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REARRANGEMENTS IN THE TERPENE SERIES. I. ISOMERIZATION AND ESTERIFICATION OF α-PINENE

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Introduction. It was first observed by Bouchardat and LaFont (1) that α-pinene reacts with certain organic acids to produce esters of borneol, in addition to isomerization products. Since that time, the direct esterification of α-pinene by organic acids has been studied by various investigators (2). Correlations between the properties of the acids and their tendency to form borneol esters are almost entirely lacking. Haller (2 f) mentions that tetrachlorophthalic acid was used "because it is exempt from Viktor Meyer's law of steric hindrance" (3). However, since the esterification of α-pinene is not analogous to the esterifications described by Meyer, and since later work (2 c, g) shows that a number of ortho substituted acids (*e.g.*, *ortho*-benzoylbenzoic acid) give good yields of ester, it is doubtful whether steric hindrance affects the course of the reaction.

Delepine, Reisman, and Suau (2 d) have observed that the reactivities of acids towards α-pinene are roughly proportional to their ionization constants. This conclusion is based upon the destruction of α-pinene by acids of varying strength; it does not correlate the quantity of borneol ester formed with the acid strength.

Present investigation. The present work is a study of the factors influencing the formation of borneol esters by the direct action of organic acids on α-pinene, with particular emphasis upon the nature of the rearrangements involved both in the main reaction and in the formation of various by-products. In all experiments *d*-α-pinene obtained by fractionation of Florida turpentine was used.

In order to determine the influence of acid strength upon the yield of borneol esters, a series of monobasic organic acids with ionization constants between 0.3×10^{-4} and 350×10^{-4} at 25° was selected. All of the acids were miscible with α-pinene in the proportions used at the reaction temperature. In all examples, 0.18 mole of acid was heated with 0.38 mole of α-pinene on an oil-bath at 135–140° for 43 hours. The terpene (largely *d*-limonene, rotation 67° in 2-decimeter tube) was removed by steam distillation, and the residual ester saponified with excess alkali. The borneol was removed from the saponification mixture by steam distillation. Yields were based upon the amount of acid used and the product obtained; this was a mixture of borneol with small quantities of isoborneol. Results are recorded in Table I.

In Figure 1 the yields are plotted against the ionization constants of the acids. The maximum lies between $K = 3.7 \times 10^{-4}$ and $K = 8 \times 10^{-4}$.

The highest possible yield of borneol under the conditions used is probably less than 80 or 85%, since, under these conditions, there is always a good deal of isomerization of the α-pinene to *d*-limonene. At higher temperatures, the

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TABLE I

Function of Acid in the Formation of Borneols from α-Pinene

ACID	NO., FIG. 1.	$K \times 10^4$ (25°)	YIELD OF BORNEOLS, %
p-Methoxybenzoic	1	0.3	0.5
Cinnamic	2	0.36	4.0
Benzoic	3	0.58	2.
o-Methoxybenzoic	4	0.8	1.5
Alpha-naphthoic	5	2.	20.
Ethoxyacetic	6	2.3	27.
m-Nitrobenzoic	7	3.16	61.
o-Benzoylbenzoic	8	3.7	68.
Salicyclic	9	10.	63.
o-Chlorobenzoic	10	12.	49.
o-Bromobenzoic	11	14.2	45.
3,5-Dinitrobenzoic	12	15.5	32.
Chloroacetic	13	15.2	42.
5-Bromosalicylic	14	24.	46.
o-Nitrobenzoic	15	64.	31.
2,4-Dinitrobenzoic	16	350	27.
Trichloroacetic	17	very strong	25.

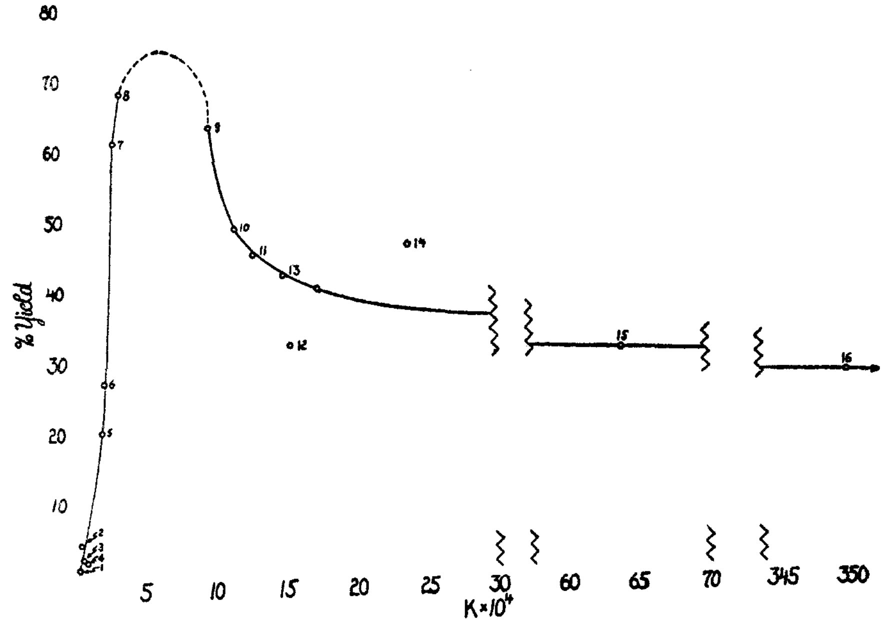


Figure 1. Effect of Acid Constant on Yield of Borneol.

optimum acid strength required for best yields of borneol esters is somewhat lower. Thus, benzoic acid at 200° gives more than 30% of borneol as compared with 2% at 140°. Two factors probably influence the increased yield at higher temperature. First, the α-pinene is activated, as is indicated by the rapid thermal isomerization to dipentene (*dl*-limonene). Second, an acid such as benzoic, the strength of which at 140° is less than the optimum, would be expected to be more effective at a higher temperature.

Effect of phenols. Since the strength of benzoic acid is less than the optimum at 140°, it was anticipated that the addition of polar solvents might increase the effectiveness of this acid at the temperature in question. In a series of experiments, 0.2 mole of benzoic acid plus 0.2 mole of solvent were heated with 0.38 mole of α-pinene for 43 hours at 135–140°. The reaction mixtures were worked up as previously described to recover crude borneol. The results are tabulated in Table II. Yields are based upon the amount of acid used.

It will be noted that phenols greatly increase the capacity of benzoic acid to esterify α-pinene. This effect cannot be attributed to increase in the dielectric constant of the medium.

TABLE II

FUNCTION OF DIELECTRIC OF SOLVENT IN THE FORMATION OF BORNEOLS FROM α-PINENE

SOLVENT	YIELD OF BORNEOL, %	*k* (DIELECTRIC OF PURE SOLVENT)
Anisole	2.	4.3 (20°)
Nitrobenzene	3.	36. (20°)
Quinoline	5.	9. (20°)
Catechol	22.	
o-Cresol	23.	8. (40°)
p-Nitrophenol	27.	
Resorcinol	26.	3.2 (22°)
Beta-naphthol	34.	
Phenol	32.	4.3 (10°)
o-Cresol	36.	13. (40°)
m-Cresol	40.	13. (40°)
Benzonitrile	9.	26. (20°)

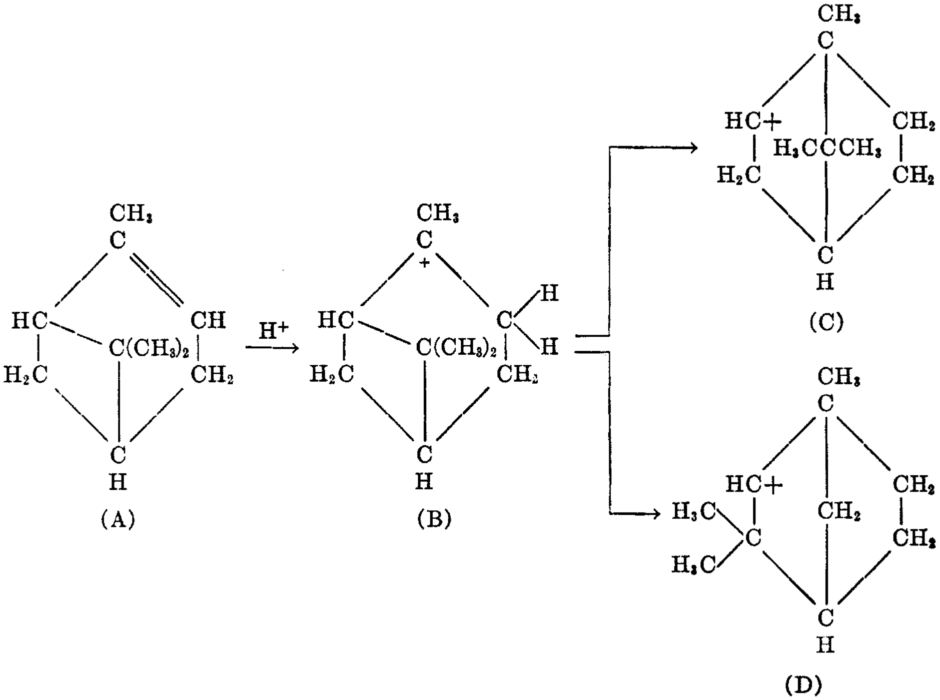
It has been observed that certain phenols isomerize α-pinene to camphene (2 k). Since camphene esterifies readily when heated with organic acids, it at first appeared probable that the function of the phenols was to isomerize the α-pinene to camphene, which was then esterified by the acid. That this is not the mechanism, however, is proved by two considerations. First, the phenols used in the experiments here described do not isomerize α-pinene to camphene under the conditions used; second, the character of the products formed where phenols are used precludes the formation of these products by the esterification of camphene. Camphene, when treated with organic acids, yields isoborneol esters almost exclusively, whereas the direct esterification of α-pinene produces borneol esters. Haller (4) has observed that the specific rotation of isoborneol is nearly twice as great in ethanol as in toluene, whereas the rotation of borneol is approximately the same in the two solvents. Austerweil (2 e) made use of this fact to estimate the percentage content of *d*-borneol and *l*-isoborneol in samples obtained by esterifying α-pinenes. Austerweil's method would be valid if the components of the mixture were optically pure. But the alcohols obtained from α-pinene (which varies in optical purity depending upon its source) are not pure. Both *d*-borneol and *l*-isoborneol oxidize to *d*-camphor. By oxidizing a mixture of the two, their optical purity (p) can be determined from the ratio of the rotation of the camphor obtained to the rotation of pure *d*-camphor. The known optical values are:

$$\left.\begin{array}{l}[\alpha]_D \text{ for } d\text{-borneol} = 37.33^\circ \\ [\alpha]_D \text{ for } l\text{-isoborneol} = -32.9^\circ\end{array}\right\} \text{ in ethanol}$$

$$\left.\begin{array}{l}[\alpha]_D' \text{ for } d\text{-borneol} = 37.87^\circ \\ [\alpha]_D' \text{ for } l\text{-isoborneol} = -18.93^\circ\end{array}\right\} \text{ in toluene}$$

$$[\alpha]_D \text{ for } d\text{-camphor} = 43.15^\circ \qquad \text{in ethanol}$$

With the aid of these values, Delepine, Reisman, and Suau (2 d) calculate the fraction (X or X') of isoborneol in a mixture by the equations: $X = \frac{(37.33)\,(p) - [\alpha]_D}{(70{:}23)\,(p)}$ or $X' = \frac{(37.87)\,(p) - [\alpha]_D'}{(56.80)\,(p)}$ where p is the optical purity as already defined and $[\alpha]_D$ and $[\alpha]_D'$ are the rotations of the borneol-isoborneol mixture in alcohol and toluene, respectively.

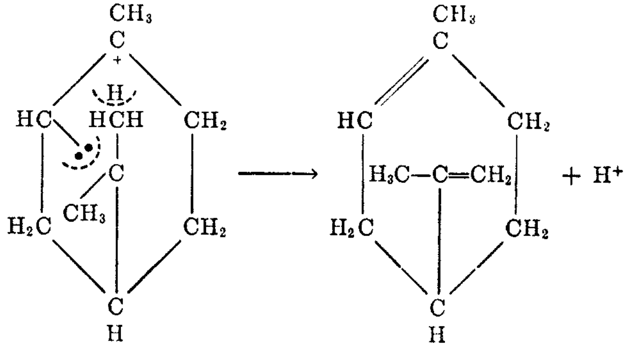


A sample of the crude borneol here obtained from α-pinene by the action of benzoic acid and cresol had the specific rotation 18.8° in ethanol (1.5 g./25 cc.) and 20.2° in toluene (1.5 g./25 cc.); this sample, when oxidized with nitric acid, gave a camphor with $[\alpha]_D$ 25.2° (1 g./25 cc. ethanol). Accordingly $p = 0.485$, $X = 0.07$, and $X' = 0.06$. Obviously, less than 10% of the crude sample was isoborneol. This fact precludes formation of the esters from camphene. The effect of phenols upon the reaction is probably due to the increased availability of hydrogen ion in phenolic solutions of organic acids.

Mechanism of the reaction. Meerwein (5) has pointed out the analogy between rearrangements in the terpene series and the well known pinacol-pinacolin or Wagner rearrangements. *d*-Limonene is invariably formed as a principal by-product in the organic acid esterification of *d*-α-pinene. Consequently, it seems logical to regard the isomerization and esterification as parts of a single mechanism and to assume that the double bond is the point of attack. If the first step in either reaction is the capture of a hydrogen ion, a positive charge is induced on the carbon atom holding the methyl group. Since the ion thus formed is the typical unstable ion of the pinacol-pinacolin and Wagner rearrangements, it should stabilize itself by the shift of one of the bonds in the cyclobutane ring to the positive carbon holding the methyl group. These steps may be represented structurally in the formula scheme A–D on p. 151.

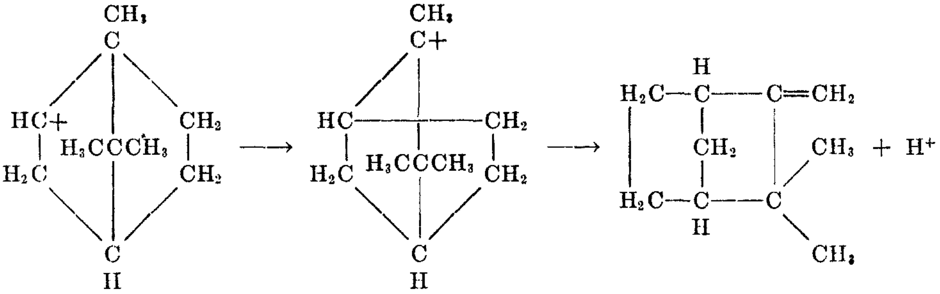
The addition of the acid radical to the ion (C) gives an ester of borneol or isoborneol, depending upon whether the addition occurs cis or trans to the endo ring, whereas addition to the ion (D) gives an ester of fenchyl alcohol. Small quantities of fenchyl esters are always formed in this reaction.

d-Limonene can be formed by the elimination of a hydrogen ion from either (B) or (C) as follows:



In the course of the present work, it was found that amides, such as formamide and acetamide, inhibit the esterification of α-pinene by organic acids, but do not inhibit the isomerization to *d*-limonene. Thus *d*-α-pinene can be successfully converted into *d*-limonene by means of organic acids in the presence of amides. The yields are very good (90 % of product, B.R. 170–180°, rotation 67° in a 2-dcm. tube). Thermal isomerization of α-pinene produces dipentene (*dl*-limonene) (6).

The isomerization of α-pinene to camphene, which can be brought about by phenols and various acid catalysts is easily understood by referring to the above schemes. The ion (C), in the absence of an anion to add to the positive carbon, might rearrange and eliminate a proton to give camphene according to the following scheme:



The small amount of isoborneol formed in the direct esterification of α-pinene may be due to such an isomerization with subsequent esterification of the camphene formed.

It seems probable that the ion (A), rather than a tertiary ester formed by direct addition of the acid to the α-pinene double bond, is actually the first product of the esterification reaction. If a tertiary ester were the first product of the reaction, benzoylbenzoic acid should esterify ethylenic compounds such as ethyl maleate, ethyl fumarate, trimethylethylene, cyclohexene, and 1-methylcyclohexene. In spite of attempts under varying conditions, none of these compounds could be esterified with benzoylbenzoic zcid. Esterifications with organic acids of the type reported in the present investigation seem to be limited to compounds such as pinene, camphene, fenchene, etc., which undergo a simultaneous rearrangement.

SUMMARY

1. The yield of borneol esters obtained by direct esterification of α-pinene with organic acids depends upon the ionization constant of the acid used. High yields at 140° are obtained over a very narrow range of ionization constant, $K = 3.7 \times 10^{-4}$ to 8×10^{-4}. At higher temperatures, acids with lower ionization constants are fairly effective.

2. The yields of borneol esters formed by acids of lower than optimum ionization are greatly improved by the addition of phenols to the reaction mixture. This improvement is due to increased availability of hydrogen ion, not to increase in dielectric constant of the reaction medium, or to isomerization of α-pinene to camphene.

3. *d*-α-Pinene, when heated with a mixture of an organic acid and amide, is converted to *d*-limonene. The yields are good. The amide appears to inhibit esterification.

4. The principal products formed in the reaction of α-pinene with organic acids can be explained by assuming the preliminary capture of a proton by the α-pinene; the unstable ion thus formed rearranges and stabilizes itself in a variety of ways.

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