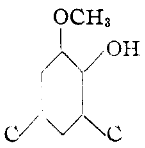
[CONTRIBUTION FROM THE NORTHERN RESEARCH LABORATORY[1]]

Interpretation of Lignin. I. The Synthesis of Gymnosperm Lignin

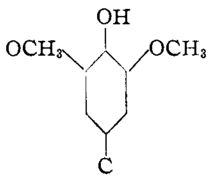
BY ALFRED RUSSELL[2]

Lignin, from whatever source it is obtained, is an amorphous material with none of the usual criteria of purity. It cannot be assumed to have a constant composition since it seems to undergo changes easily. It is a plant product without definite character and is probably best described as the residual plant structural material after carbohydrates, coloring matters, waxes, resins and the like have been removed. The fission products are in harmony with a simple structure of the familiar 2-phenylbenzopyran type but it is impossible for lignin to be a single such unit. It is certain that lignin in the plant is sensitive enough to undergo some structural change during the process of extraction. The alteration may be minor when extraction is carried out with non-destructive solvents, such as alcohols containing traces of mineral acids, but it is impossible to ignore the likelihood that the use of strong mineral acids, aqueous alkalies and alkaline bisulfites may cause extensive structural changes. This has been recognized by a few workers who have tried to look on the process of extraction as a reaction to which unaltered lignin is exposed and of which the material extracted represents the product. There is general evidence in favor of this idea in the fact that totally inert solvents will not dissolve lignin.

The available evidence indicates that there are two varieties of lignin both largely aromatic in character. As significant cleavage products one variety (from gymnosperms) gives, on degradation, only derivatives of catechol-2-methyl ether (guaiacol) with carbon atoms attached in the -4- and -6- positions (I); and the other (from angiosperms) gives the same derivatives of catechol-2-methyl ether and of pyrogallol-1,3-dimethyl ether with a carbon atom attached in the -5- position (II).

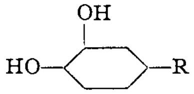


I

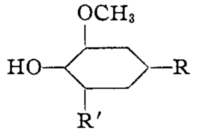


II

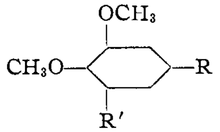
As examples of the cleavage products of a typical gymnosperm, those of spruce lignin, the most exhaustively examined one, may be described (a) alkali fusion gives protocatechnic acid (III, R = CO_2H) and catechol (III, R = H); (b)



(III)

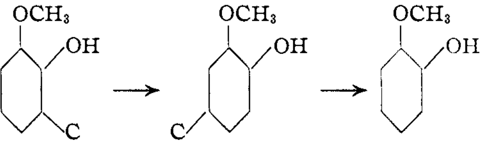


(IV)



(V)

methylation with dimethyl sulfate and alkali followed by oxidation with potassium permanganate, gives veratric acid (V, R′ = H, R = CO_2H), isohemipinic acid (V, R = R′ = CO_2H) and veratrole (V, R = R′ = H) and dehydrodiveratric acid; (c) treatment of sulfonated lignin with alkali at 160° gives vanillin (IV, R′ = H, R = CHO), acetovanillone (IV, R′ = H, R = $COCOCH_3$) and guaiacol (IV, R = R′ = H); (d) dry distillation gives guaiacol (IV, R = R′ = H), vanillic acid (IV, R′ = H, R = CO_2H) and eugenol (IV, R′ = H, R = $CH_2CH{=}CH_2$); (e) zinc dust distillation gives guaiacol (IV, R′ = R = H) and 4-*n*-propylguaiacol (IV, R′ = H, R = *n*-C_3H_7); (f) Oxidation with nitrobenzene gives vanillin-5-carboxylic acid (IV, R = CHO, R′ = CO_2H) and vanillin (IV, R = CHO, R′ = H). It is clear from these cleavage products that the changes (VI) → (VII) → (VIII) occur readily.



(VI) (VII) (VIII)

The occurrence among lignin degradation products of small amounts of formaldehyde, methanol, acetic acid and the like has little significance. Decomposition of any carbon chain will rise to similar products. It is significant, however, that there is no report of a simple fission product containing more than two carbon atoms (the products of hydrogenation of hydrogenolysis are, naturally, excluded).

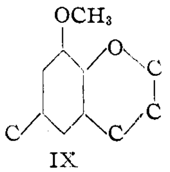
Now, referring to the lignin from gymnosperms, it has to be inferred that one or both of the carbon atoms free in the skeleton (I) must be joined to at least one other carbon atom. The occurrence of an oxygen atom in (I) in the *ortho* position to an attached carbon atom and the absence of typical free phenolic hydroxyl groups in this lignin makes the benzopyran structure almost inevitable, hence, (I) may be expanded to (IX). Specific examples of such a structure among natural products are common. The occurrence of 4-*n*-propyl-

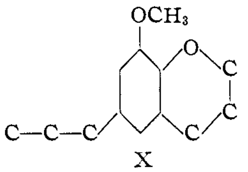
---

(1) One of the laboratories of the Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, U. S. Department of Agriculture.

(2) Chemist, Industrial Chemical Section, Agricultural Residues Division.

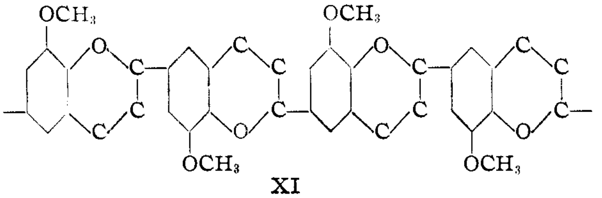
guaiacol (IV, $R = H$, $R = n\text{-}C_3H_7$) and similar compounds as cleavage products of this lignin under certain conditions means that the skeleton (IX) must be expanded to (X) to explain the occurrence of a three-carbon chain *para* to the hydroxyl group in such cleavage products.


IX


X

Few, if any, common natural products have very complicated structures. Consequently the elaborations proposed by Cross and Bevan,[3] Fuchs,[4] Pavolini,[5] Schrauth,[6] and the meticulous detail of the structure proposed by Brauns[7] have little to recommend them.

It is much more likely, as has long been supposed in a general way, that lignin (in this case, that from gymnosperms) is composed of a series of *n*-propylbenzene units. If this, as most likely, is true, then referring to the skeleton (X), the three carbon atoms in the chain *para* to the pyranose oxygen must be the three carbon atoms of a *second* pyranose ring. This implies a continuing structure of the type (XI).


XI

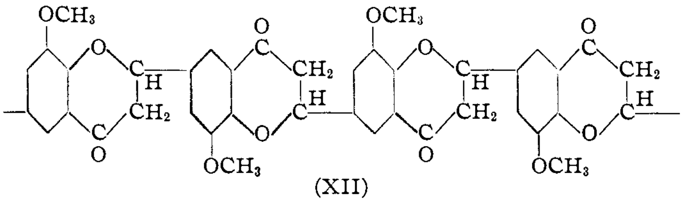
With other suggested structures, one, not dissimilar to the above, but containing methyl furan rings has been tentatively put forward by Erdtman and, separately, by Freudenberg, and Hibbert has come close to advocating a benzopyran unit structure.

To account for the hydrogen and oxygen content of the lignin under consideration, the skeletal structure (XI) must be completed by adding an oxygen atom and three hydrogen atoms to each pyran ring. The most plausible way to do this, by analogy with other plant products, such as flavanones, flavones, and flavonols is to make it the poly-8-methoxydihydrobenzopyrone (XII).

This material is available synthetically by the following steps: vanillin mono-acetate (XIII), by Fries rearrangement, will give 2-hydroxy-3-methoxy-5-formyl acetophenone (XIV). This will undergo easy condensation polymerization (aldolization, loss of water—Claisen condensation) to give (XV) which, in turn, will cyclicize to the product required. Under most conditions (XV) and (XI) will be in equilibrium.

The intermediate ketoaldehyde (XIV) is sufficiently reactive that, in any conditions under which it is formed, the final product (XII) is likely to result at once. By Fries rearrangement of vanillin monoacetate, then, the product (XII) is likely to be obtained with no intermediates.

The properties of the product (XII) should be entirely analogous to those recorded for lignin. The carbonyl group would not be very typical and lignin does not give satisfactory carbonyl derivatives. Enolization would be easy and this, with the easily opened pyranose ring and the possible occurrence of a hydrated form, would give a series of enolic derivatives. The hydrogens of the methylene group in the cyclic form would be rather reactive; consequently, halogens would substitute more easily in this form than add to the enol form. Lignin, again, undergoes a substitution rather than an addition reaction with halogens. Moreover, the product (XII) would have to give the same cleavage products as the lignin from gymnosperms.


(XII)

The synthesis described has been carried out and the synthetic material, apart from being somewhat darker in color, has the same qualitative properties as those recorded for spruce lignin and, where direct comparison has been made, with those observed for a specimen of "alkali" lignin obtained from the saccharification processing of corncobs. The solubility characteristics are the same; like lignin, the synthetic material is soluble in aqueous alkali, ethanol, acetone and dioxane; insoluble in dilute mineral acids, water, ether, hydrocarbons and halogenated solvents. Parallel to the solubility of unaltered natural lignin in alkaline bisulfites, the synthetic product is soluble in aqueous sodium bisulfite. In all probability this corresponds to the formation of a stable sulfonic acid by the familiar 1,4-addition process to the open chain form.

The synthetic material suspended on paper pulp and treated in succession with chlorine, aqueous sulfur dioxide, and aqueous sodium sulfite gives the pink color characteristic of lignin specimens. For purposes of comparison the test was run simultaneously on a specimen of alkali lignin from the saccharification processing of corncobs. Moreover, dispersed on filter paper, the synthetic material gives the pink color typical of lignin with

---

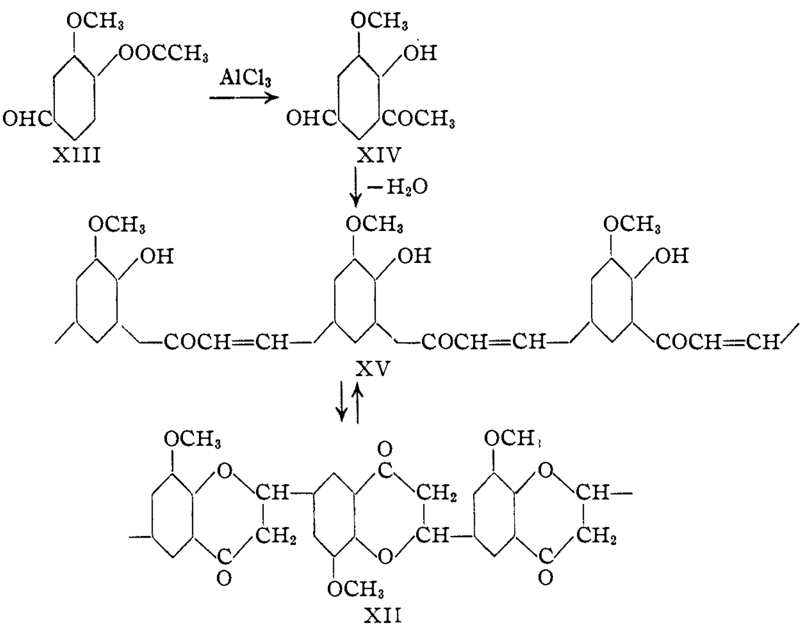
(3) Cross and Bevan, *Ber.*, **26**, 2520 (1893).

(4) Fuchs, *Z. angew. Chem.*, **44**, 111 (1931).

(5) Pavolini, *Industria Chemica*, **6**, 1367 (1931).

(6) Schrauth, *Z. angew. Chem.*, **36**, 149 (1923).

(7) Brauns, Report to Second Southwest Chemurgic Clinic, National Farm Chemurgic Council, Mimeographed Circular No. 483, Oklahoma City, Oklahoma, June 3, 1946.



phloroglucinol dissolved in 12% aqueous hydrochloric acid.

There never has been any way of measuring the purity or degree of alteration of any lignin specimen or derivative. Consequently no recorded experiment could ever be repeated exactly, using the synthetic product for comparison purposes. The synthetic material must give the same recognizable simple cleavage products as gymnosperm lignin. Apart from such simple products, lignin does not give derivatives that can be positively identified. It may be methylated, acetylated and so on but the reactions must be regarded as stepwise since the analytical values of the products vary continuously. However, so many methylations, acetylations, and the like have been carried out that the *maximum* values on record should correspond rather closely to those for total reaction. Indeed, it is obvious that such maxima are the only values to which any meaning may be attached.

Apart from an anticipated low methoxyl value (aluminum chloride is an effective demethylating agent) and consequent lowering of hydrogen content, the analytical values for the synthetic material are close enough to the range reported for gymnosperm lignins and to the calculated range for the monomer ($C_{10}H_{10}O_4$) and the polymer ($C_{10}H_8O_3$).

Many "acetyl" values are on record for the acetylated lignin from gymnosperms and the maximum is 27.2%. Acetylation of the synthetic material with acetic anhydride gives a product having an "acetyl" content of 29.5%. Two acetyl groups for each monomeric residue is the maximum number that could be introduced and this would correspond to an acetyl content of 30.9%. It is evident that the triacetate implied by the open-chain formula is most improbable since the carbonyl oxygen, in this form, is chelated with the hydrogen of the phenolic hydroxyl group and, furthermore, the same carbonyl group forms part of a stable, total crossed conjugated system. The diacetate formed is the geminal diacetate of the pyranose form.

Like the acetylation, the methylation of lignin appears to be a continuous process. The maximum value reported for "methoxyl" is 32.4% corresponding to the calculated (32.3%) value for two methoxyl groups in each monomeric residue and implying the methylation of one free hydroxyl group in each. By exhaustive treatment with dimethyl sulfate and alkali, the synthetic material gives a methylated product containing 29.6% of "methoxyl."

It is, of course, very evident that the alkaline conditions of methylation and the acid conditions of acylation favor, respectively, the open and closed ring forms.

Reports on halogenation experiments indicate that the maximum halogen content of chlorinated spruce lignin is about 38%. This corresponds to the introduction of three chlorine atoms into each monomeric residue in the polymer (requires: Cl, 38.1%). There have been few attempts to brominate lignins and not enough figures are on record for comparison. However, bromination of the synthetic material with excess bromine in acetic acid in the presence of iodine gives a product containing about 57% of the halogen. For three bromines in each monomeric residue the calculated value is 58.1%. In a word, three hydrogen atoms in each monomeric residue may be replaced by halogens. The replaceable hydrogens are, of course, the active ones in the pyranose ring. Halogenation values then for spruce lignin and the synthetic material are in good agreement.

Although experimental verification might be difficult, it is worth recording that the methoxyl values for methylated spruce lignin sulfonic acid (20.7–25.4%) are in agreement with the calculated value for the synthetic material having two methoxyl groups and one sulfonic acid group for each monomeric residue (22.8%).

Again, although its significance is obscure, a Klason lignin determination run on the synthetic material gave a value of 85.7%. A simultaneous determination run on a purified specimen of alkali lignin from the saccharification processing of corncobs gave a value of 88.3%.

Finally, although in the ordinary way the comparison of two analytical values obtained from amorphous materials provides questionable evidence of constitution; in each instance quoted in this particular case it is impossible for the repeated coincidence of *three* values to be fortuitous. There cannot be anything casual about such repeated agreements. When the additional evidence of what is, under the circumstances, an unambiguous synthesis, and the same fission products with, almost complete qualitative identity is taken into account, the matter must be considered reasonably well established.

Experimental[8]

Vanillin Monoacetate.—Vanillin (15.2 g., 1 mole) was dissolved in dry pyridine (40 cc.) and acetyl chloride (10 g., 1.25 mole tech. grade) added portionwise over ten minutes with occasional shaking. The hot orange-colored reaction mixture was heated on the steam-bath for thirty minutes. The somewhat-cooled reaction mixture was poured into ice and water, the precipitate collected, washed (water) and recrystallized from dilute ethanol (charcoal); slender white needles, m. p. 77–78°, yield 62%.

Anal. Calcd. for $C_{10}H_{10}O_4$: C, 61.8; H, 5.15; "OMe," 15.9; "CH_3CO," 22.16. Found: C, 61.6; H, 5.18; "OMe," 15.88, 15.98; "CH_3CO," 22.2, 22.8, 22.8.

Fries Rearrangement of Vanillin Monoacetate into Poly-8-methoxydihydrobenzopyrone.—Vanillin monoacetate (9.7 g., 1 mole) was dissolved in anhydrous nitrobenzene (50 g.) and dry aluminum chloride (13.3 g., 2 mole) added portionwise with shaking. The temperature rose and as addition proceeded the straw-colored reaction mixture became very dark and viscous. After all the aluminum chloride had been added the reaction mixture was heated to 93–100° (oil-bath temperature) for two hours. The cooled reaction mixture was treated with sufficient dilute hydrochloric acid and the nitrobenzene removed by steam distillation. The dark-colored, resinous residue was collected and washed with water. It could not be crystallized and was reprecipitated several times from solution in ethanol by cold, very dilute hydrochloric acid. The flocculent, near-gelatinous, light-brown precipitate was collected and dried and formed a dark-brown (almost black), brittle solid. After nearly complete drying (six days at 23 mm. over potassium hydroxide) the material was no longer totally soluble in ethanol or acetone. It could not easily be reduced to a powder because of its electrical properties.

Anal. Calcd. for $C_{10}H_8O_5$: C, 68.2; H, 4.55; "OMe," 17.6. Calcd. for $C_{10}H_{10}O_4$: C, 61.8, H, 5.15; "OMe," 15.9. Found: C, 65.9, 66.0; H, 4.35, 4.44; "OMe," 9.96, 9.95. Lignin recorded: C, 62–64; H, 5–6; "OMe," 15–17.

Acetylation of Poly-8-methoxydihydrobenzopyrone.—Poly-8-methoxydihydrobenzopyrone (1 g.) was dissolved in acetic anhydride (5 cc.) and the solution boiled for two hours. The reaction mixture was decomposed with water and the brown precipitate collected. It was insouble in ethanol and was precipitated several times from solution in acetone with ice water. Finally, it was collected and dried (at least six days, 23 mm., potassium hydroxide). The "acetyl" value corresponds to two acetyl groups for each monomeric residue.

Calcd.: "OAc," 30.9. Found: "OAc," 29.4, 29.5.

Methylation of Poly-8-methoxydihydrobenzopyrone.—Poly-8-methoxydihydrobenzopyrone (1 g.) was dissolved (heat) in aqueous sodium hydroxide (20 cc., 10%). Dimethyl sulfate (6 g.) was added portionwise with shaking at about 70°. Then with heating and shaking, more dimethyl sulfate (12 g.) was added portionwise and the reaction mixture kept hot and alkaline by addition, from time to time, of aqueous sodium hydroxide (20%). In about ninety minutes a considerable amount of alkali-insoluble material had separated. This was collected after dilution with water, washed and reprecipitated several times from solution in acetone with water. The finely divided precipitate was very hard to handle. It was dried (six days, 23 mm., potassium hydroxide).

Anal. Calcd.: (two "OMe" groups for each monomeric residue) "OMe," 32.3. Found: "OMe," 29.3, 29.6.

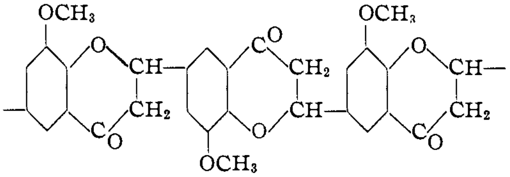
Bromination of Poly-8-methoxydihydrobenzopyrone.—Poly-8-methoxydihydrobenzopyrone (1 g.) was suspended in glacial acetic acid (25 cc.), a crystal of iodine and bromine (10 cc.) added. The reaction mixture was heated at 90° for ten hours, diluted with water (200 cc.) and the dark-red, finely-divided precipitate collected, washed three times with water and reprecipitated twice with water from solution in ethanol. The finely-divided dark-orange colored, flocculent precipitate was collected and dried (six days, 23 mm., potassium hydroxide).

Anal. Calcd.: (for three bromines for each monomeric residue) Br, 58.1. Found: Br, 56.3, 57.4.

Summary

The existence of at least two varieties of lignin appears to be definitely established. One of these is associated with gymnosperms and gives, as significant fission products, only derivatives of catechol monomethyl ether (guaiacol). The other is associated with angiosperms and gives, as significant cleavage products, the same derivatives of catechol monomethyl ether and some derivatives of pyrogallol-1,3-dimethyl ether. The possible occurrence of other varieties of lignin giving other fission products is not excluded.

Examination of the analytical evidence accumulated over the past, some seventy years, excludes the improbable elaborate formulas previously proposed and what appears to be a reasonable structure has been advanced. It is concluded from a study of the existing evidence that the lignin from gymnosperms is a poly-8-methoxydihydrobenzopyrone (XII). The lignin from angiosperms is likely constituted in the same way but with pyrogallol-1,3-dimethyl ether groups terminally, or otherwise, attached. The pyrogallol-1,3-dimethyl ether nuclei could not form part of a continuing chain as in (XII) unless the migration of a methyl group occurs during degradation. However, such nuclei could form part of the open chain form and a "mixed" chain is easily visualized.



XII

The proposed polymeric structures may not be absolutely correct and may need some modification later but it is in harmony with the known facts and with such plausible suggestions as have been made in the past. It is a cyclized condensation polymer of 2-hydroxy-3-methoxy-5-formyl-

---

[8] All analyses are micro determinations by Mr. Van Etten and Mrs. Wiele of this Laboratory.

acetophenone and is available in a single step by Fries rearrangement of vanillin monoacetate.

A polymeric material having its proposed structure has been synthesized and properties found not to differ qualitatively or, quantitatively from those recorded for spruce lignin. Solubility characteristics and general behavior are identical and it may be methylated, acetylated and halogenated (brominated) in the same fashion giving entirely analogous derivatives. The methoxyl content is noticeably lower than the calculated values but aluminum chloride is a good demethylating agent, and the introduction of free phenol groups could easily be responsible for the darker color.

PEORIA, ILLINOIS RECEIVED AUGUST 13, 1947

[CONTRIBUTION FROM THE NORTHERN REGIONAL RESEARCH LABORATORY[1]]

Methyl 2,4:5,6-Dimethylene-D-gluconate

BY C. L. MEHLTRETTER, R. L. MELLIES AND C. E. RIST

In an attempt to prepare polyesters of 2,4:3,5-dimethylene-D-gluconic acid by heating the methyl ester (I)[2] *in vacuo*, there was obtained by sublimation a mixture of compounds from which a new methyl dimethylene gluconate was isolated in 22% yield. This compound has now been shown to be methyl 2,4:5,6-dimethylene-D-gluconate (II). It is apparent from structures (I) and (II) that a methylene cyclic acetal rearrangement has occurred from carbons 3,5 to 5,6 of the gluconic acid chain. Cyclic acetal rearrangements were observed by Hibbert and his associates[3] who found that isomeric methylene, benzylidene and *p*-nitrobenzylidene cyclic acetals of glycerol were readily interconverted in the presence of hydrogen chloride. More recently Hann, Maclay and Hudson[4] have reported a cyclic acetal shift in the benzoylation of α-diacetone dulcitol.

The separation of the methyl dimethylene gluconate (II) from unchanged methyl 2,4:3,5-dimethylene-D-gluconate (I) and other products was effected by fractional crystallization of the sublimate mixture from methanol. The purified product, which melted at the same temperature as methyl 2,4:3,5-dimethylene-D-gluconate (152°), formed a crystalline amide and a crystalline tosyl derivative. The new product gave a specific rotation of −14.4° in methanol, as compared to +13.3° for methyl 2,4:3,5-dimethylene-D-gluconate. Efforts to establish the presence of a primary or secondary alcohol group in the methyl dimethylene gluconate by subjecting the tosylated compound to iodination by the Oldham and Rutherford[5] procedure gave only anomalous results.

The removal of a methylene group from the methyl dimethylene gluconate (II) would provide a monomethylene acetal, the structure of which if known would aid considerably in establishing the structure of the original ester. Hudson and Hann and their associates[6] have shown that the controlled acetolysis of a number of methylene sugar alcohol acetals by an acetic anhydride–acetic acid solution containing 1 to 2% sulfuric acid results in the preferential cleavage of certain methylene acetal linkages. Those formed through primary hydroxyl groups are readily cleaved. Where two secondary alcoholic acetal linkages are involved, such as in 2,4:3,5-dimethylene-D-sorbitol, the 2,4-methylene acetal ring is the more stable to acetolysis.

The acetolysis reaction was first applied to methyl 2,4:3,5-dimethylene-D-gluconate (I) to ascertain whether it would proceed according to rule. A crystalline substance was produced which was presumed to be methyl 3-acetoxymethyl-5,6-diacetyl-2,4-methylene-D-gluconate (IV). Catalytic removal of the acetyl and acetoxymethyl groups of this compound with sodium methoxide and reaction of the crude product with methanol–ammonia gave crystalline 2,4-methylene-D-gluconamide (V). The structure of the latter compound was established by the oxidative degradation of the product obtained by saponification of (IV) to 2,4-methylene-xylotrihydroxyglutaric acid. This substance was esterified and isolated as the methyl ester[7] (VII). Thus the acetolysis of methyl 2,4:3,5-dimethylene-D-gluconate results in the cleavage of only the 3,5-methylene cyclic acetal linkage as was found to be the case with 2,4:3,5-dimethylene-D-sorbitol.[6]

When analogous reactions were carried out with the methyl dimethylene gluconate, 2,4-methylene-D-gluconamide was again produced. This fact not only is evidence that the methyl dimethylene gluconate contains a 2,4-methylene acetal linkage but it also limits its structure to methyl 2,4:3,6-dimethylene-D-gluconate or methyl 2,4:5,6-dimethylene-D-gluconate (II). Conclusive proof for the latter structure was obtained from a study of

---

[1] One of the laboratories of the Bureau of Agricultural and Industrial Chemistry, Agricultural Research Administration, U. S. Department of Agriculture.

[2] Mehltretter, Mellies, Rist and Hilbert, THIS JOURNAL, **69**, 2130 (1947).

[3] Hill, Whelan and Hibbert, *ibid.*, **50**, 2235 (1928); Hibbert and Carter, *ibid.*, **50**, 3120, 3376 (1928).

[4] Hann, Maclay and Hudson, *ibid.*, **61**, 2432 (1939).

[5] Oldham and Rutherford, *ibid.*, **54**, 336 (1932); Ness, Hann and Hudson, *ibid.*, **66**, 1901 (1944).

[6] Ness, Hann and Hudson, *ibid.*, **65**, 2215 (1943); **66**, 665 and 670 (1944); Hann, Wolfe and Hudson, *ibid.*, **66**, 1898 (1944).

[7] Jones and Wiggins, *J. Chem. Soc.*, 382, 364 (1944).