Reactions of Sugars

Introduction

The reactions of sugars that are critical in food science applications can be organized into a few general types of reactions that are heavily influenced by pH. Although there are a few exceptions, most of these reactions occur under the relatively mild conditions that prevail during processing and storage. This chapter will not address reactions of chemical synthesis and sugar structure proof. The monograph Carbohydrates—The Sweet Molecules of Life by R. V. Stick (2001) is recommended for its excellent treatment of sugar synthesis and basic sugar reactions.

Mutarotation

Mutarotation can be defined as the change in optical rotation that is observed when a reducing sugar is dissolved in water, due to the formation of different tautomeric forms. A sugar crystal will consist of molecules having a specific anomeric ring form (furanose or pyranose with α- or β-configuration). Upon dissolution, ring opening (hydrolysis) and
subsequent ring closure will occur, producing the \( \alpha \)- and \( \beta \)-pyranose and \( \alpha \)- and \( \beta \)-furanose forms. These forms have different chemical and physical properties (e.g., optical rotation, solubility, chemical reactivity, relative sweetness, etc.). Figure 3.1 shows the five forms of D-glucose that will theoretically exist in solution. For glucose, only the \( \alpha \)- and \( \beta \)-pyranose forms exist in significant amounts. \( \alpha \)-D-Glucopyranose has an “initial” optical rotation of +112°, whereas \( \beta \)-D-glucopyranose has an “initial” rotation of +19°. The amounts of the tautomers will be governed by conformational free energy. \( \beta \)-D-Glucopyranose has the greatest stability and predominates by being present at 63.6% at equilibrium at 20°C. Table 3.1 gives the distribution of selected D-sugar tautomers at equilibrium in water solution.

Glucose is classified as undergoing “simple” mutarotation since, for practical purposes, only two tautomers are present. This permits
Table 3.1 Distribution of D-Sugar Tautomers at Equilibrium in Aqueous Solution

<table>
<thead>
<tr>
<th>Sugar</th>
<th>Mutarotation Type</th>
<th>Temp (°C)</th>
<th>α-Pyranose (%)</th>
<th>β-Pyranose (%)</th>
<th>α-Furanose (%)</th>
<th>β-Furanose (%)</th>
<th>Open-chain (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glucose</td>
<td>Simple</td>
<td>20</td>
<td>36.4</td>
<td>63.6</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>38</td>
<td>62</td>
<td>0.5</td>
<td>0.5</td>
<td>0.002</td>
</tr>
<tr>
<td>Galactose</td>
<td>Complex</td>
<td>20</td>
<td>32</td>
<td>63.9</td>
<td>1</td>
<td>3.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>30</td>
<td>64</td>
<td>2.5</td>
<td>3.5</td>
<td>0.02</td>
</tr>
<tr>
<td>Fructose</td>
<td>Complex</td>
<td>27</td>
<td>—</td>
<td>75</td>
<td>4</td>
<td>21</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>2.5</td>
<td>65</td>
<td>6.5</td>
<td>25</td>
<td>0.8</td>
</tr>
<tr>
<td>Xylose</td>
<td>Simple</td>
<td>20</td>
<td>34.8</td>
<td>65.2</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td>31</td>
<td>36.5</td>
<td>58.5</td>
<td>6.4</td>
<td>13.5</td>
<td>0.05</td>
</tr>
</tbody>
</table>

*Modified from Cui 2005.

Calculation of the amounts of α- and β-pyranose algebraically.

Let \( X = \% \alpha-d\)-glucopyranose at time \( t \);
then \( 1 - X = \% \beta-d\)-glucopyranose.

\[
[a]_D \alpha-d\)-glucopyranose = +112°; [\alpha]_D \alpha-d\)-glucopyranose = +19°;
[a]_D at equilibrium = +52° X (112) + (1 - X)(19) = 52
112 X + 19 - 19X = 52; 93X = 33;
X = 33/93 = 33%\alpha-d-glucopyranose; 66%\beta-d-glucopyranose

Note that in Table 1.3 the distribution of sugar tautomers is temperature-dependent. As the temperature is increased from 20°C to 31°C, the amounts of higher energy α-pyranose, furanose, and open-chain forms of xylose increase so that “complex” mutarotation is the appropriate classification. (Complex mutarotation denotes that more than 3 tautomers are present in significant amounts, making calculation of quantities from optical rotation measurements difficult, if not impossible.) This temperature effect can have some very important ramifications for foods that are consumed hot, ice-cold, or at room temperature. Figure 3.2 shows the effect of temperature on the relative sweetness of four different sugars. Although fructose is much sweeter than glucose or sucrose (sucrose = 100, the reference for sweetness) at low temperatures, it is less sweet than sucrose at 60°C. This is because higher amounts of \( \beta-D\)-fructopyranose, which is intensely sweet, exist at the colder temperature. Larger amounts of the open-chain form exist at higher temperatures. Many sugar reactions, such as reaction of reducing sugars with amino compounds in the Maillard reaction (Chapter 4), will occur at a more rapid rate proportional to the amount of sugar in the open-chain form. In general, pentose sugars have higher
amounts in the open-chain form than hexose sugars and are more reactive in Maillard browning.

Ring opening can be catalyzed by both acid and base (Figure 3.3). Under acidic conditions, a proton will attack the ring oxygen with subsequent ring opening. In alkaline conditions, the hydroxide ion will initiate ring opening through removal of the proton of the anomeric hydroxyl group. The mechanism was substantiated by conducting experiments in H$_2$O$^{18}$. There was no incorporation of O$^{18}$ into the sugar molecule; therefore,
hydroxide ion did not displace the anomeric hydroxyl group (Capon 1969). Mutarotation will occur under neutral conditions because water can function as either an acid or a base. The rate of reaction will occur much faster, however, in the presence of H⁺ or OH⁻. The Appendix includes a laboratory experiment that demonstrates mutarotation and the optical properties of sugar solutions using a polarimeter.

Oxidation of Sugars

Aldose sugars can be readily oxidized to aldonic acids (e.g., D-glucose to D-gluconic acid). There are a number of qualitative and quantitative tests used to detect and measure reducing sugars that are based on sugar oxidation. In the Fehling’s test, an alkaline solution of copper(II) sulfate oxidizes the aldose to an aldonic acid, the cupric ion being reduced to cuprous hydroxide that precipitates as red-colored cuprous oxide.

\[ 2 \text{Cu (OH)}_2 + \text{Aldose sugar} \rightarrow \text{Aldonic Acid} + \text{Cu}_2\text{O} + \text{H}_2\text{O} \]

**Reaction 3.2**

Under these conditions, fructose isomerizes to aldose sugars and gives a positive test. (Not all ketoses will give a positive test, however.) A laboratory experiment is described in the Appendix that uses the Fehling’s test for determination of whether a selection of carbohydrate materials is reducing or nonreducing. The described protocol is qualitative. It can be modified to be quantitative and is frequently used in the wine industry to determine the amount of reducing sugars (Zoecklein et al. 1995; refer to Chapter 6). There are other similar methods for determining reducing sugars that are based on sugar oxidation and metal ion reduction, for example, Somogyi-Nelson, Munson-Walker, etc. (BeMiller 2010).
Glucose oxidase specifically oxidizes D-glucopyranose to D-gluconic acid. Enzyme test kits are available that permit measurement of D-glucose content in the presence of other sugars in foods and biological systems (see Chapter 6). Another food application is the use of a combination of glucose oxidase and catalase in glucose-containing foods for removal of either glucose or oxygen (Parkin 2008). It is used to deplete egg white of glucose before spray drying to minimize the Maillard reaction (see Chapter 4). It is also effective for removal of oxygen in citrus fruit juices and within sealed package systems.

\[
\text{Glucose} + O_2 \xrightarrow{\text{Glucose oxidase}} \text{D-gluconic acid} + H_2O_2 \xrightarrow{\text{catalase}} H_2O + \frac{1}{2}O_2
\]

Reaction 3.3

**Glycoside Formation**

Reducing sugars will react with alcohol under anhydrous and acidic conditions to form acetals or ketals, which are nonreducing. This is illustrated by the reaction of glucose and methanol to give methyl-\(\alpha\)-D-glucopyranoside and methyl-\(\beta\)-D-glucopyranoside.

![Reaction 3.4](image_url)

**Glycoside Formation**

The traditional process for corn syrup manufacture (see Chapter 2) gives reaction conditions suitable for glycoside formation during the latter stages of processing (high concentration of glucose, heat, and acid). **Reversion sugars** are oligosaccharides that are formed from acid-catalyzed condensation of glucose.

![Reaction 3.5](image_url)
Gentiobiose (6-O-β-D-glucopyranosyl-β-D-glucopyranose), which has a bitter taste, is formed in significant quantities. The condensation reaction is nonspecific, and although β-1-6 predominates, 1-4, 1-3, and 1-2 oligosaccharides are also formed in decreasing amounts, respectively (Shallenberger and Birch 1975). There will be a mixture of α and β glycosidic linkages. Condensation between the anomeric hydroxyls to produce trehalose (α-D-glucopyranosyl-α-D-glucopyranoside) does not occur because the mechanism requires both a hydroxyl that is a strong proton donor (anomeric OH) and one that is also a strong proton acceptor. The hydroxyl functions on carbons 2, 3, 4, and 6 will serve as a proton acceptor, but the anomeric hydroxyl is ineffective in this regard.

**Glycosans** (anhydro sugars), which are intramolecular glycosides and therefore nonreducing, can be formed from aldose sugars subjected to acid and heat. When glucose and idose are subjected to identical reaction conditions, levoglucosan will be produced in only 0.3% yield, whereas idose will produce the corresponding glycosan in 80% yield. In order for the reaction to occur, the sugar must be in the 1-C conformation, which is the preferred conformation for idose and almost nonexistent for glucose. The important role of conformation for this reaction is clearly demonstrated with molecular models.

Polydextrose, also marketed as Litesse™, Sta-lite™, and Trimcal™ is a water-soluble, reduced-calorie bulking agent approved for food use. It is classified as soluble fiber and is used to increase the nondietary fiber content of foods through partial replacement of sugar, starch, and fat in a wide range of food products. The polymer is manufactured by pyrolysis of glucose, sorbitol, and citric acid with the proportions of 89 parts glucose, 10 parts sorbitol, and 1 part citric acid. The product is randomly cross-linked, with 1-6 linkages predominating and a mixture of α and β linkages. The carbohydrate enzymes in the intestinal mucosa will not hydrolyze many of these linkages. Hence, much of the material is not digested, absorbed, or used. The caloric value is approximately 1 cal/g.

The formation of trimethylsilyl derivatives of sugars permits analysis of anomeric and ring forms of sugars by gas-liquid chromatography. The
analysis is extremely sensitive. In the derivation reaction shown in Reaction 3.7, a trimethylsily glycoside is formed at the anomeric carbon, with trimethylsily ethers being formed at the other hydroxyls (see Chapter 6).

\[
\text{Reaction 3.7}
\]

**Acid Catalyzed Sugar Reactions**

Attack by a proton on the ring oxygen of a reducing sugar results in ring opening and mutarotation as previously described (Figure 3.3). Hydrolysis of the glycosidic linkage in reducing and nonreducing sugars is catalyzed by protonation of the exocyclic OR group. A carbonium ion is formed that abstracts a hydroxyl group from water to form free sugars (Wong 1989).

\[
\text{Reaction 3.8}
\]

Hydrolysis rates are predictable with furanose linkages being hydrolyzed much faster than pyranose linkages. α-Glycosidic linkages are hydrolyzed faster than β. Hydrolysis rates of glycosidic linkages occur in the following decreasing order: 1-2 > 1-3 > 1-4 > 1-6. Therefore, one can predict that sucrose (α-furanose) will be hydrolyzed much easier than maltose (α-1-4), which undergoes hydrolysis at a faster rate than lactose or cellobiose (both β-1-4). It also explains why gentiobiase (β-1-6) accumulates in corn syrup manufacture.

Aldose sugars will undergo acid-catalyzed dehydration to form deoxy sugars and furfurals. Figure 3.4 shows the mechanism for dehydration of
Reactions of Sugars

Figure 3.4 Dehydration of glucose via 2-3-enolization to form 3-deoxyglucosone.

Glucose through 2-3-enolization to form 3-deoxyglucosone. Initial proton attack at C-3 results in hydroxyl removal at C-3, and subsequent proton removal at C-2 gives the 2-3-enol form; ketol-enol rearrangement produces 3-deoxyglucosone. Further dehydration occurs down the chain with subsequent ring closure to produce hydroxymethylfurfural from aldose sugars and furfural from pentoses.

Structure 3.9 Hydroxymethylfurfural and Furfural

Furfurals have flavor significance, and they are reactive in polymerization reactions. Another laboratory application is for visualization of sugars in different chromatographic systems. For example, a thin-layer chromatogram of separated sugars can be sprayed with an acidic solution and heated to produce furfurals that are subsequently reacted with amines to give a colored complex (Lewis and Smith 1969).

Alkaline-Catalyzed Sugar Reactions

Mutarotation can be alkaline catalyzed whereby hydroxide ion initiates proton removal from the anomeric hydroxyl, followed by ring opening (Figure 3.3). In the case of nonreducing sugars, there is no anomeric hydroxyl group. Therefore, under alkaline conditions, hydrolysis will not take place.

A practical application is the use of lime in sugar refining to render the extract alkaline so that hydrolysis of the acid-labile α-furanose linkage (sucrose inversion) does not take place.
Reducing sugars will undergo 1-2-enolization to form different isomers (Figure 3.5). The reaction is favored in alkali but can also occur under acidic conditions. This is one reason that Fehling’s reagent is alkaline (refer to the Fehling’s test for reducing sugars in the Appendix). The enediol is readily oxidized by metal ions, and, in addition, acid hydrolysis of labile nonreducing sugars, such as sucrose, is prevented. One application of this reaction is to convert the glucose moiety of lactose (4-O-β-D-galactopyranosyl-D-glucose) to lactulose (4-O-β-D-galactopyranosyl-D-fructose). The reaction is catalyzed by sodium aluminate.

Lactulose has higher water solubility than lactose, and it is somewhat sweeter than lactose, 0.5× sucrose versus 0.4× sucrose. Lactulose is not hydrolyzed by lactase, not absorbed, and noncaloric. It is used as a laxative but is not approved for food use.
Reactions of Sugars

Summary

Key reactions in carbohydrate chemistry are influenced by conditions of acidity and alkalinity. Table 3.2 summarizes those effects.

Similarly, many carbohydrate reactions can be categorized as being reactions of reducing and nonreducing sugars. The properties of reducing and nonreducing sugars can be summarized as shown in Table 3.3.

Figure 3.6 summarizes several key reactions of sugars. Transformation of β-D-glucopyranose (compound 2) to α-D-glucopyranose (compound 1) via the open-chain form (compound 5) is mutarotation. Transformation of compound 2 to compound 3 is conformational change (C-1 to 1-C). Conversion of compound 3 to compound 4 is formation of the

Table 3.2 Key Carbohydrate Reactions as Influenced by Acid and Alkali

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Favored in Acid</th>
<th>Favored in Alkali</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutarotation</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Hydrolysis of hemiacetals and hemiketals</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Hydrolysis of acetals and ketals</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>Polymerization</td>
<td>+</td>
<td></td>
</tr>
<tr>
<td>Dehydration</td>
<td>+</td>
<td></td>
</tr>
</tbody>
</table>
| Enolization 
  2→3                                   | + (2→3)         | + (1→2)           |
Table 3.3  Properties of Reducing and Nonreducing Sugars

<table>
<thead>
<tr>
<th>Reducing Sugars</th>
<th>Nonreducing Sugars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Will reduce metal ions</td>
<td>Not oxidized by metal ions</td>
</tr>
<tr>
<td>Undergo mutarotation</td>
<td>Will not undergo mutarotation</td>
</tr>
<tr>
<td>Undergo acid hydrolysis</td>
<td>Undergo acid hydrolysis</td>
</tr>
<tr>
<td>Hydrolyzed by alkali</td>
<td>Not hydrolyzed by alkali</td>
</tr>
<tr>
<td>Hemiacetals and hemiketals</td>
<td>Acetals and ketals</td>
</tr>
<tr>
<td>-ose suffix</td>
<td>-ide suffix</td>
</tr>
<tr>
<td>Condense with amines in Maillard reaction</td>
<td>Nonreactive in Maillard reaction</td>
</tr>
</tbody>
</table>

Figure 3.6  Reactions of reducing sugars in solution.

Source: Shallenberger and Birch 1975.
anhydrosugar, levoglycosan. Conversion of compound 5 to 6 is 1-2-enolization, with subsequent isomerization to fructose (compounds 10 and 11) and mannose (compounds 8 and 9). Acid catalyzed 2-3-enolization (compound 7) leads to formation of hydroxymethylfurfural (compound 12) and formation of polymers and saccharinic acids.

**Vocabulary**

Mutarotation—The change in optical rotation that is observed when a reducing sugar is dissolved in water due to the formation of different tautomeric forms. “Simple” mutarotation describes the case when only two tautomers exist, and “complex” mutarotation describes the existence of three or more tautomers.

Reversion sugars—Oligosaccharides formed from acid-catalyzed condensation of glucose

Glycosans—Anhydro sugars, which are intramolecular glycosides and therefore nonreducing

**References**


