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# Selectivity in the Catalytic Hydrogenation of D-Xylo-5-hexulosonate by Metals

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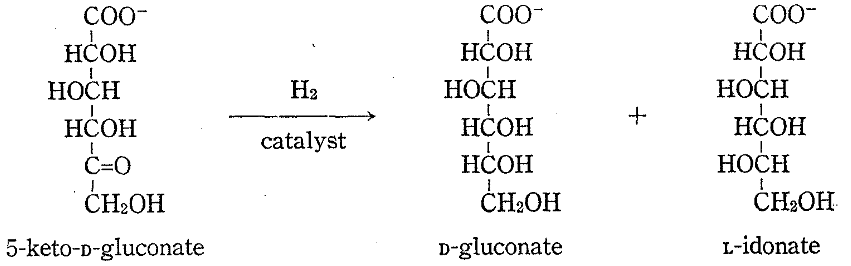
Catalytic hydrogenation of sodium D-xylo-5-hexulosonate (sodium 5-keto-D-gluconate) and its acid has been investigated on nickel, ruthenium, rhodium and palladium with or without boron-modification. It was found that nickel and palladium catalysts produce more L-idonate than D-gluconate especially when the metals are prepared by treating their salts with sodium borohydride.

Two adsorbed models for the substrate were presented to account for the observed hydrogenation selectivity, and the role of boron at the surface was discussed in terms of complexing with two hydroxyls of L-idonate.

## Introduction

In the synthesis of L-ascorbic acid from D-glucose, according to Gray's method,[2] is included a process of catalytic hydrogenation of D-xylo-5-hexulosonate (5-keto-D-gluconate). This hydrogenation process is known to give nearly equal amount of L-idonate and D-gluconate in the presence of a Raney nickel catalyst.[3]



Attempts have been made so far to obtain preferentially L-idonate,[4] but major factors controlling the selectivity for the hydrogenation are still unknown.

In a previous publication[5] from this laboratory, the hydrogenation of calcium 5-keto-D-gluconate has been investigated over various transition metal catalysts. That paper dealt with kinetic law, ratios of L-idonate over D-gluconate formed, and it was found that boron-modified-palladium gives rise to preferential formation of L-idonate.

Since the preferential formation of L-idonate is not only important from industrial viewpoint but also highly interesting in connection with its stereospecific nature, it was considered worthwhile to investigate this catalytic hydrogenation more in detail. Use of sodium 5-keto-D-gluconate or its acid as the substrate was thought to be advantageous to elucidate the mechanism of the selective hydrogenation. Because, calcium 5-keto-D-gluconate, used in the earlier work,[5] had limited solubility in aqueous solutions. In the present paper are reported

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1) Location: *7-3 Hongo, Bunkyo-ku, Tokyo.*
2) B.E. Gray, U.S. Patent 2421611 (1947).
3) R.M. Alieva, Vestn. Leningr. Univ., **18**(21), Ser. Biol. No. 4, 148 (1963) (*Chem. Abst.*, **60**, 9346).
4) T. Miki, T. Hasegawa and Y. Sahashi, *J. Vitaminol.*, **6**, 205 (1960).
5) C.Y. Chen, H. Yamamoto and T. Kwan, *Chem. Pharm. Bull.* (Tokyo), **17**, 2349 (1969).

results of the selective hydrogenation of sodium 5-keto-D-gluconate and its acid on both boron-modified and unmodified metal catalysts.

## Experimental

**Catalyst**——Commercially available metal catalysts were investigated. These were iron, cobalt, nickel and copper of Raney type, and 5% ruthenium, rhodium, palladium, platinum supported on an activated carbon. Boron-modified-metals were prepared by treating metal salts in aqueous solutions with sodium borohydride, and investigated also for their hydrogenation selectivities.

**Substrate**——5-Keto-D-gluconic acid was obtained by passing calcium 5-keto-D-gluconate through the column packed with Amberlite CG-120 $H^+$ type ion exchange resin. Its sodium salt was obtained by neutralizing the acid to pH 7.0 with sodium hydroxide solution.

**Experimental Procedure**——A 20—50 ml solution (0.4 mole/liter) of sodium 5-keto-D-gluconate and a given catalyst amounting 0.1—3.0 g was put in an autoclave. The reacting system was stirred by means of an electromagnetic stirrer under hydrogen pressures 60—100 kg/cm$^2$ at reaction temperatures from room temperature to 80° for 1—2 hr. The reaction products were analyzed by a gas chromatograph equipped with hydrogen flame detector.[6]

## Results

### Preliminary Experiments

The hydrogenation of calcium 5-keto-D-gluconate by sodium borohydride has already been reported by Hamilton and Smith[7] who found that L-idonate and D-gluconate are equally produced. To confirm this finding, sodium 5-keto-D-gluconate was subjected to hydrogenation by sodium borohydride under a similar condition with that of calcium salt. The result was that the preferential formation of either diastereoisomer is not effective. On the other hand, the catalytic hydrogenation of sodium 5-keto-D-gluconate in the presence of metals was found, depending on the kind of catalyst, to produce one of the isomers more than the other, while the isomerization between the two isomers was absent during the reaction.

The hydrogenation was completed on most metal catalysts usually within 1—2 hr at 80° under the hydrogen pressure 60 kg/cm$^2$, except iron, cobalt and copper catalysts which showed low hydrogenation activities. Platinum-carbon catalyst was active enough during the initial stage of reaction but gave rise to unidentified fragments with the progress of reaction. Thus, the platinum catalyst was unfavourable to the present work. Below pH 2 or over pH 10, many fragments were also formed on any catalyst, suggesting that optimum pH is present.

Thus, the catalytic hydrogenations were performed primarily on nickel, ruthenium, rhodium and palladium with or without boron modification, and the gas chromatographic analyses were carried out with respect to the hydrogenated products exceeding 90% yield.

### Catalytic Hydrogenation of Sodium 5-Keto-D-gluconate by Metals

Catalytic hydrogenation of sodium 5-keto-D-gluconate was investigated over commercial nickel, ruthenium, rhodium and palladium catalyst, respectively. The reaction products were quantitatively determined, as has been already described, by a gas chromatographic method.[6] A typical gas chromatogram obtained with a Raney nickel catalyst is shown in Fig. 1. The ratio of L-idonate (I) over D-gluconate (G) produced, determined by the corresponding peak area, is denoted as the selectivity of hydrogenation:

$$S=\frac{\mathrm{I}}{\mathrm{G}}$$

The values for $S$, observed on nickel, ruthenium, rhodium and palladium, respectively, are shown in Table I. It is shown in Table I that nickel and ruthenium give L-idonate twice as

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[6] C.Y. Chen, T. Imanari, H. Yamamoto and T. Kwan, *Chem. Pharm. Bull.* (Tokyo), **16**, 755 (1968).

[7] J.K. Hamilton and F. Smith, *J. Am. Chem. Soc.*, **76**, 3543 (1954).

much as D-gluconate, whereas rhodium and palladium yield the two isomers almost equally well. The result may indicate that the "asymmetric induction" can occur over nickel and ruthenium but very little on rhodium and palladium or by sodium borohydride.

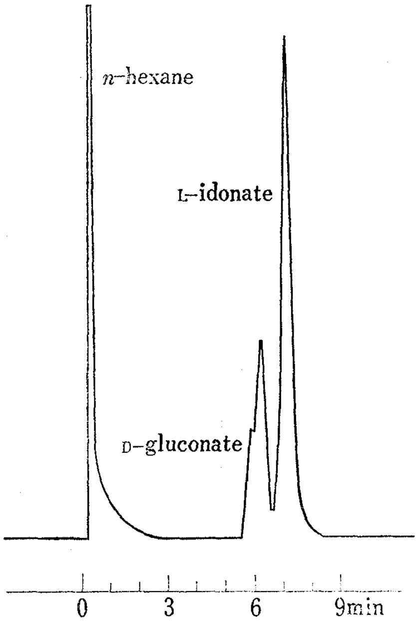

Fig. 1. Gas Chromatogram for the Hydrogenation Products of Sodium 5-Keto-D-gluconate Catalyzed by a Raney Nickel

TABLE I. The Ratio of L-Idonate over D-Gluconate formed in the Presence of Metal Catalysts

| Substrate | Metal | | | |
|---|---|---|---|---|
| | Ni | Ru | Rh | Pd |
| Na-KG | 2.2 | 1.8 | 1.2 | 1.1 |
| H-KG | × | 2.0 | 1.1 | 1.0 |

TABLE II. The Ratio of L-Idonate over D-Gluconate formed in the Presence of Boron-modified-metal Catalysts

| Substrate | Metal | | | | |
|---|---|---|---|---|---|
| | Ni | Ru | Rh | Pd | Pt |
| Na-KG | 2.7 | 1.8 | 1.2 | 3.4 | 0.9 |
| H-KG | 1.7 | 1.9 | 1.1 | 1.0 | — |

In Table II is shown the result of hydrogenation over boron-modified-metal catalysts. We have already reported[8] that boron-modified-nickel possesses the composition of $Ni_{2-3}B$ and boron-modified-palladium $Pd_{10}B$. Chemical stoichiometry for boron-modified-ruthenium or -rhodium was not quantitatively investigated, but qualitative analysis of these catalysts by curcumine tincture indicated that boron is present in the catalyst. It is apparent from Table I and II that nickel and palladium considerably contribute to the preferential formation of L-idonate when prepared with sodium borohydride.

### Effect of pH on the Selectivity

The pH of 5-keto-D-gluconic acid is about 3 in aqueous solutions. Under such low pH the acid is believed to exist as $\gamma$-lactone, although it is not in neutral solution.[9] Hence, it would be expected that such changes in the molecular form of 5-keto-D-gluconic acid greatly affect the nature of the selective hydrogenation. Thus, the hydrogenation of 5-keto-D-gluconate was investigated on adding 0.5N sodium hydroxide, in other words, in the pH range from 3 to 10. Typical gas chromatogram obtained on boron-modified-palladium is shown in Fig. 2. In Fig. 3a, are shown changes in the selectivity, $S$, against the amount of sodium hydroxide added. $S$ remained constant, as shown in Fig. 3a, up to about pH 6 while it increased to a remarkable extent beyond this pH. It is noted, however, that many fragments are formed above pH=10 resulting in a considerable decrease of $S$. In Fig. 3b is shown the titration curve which gives the relation between pH and the amount of sodium hydroxide added. It is clear that both changes are parallel. The result suggests that $\gamma$-lactone form is not accessible

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[8] C.Y. Chen, H. Yamamoto and T. Kwan, *Chem. Pharm. Bull.* (Tokyo), **17**, 1287 (1969).
[9] C.Y. Chen, H. Yamamoto and T. Kwan, *Chem. Pharm. Bull.* (Tokyo), **18**, 815 (1970).

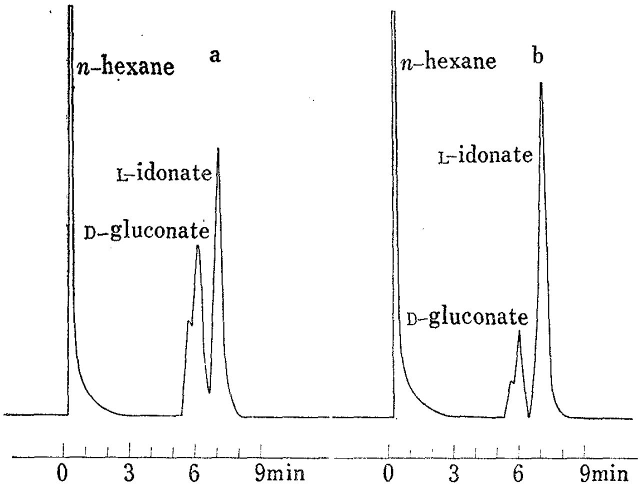

Fig. 2. Gas Chromatogram for the Hydrogenation Products of a 5-Keto-D-gluconic Acid and b. Its Sodium Salt catalyzed by Boron-modified-palladium Catalyst

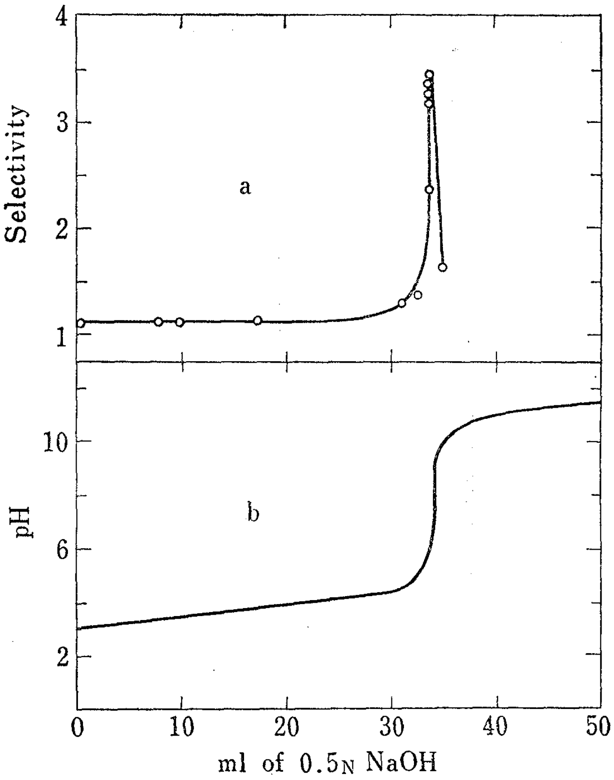

Fig. 3. Effect of pH on the Selectivity

a : effect of pH on the selectivity
b : titration curve of 5- keto-D-gluconic acid

to the formation of L-idonate. It should be noted, however, that such pH dependence of the selective hydrogenation is absent on unmodified palladium catalyst.

## Discussion

As described above, there seems to be two main experimental findings in the catalytic hydrogenation of 5-keto-D-gluconate, the mechanism of which is worthy of discussion. First, palladium catalyst, when prepared with sodium borohydride, was found to yield L-idonate more than D-gluconate. Since the palladium catalyst has been found to contain boron in a ratio of Pd:B=10:1,[8] the boron must have played an important role in the selective hydrogenation of this kind. Second, 5-keto-D-glucono-$\gamma$-lactone form was not found to be effective for the preferential formation of L-idonate. So, either ketal or ketone form may be regarded as a reactive entity for the hydrogenation.

We have already shown[9] that ketone form does exist for 5-keto-D-gluconate in aqueous solutions while it is absent in solid state. In this conncection, it should be recalled that the catalytic hydrogenation of adipoin by metals can not proceed with ease.[10] The fact may suggest that the substrate exists as a dimer losing its carbonyl group. Therefore, the hydrogenation of 5-keto-D-gluconate may probably be associated with the ketone form of the substrate rather than its ketal form.

Now, to interprete the observed hydrogenation selectivity by metals, two absorbed models for 5-keto-D-gluconate are assumed (Fig. 4), taking into consideration the tendency that the substrate is adsorbed so as to best interact with its hydroxyl and carbonyl groups with the surface. Here, it must be kept in mind that the carbonyl group and the $\beta$ hydroxyl group of

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[10] J.C. Sheehan, R.C. O'Neill and M.A. White, *J. Am. Chem. Soc.*, **72**, 3376 (1950).

L are possibly in a steric hindrance. If the interaction of the substrate with the surface is strong, the adsorbed state of intramolecularly less steric hindrance, such as Fig. 4a, would be favourable. On the other hand, the adsorbed state, such as Fig. 4b, may be allowed to exist, when weakly absorbed, even if this state is intramolecularly less stable; the 5-keto-D-gluconate molecule is supposed to be more or less flexible on the surface.

It is generally accepted that the adsorbality of nickel is greater than that of palladium. So, the adsorbed model of the substrate, Fig. 4a, may perhaps be adequate on nickel. The hydrogenation of carbonyl group would then yield more L-idonate than D-gluconate. The supposition is consistent with the result of Table I where nickel produces more L-idonate than palladium. On the other hand, if 5-keto-D-gluconate is weakly adsorbed on such metal as rhodium or palladium, the adsorbed model, Fig. 4b, may come into play so that D-gluconate can be produced.

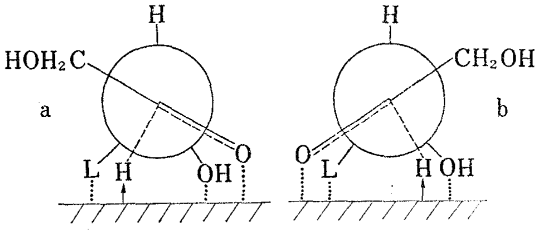

Fig. 4. Adsorption Models for 5-Keto-D-gluconate on the Surface of Catalysts

Boron is well known to complex with carbohydrates. The effect of boron on the preferential formation of L-idonate, as found on boron–modified–palladium as well as on boron–modified–nickel, would perhaps be associated with this sort of complexing. The formation of 5-membered ring between two hydroxyl groups of L-idonate and surface boron is ready for the adsorbed model, Fig. 4a, but not for the model Fig. 4b, and seems to contribute to the selective formation of L-idonate.

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