The temperature of the solution was raised then to 76° at which point the chromic acid solution turned green upon addition. The mixture was maintained at this temperature for 5.5 hours with stirring and then was poured into cold water. The aqueous mixture was extracted repeatedly with pentane, and the pentane extracts were then combined and extracted with 5% aqueous sodium carbonate solution. The pentane solution was then dried over sodium sulfate and put aside for the moment.

The carbonate extracts were acidified with concentrated hydrochloric acid and extracted with ether. The dried ether extracts were freed of solvent and the residual 0.88 g. of liquid was evaporatively distilled, giving 0.73 g. of a colorless, viscous liquid, $n^{25}\mathrm{D}$ 1.4868, $n^{50}\mathrm{D}$ 1.4775, whose infrared spectrum contained carboxylic acid absorption, 5.84 μ, and was similar to that of the acids obtained from the decomposition of the chromate diester I of II in acetic acid. This liquid is believed to be a mixture of fenchane- and camphane-2-carboxylic acids.

Anal. Calcd. for $C_{11}H_{18}O_2$: C, 72.43; H, 9.95. Found: C, 72.07; H, 9.84.

The neutral material in the pentane solution was placed on a column of alumina and chromatographed using pentane and pentane–ether as developing solvents for the separation of olefinic and carbonyl fractions. The olefinic mixture of V and VI was sublimed: 0.29 g., m.p. 43.5–57°, $n^{56.5}\mathrm{D}$ 1.4551. Its infrared spectrum showed absorption at 6.04 and 11.40 μ and was the same as that of the dehydration products of II and IV.

The infrared spectrum of the carbonyl material, when compared with the spectra of synthetic mixtures of camphor or fenchone, indicated the presence of these two ketones in approximately the amounts of 60–65% and 40–35%, respectively.

Oxidation of the Olefins from 2-Methylborneol with Chromic Acid.—The olefinic mixture of 1-methylcamphene and 1-methyl-α-fenchene[27] (2.4 g.) was dissolved in 20 ml. of glacial acetic acid and treated dropwise with a solution of 2.13 g. of chromic anhydride (mole ratio: 0.016/0.021) in 3 ml. of water and 27 ml. of acetic acid. Oxidation was evident from the change in color (red to green) of the first drop of chromic acid solution. Addition was completed in 80 minutes at 25–28° with stirring, after which the solution was heated to 80° and maintained at that temperature for 5.75 hours to ensure completion of reaction. The brownish-green mixture was poured into 350 ml. of water and extracted with pentane. The separation techniques from this point on were the same as those described in the preceding experiment. A total of 0.44 g. of mixed fenchane- and camphane-2-carboxylic acids, $n^{50}\mathrm{D}$ 1.4777, was obtained as a viscous distillate, similar to that obtained from the oxidation of II.

Anal. Calcd. for $C_{11}H_{12}O_2$: C, 72.43; H, 9.95. Found: C, 72.67; H, 9.82.

The neutral fraction contained a mixture of V and VI, 0.39 g., m.p. 35–42.5°, $n^{56.5}\mathrm{D}$ 1.4536, identical with the starting material (infrared). The ketonic fraction, 0.39 g., contained camphor and fenchone in the approximate amounts of 55–60 and 45–40%, respectively, as indicated by comparing the absorption peaks at 9.55 and 9.77 μ in its infrared spectrum with those in the spectra of synthetic mixtures of camphor and α-fenchone.

Methanolysis of Hydrogen 2-Methylfenchyl Phthalate.—The hydrogen phthalate of II (5.0), m.p. 140.5–141.5° (dec., uncor.) was dissolved in and treated with 70 ml. of absolute methanol in a sealed tube experiment at 65°. After seven days the contents of the tube were poured into 300 ml. of a 5% aqueous sodium carbonate solution and extracted with pentane. After drying over sodium carbonate the pentane was removed from its solution leaving 1.12 g. of crude product containing both olefin (6.04 and 11.40 μ) and carbonyl material in very small amount (dimethyl phthalate). The mixture was chromatographed on alumina using pentane and ether and separated into the well-characterized olefin mixture, 0.76 g., m.p. 40–49°, $n^{56.5}\mathrm{D}$ 1.4546, and the carbonyl fraction mentioned above. The olefins however were still contaminated with methyl ethers as shown by differences in the 8.5–9.5 μ region of its infrared spectrum.

After standing 2 days the carbonate solution was acidified with concentrated hydrochloric acid and extracted with ether. Removal of the dried ether left 2.82 g. of a solid which was reduced to 0.66 g. by Soxhlet extraction using benzene:phthalic acid. The extracted solid, 1.96 g., m.p. 114–170°, is undoubtedly a mixture of the unreacted hydrogen phthalate of II, the half-ester of methanol and a small amount of phthalic acid.

For purposes of comparison the *methyl ether* of 2-methylfenchol was prepared by treating the potassium salt of II with methyl iodide in benzene according to the procedure already described for tertiary alcohols.[28] The crude ether, 0.56 g., m.p. 42.5–64.5°, was distilled from molten potassium: 0.48 g., m.p. 51.5–69°. This was chromatographed on alumina with pentane alone, and then was sublimed once, 0.33 g., m.p. 74.5–83°, and again, 0.29 g., m.p. 72.5–80.5°. Its infrared absorption bands in the 8.5–9.5 μ region, 8.68, 8.89, 9.18 and 9.58 μ, differentiated the ether from both II and the V–VI mixture.

Anal. Calcd. for $C_{12}H_{22}O$: C, 79.06; H, 12.17. Found: C, 79.12; H, 11.98.

Ozonization of Olefins.—The olefinic mixtures obtained in the experiments described were ozonized according to the procedure originally employed by Ruzicka[15c] with some modifications. In all cases a mixture of camphor and α-fenchone was isolated. A typical ozonization can be illustrated with olefins (0.105 g.) derived from the dehydration of 2-methylborneol. A solution of this mixture was dissolved in a total of 120 ml. of pentane, cooled to −70° and ozonized until the effluent gases caused red color in a saturated boric acid solution (135 minutes) of KI. The reaction mixture was concentrated at atmospheric pressure to a volume of 25 ml. and then added to 47 ml. of an aqueous sodium hydroxide solution which was allowed to stand overnight. An alternate method of decomposing the ozonides by steam distillation of the basic solution was used with some of the olefinic mixtures, and this had a profound effect on the proportion of various products (see below). The two layers were separated, the pentane layer was re-extracted with fresh alkali and the basic layer with fresh pentane. The dried pentane solutions were chromatographed on alumina using pentane and ether for development. A small amount of unreacted olefin was isolated first, followed by the ketonic fraction. Comparison of the infrared spectrum of these ketones, using characteristic absorption bands at 9.55 and 9.77 μ, indicated the ratio of camphor to fenchone to be 40:60%. All olefinic mixtures ozonized and decom-

TABLE I

OZONOLYSIS

Source of Olefin	No.	Ketone, %	Camphor, %	Fenchone, %	Acid, %
I–CH_3OH	1	32	50	50	30
I–$CCl_4(CH_3OH)$	2	33	50–55	50–45	26
IV–$KHSO_4$	3	9	40	60	35
I–CH_3COOH	4[a]	18	15	85	71
I–CH_3CN	5[a]	21	20	80	68
III–CH_3OH	6[a]	10	15	85	41
Hydrogen phthalate of II–CH_3OH	7[a]	16	15–20	85–80	49
Hydrogen phthalate of II–CCl_4	8a	29	60	40	40
	8b[a]	16	20	80	59

[a] Ozonides decomposed by steam distillation from basic solution.

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(27) The individual examination of all olefinic mixtures obtained in the course of this work did not reveal the presence of either methyltricyclene or 2-methylbornylene.

(28) W. von E. Doering and H. H. Zeiss, THIS JOURNAL, **75**, 4733 (1953).

posed by this procedure consistently gave camphor–fenchone ratios in the range of 40–60:60–40%. If, however, the ozonide was decomposed in the alternate manner mentioned above, the ratio of camphor to fenchone was changed to the range, 15–20:85–80%. As a check one of the ozonization mixtures was divided into two portions and each was decomposed with and without steam distillation. The consistency of the result is shown in Table I.

The basic aqueous solution was acidified with hydrochloric acid and extracted with ether. Removal of ether from the dried solution left the mixed acids as an oil.

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[CONTRIBUTION NO. 2075 FROM THE GATES AND CRELLIN LABORATORIES OF CHEMISTRY, CALIFORNIA INSTITUTE OF TECHNOLOGY]

The Hydrolytic Cleavage Products of Boron Trifluoride Complexes of β-Carotene, Some Dehydrogenated Carotenes and Anhydrovitamin A_1

BY F. J. PETRACEK AND L. ZECHMEISTER

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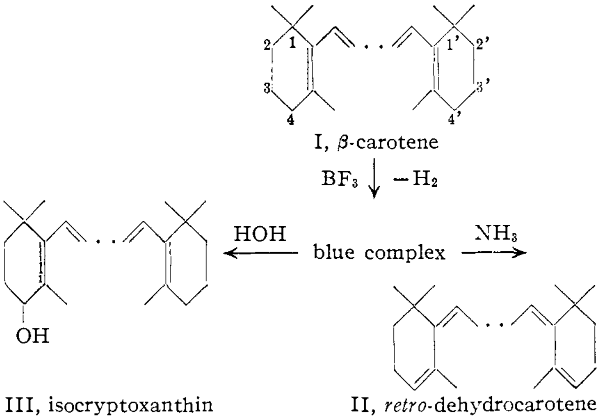
β-Carotene in chloroform when treated with BF_3-etherate yielded, upon hydrolysis of the blue complex, isocryptoxanthin, whereby the trifluoride had acted first as a dehydrogenating agent. From the 3,4-dehydro-α-carotene and 3,4-dehydro-β-carotene complexes the corresponding 4-hydroxy derivatives were obtained. *retro*-Bisdehydrocarotene yielded 2-hydroxy-3,4-dehydro-β-carotene. By dehydrating the latter compound with HCl–chloroform, the *retro*-bisdehydrocarotene was recovered. The hydrolysis of the blue complex of anhydrovitamin A_1 did not result in the recovery of the vitamin but in the formation of a new isomer, very probably 4-hydroxy-axerophthene which, under the influence of acid chloroform, dehydrated to anhydrovitamin A_1.

As reported earlier[1] a treatment of β-carotene (I), $C_{40}H_{56}$, with BF_3-etherate, followed by hydrolysis, resulted in the shortening of the chromophore and the formation of two new crystalline pigments. A similar treatment of a dehydrogenation product of β-carotene, *viz.*, *retro*-dehydrocarotene (II), $C_{40}H_{54}$,[2] yielded isocryptoxanthin (4-hydroxy-β-carotene), a structural isomer of naturally occurring cryptoxanthin.[3] Both conversions were carried out in hexane solution.

It was observed recently[4,5] that when commercial chloroform (containing 1% alcohol) was used, instead of carbon tetrachloride, as a solvent in some dehydrogenation processes, the course of the reaction was altered. The same medium, which allowed the use of higher concentrations in a one-phase system, has now been applied in the BF_3 experiments described below.

In the case of *retro*-dehydrocarotene (II) the effect of the change from hexane to chloroform was negligible, although the rate of the complex formation increased very considerably. However, the hydrolysis of the β-carotene–BF_3 complex, formed in chloroform, resulted in the isolation of isocryptoxanthin (III) instead of the two pigments mentioned.[1] This conversion so far as we know represents the first direct introduction of a hydroxyl group into the β-carotene molecule, in contrast to the indirect route, requiring dehydrogenation to *retro*-dehydrocarotene as a first step.[3]

We propose that, under the conditions applied, boron trifluoride acts on β-carotene first as a dehydrogenating agent forming a complex not with the starting material but with a dehydrogenated carotene. Indeed, when the blue complex was cleaved with dry ammonia (instead of water) *retro*-dehydrocarotene (II) was obtained (Scheme 1).



I, β-carotene

III, isocryptoxanthin

II, *retro*-dehydrocarotene

SCHEME 1

The dehydrogenating action of boron trifluoride would parallel a similar effect caused by another "Lewis acid," *viz.*, antimony trichloride, whose blue β-carotene complex yields on hydrolysis *retro*-dehydrocarotene.[6]

In connection with these experiments a reinvestigation has been carried out of the respective boron trifluoride complexes of 3,4-dehydro-α-carotene, $C_{40}H_{54}$, and 3,4-dehydro-β-carotene, $C_{40}H_{54}$. These pigments had been obtained by Karmakar and one of the writers[7] when reacting carotenes with N-bromosuccinimide in carbon tetrachloride solution yields of crystalline substance, 3.8 and 1.4%. By applying chloroform as a solvent and dehydrobrominating with N-phenylmorpholine, these yields have now been increased to 14.5 and 2%.

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[1] L. Wallcave, J. Leemann and L. Zechmeister, *Proc. Natl. Acad. Sci.*, **39**, 604 (1953).

[2] This compound was termed earlier "dehydro-β-carotene"; *cf.* R. Kuhn and E. Lederer, *Ber.*, **65**, 637 (1932); P. Karrer and G. Schwab, *Helv. Chim. Acta*, **23**, 578 (1940); H. H. Inhoffen and G. Raspé, *Ann.*, **594**, 165 (1955). The name "*retro*-dehydrocarotene" was proposed by the latter authors.

[3] L. Wallcave and L. Zechmeister, THIS JOURNAL, **75**, 4493 (1953).

[4] F. J. Petracek and L. Zechmeister, *ibid.*, **78**, 1427 (1956).

[5] F. J. Petracek, Thesis, California Institute of Technology, 1956.

[6] A. E. Gillam, I. M. Heilbron, R. A. Morton and J. C. Drummond, *Biochem. J.*, **26**, 1174 (1932); P. Karrer and G. Schwab, ref. 2; *cf.* P. Meunier and A. Vinet, "Chromatographie et Mésomérie," Paris, Masson & Cie., 1947, p. 79.

[7] G. Karmakar and L. Zechmeister, THIS JOURNAL, **77**, 55 (1955).