

Optical Activity in Compounds

Background

Ordinary white light consists of waves vibrating in all planes perpendicular to the direction in which the waves travel. Certain materials, such as a Nicol prism or the lenses of ordinary polaroid sunglasses, selectively transmit light waves vibrating in only one specific plane. This light is said to be "plane-polarized". If another polarizing material is put in the path of the plane-polarized light so that its polarizing axis is parallel to the axis of the plane-polarized light then a maximum intensity of light will pass through. However, if the axis of the second polarizing material is *perpendicular* to the axis of polarized light then a minimum of polarized light will be allowed to pass through.

In the early 1800's French scientists had stumbled upon a curious property of some kinds of crystals. The mineralogist René Haüy found types of quartz crystals were non-identical mirror images of each other. He called these forms *enantiomorphs* ("opposite form") and noted their ability to rotate plane-polarized light. Physicist Jean Baptiste Biot found that the special kind of light could be rotated to the left by one crystal form and to the right by the other--through equal degrees. He also discovered the same was possible with solutions of tartaric acid or sugar.

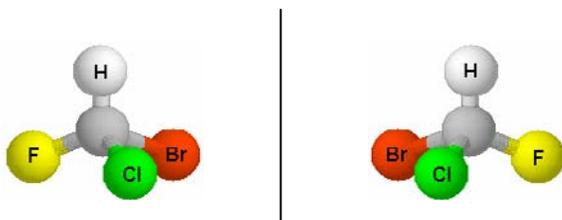
Perhaps the most famous French connection to "optical activity" (as it is called) comes through Louis Pasteur. In 1848, while employed with the French wine industry, he was investigating apparently different "types" of tartaric acid (crystals of the acid are deposited in wine casks during fermentation). One form of the acid was able to rotate plane-polarized light to the right (*dextrorotatory*). The other form showed no interaction with the light. Careful inspection of crystals of the non-active acid (then called *racemic acid*) revealed that not all of the crystals were identical. What Pasteur found was a mixture of mirror-image crystals which he proceeded to laboriously separate by hand. A solution of one of the types of crystals proved to behave the same as the known tartaric acid. The other crystals dissolved to give a solution which rotated plane-polarized light to the left, through the same number of degrees as tartaric acid. Further analysis confirmed that this substance was also tartaric acid and that "racemic acid" was simply a 50:50 mixture of the two forms [today 50:50 mixtures of mirror image forms or *enantiomers* are called *racemic mixtures*].

Pasteur reasoned (correctly) that the rotatory property of the tartaric acid must lie in the structure of the molecule itself since the crystals dissolved to give solutions which rotated the light. At about the same time period much work was being done on the nature of carbon atoms in organic compounds. A number of eminent chemists were proposing that the geometry around the apparently tetravalent carbon atoms must be tetrahedral. In 1874 the Dutch chemist J. H. van't Hoff and the Frenchman J. A. LeBel independently hypothesized that this geometry would allow the formation of mirror image molecular forms under the right circumstances (unlike square planar configurations) and that these forms might be responsible for the rotatory property (by some unknown mechanism).

An explanation of the proposed mechanism for optical activity involves a complex journey into quantum mechanical concepts of the way in which the electric and magnetic fields of plane-polarized light interact with active molecules. There is no need to pursue the matter that far, but it would be helpful to understand how it is that molecules can exist in mirror image pairs.

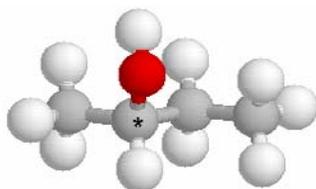
Adapted from: Synthesis, Optical Resolution and Derivatization of Co(en)_3^{3+} , Alan J. Jircitano, Penn State, The Behrend College
Synthesis and Technique in Inorganic Chemistry, Robert J. Angelici
Optical Resolution of Co(en)_3^{3+} , Adam Johnson, Harvey Mudd College

A very simple example of an optically active compound would be CHFCIBr:



The forms shown are mirror images and non-superimposable (a fact best shown with models, but a good 3D imagination will confirm this). Compounds like this simple example are said to possess "handedness", or more technically, are called *chiral* ("handed"). One of the forms will rotate plane-polarized light to the left, the other to the right. The rotations will be in the same number of degrees.

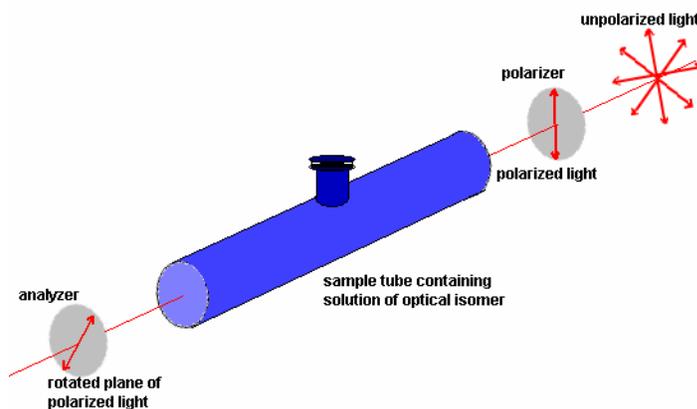
In organic compounds optical activity is the result of at least one tetrahedral carbon atom which has four different groups attached to it. Such a carbon is known variously as a *stereogenic center*, a *chiral center*, or an *asymmetric carbon*. In the example above it is clear that the four groups attached to the single carbon are different. But "long range" difference is also possible. For example, as unlikely a molecule as 2-butanol contains a stereogenic center [indicated with an *]:



Even though the chiral carbon is directly attached to two other carbon atoms, these are not exactly the same since one could be considered part of a methyl group and the other part of an ethyl group. It should not be surprising, then, that this seemingly exotic property is actually rather common in organic compounds. Ordinary table sugar (sucrose) is made up of two smaller sugar units (glucose and fructose) each of which is optically active. The sucrose itself is also chiral. Tartaric acid has been mentioned in conjunction with Pasteur already. All but the simplest amino acid (glycine) are chiral and, as is generally the case, only one form is biochemically active.

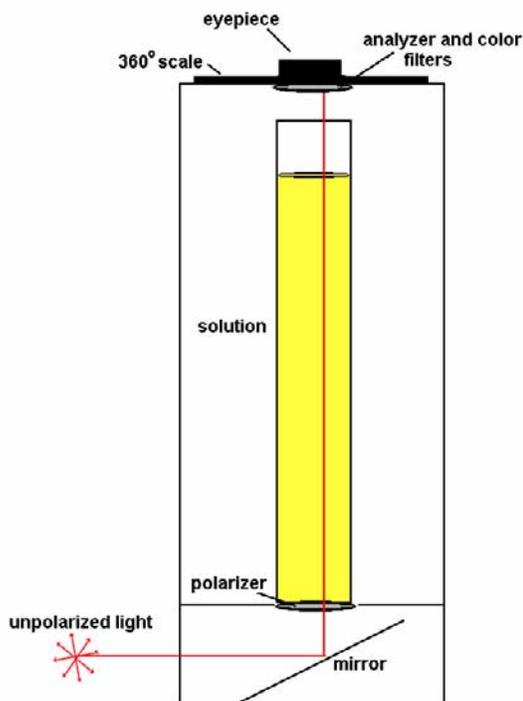
There is no way to determine which form of a molecule is which except by experiment, even if the absolute configuration of the molecule is known. The experimental procedure involves preparing a solution of known concentration and placing it between two polarizing filters to see how much and in which direction it rotates plane-polarized light. This straightforward procedure has been developed into an analytical technique.

A *polarimeter* consists of a light source, two polarizing filters and a cell that contains a solution of an *optically active compound*, as illustrated in the schematic diagram below:



A simple diagram of the instrument used in this experiment is shown at the right.

The filter that is closest to the light source is referred to as the *polarizer*, while the other filter is called the *analyzer*. When the axes of the polarizer and analyzer are at right angles to each other, no light (or very little) passes through and this situation is known as the null or zero point. When a solution of optically active compound is placed in the cell between the filters, the plane of polarized light is rotated and a certain amount of light will now pass through the analyzer. To compensate for this, the analyzer is rotated, either clockwise or counterclockwise, to produce minimum transmittance again.



[not all polarimeters operate this way; in many the rotation is measured at *maximum* light transmittance]

The rotation is proportional to the amount of active substance present. The *specific rotation*, $[\alpha]$, is defined as the rotation caused by the compound at a given concentration in a sample tube 1 dm long:

$$[\alpha]_D^{20} = \frac{\alpha}{\ell c}$$

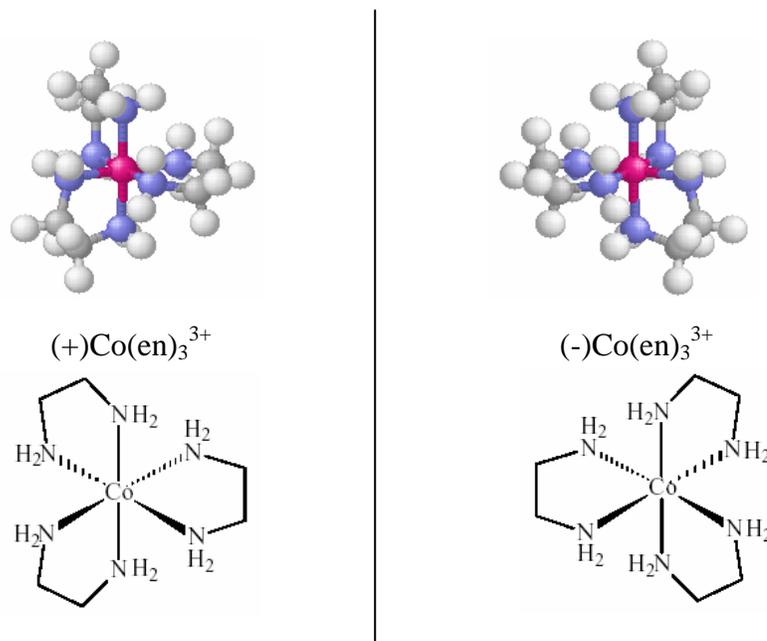
where $[\alpha]$ is the specific rotation, α is the measured rotation in degrees (clockwise = +, counterclockwise = -), ℓ is the path length of the solution in decimetres, and c is the concentration in g/mL. The ^{super} and _{sub}scripts attached to $[\alpha]$ are for temperature (°C) and the wavelength of the light being used (generally the sodium "D" line, 589 nm). Sodium vapor tubes are rather expensive. Near the eyepiece in the simple polarimeter used in this experiment there is a filter which approximates the correct wavelength.

With careful measurements and a good instrument it is thus possible to determine the purity of solutions of known compounds or even identify unknown substances from a short list.

The recognition of the tetrahedral nature of carbon through optical activity, long before the development of atomic theory and bonding, is interesting but the parallels to Alfred Werner's search for an understanding of coordination compounds are equally fascinating.

Inorganic molecules may contain asymmetric nitrogens, sulfurs, etc. But chirality is not absolutely necessary for optical activity in many cases. Overall molecular symmetry in many transition metal complex ions leads to optical activity.

Werner began his professional life as an organic chemist. He surely knew the nature of the arguments advanced for the geometry of carbon structures. Werner realized that the octahedral geometry he was proposing for many complex ions would be confirmed if he succeeded in isolating some mirror-image pairs. In 1912 Werner isolated (or *resolved*) the mirror image forms of Co(en)_3^{3+} [en = $\text{NH}_2\text{CH}_2\text{CH}_2\text{NH}_2$, a bidentate ligand, ethylenediammine]. One form rotated plane-polarized light to the right [designated as dextrorotatory or (+)] and the other to the left [designated as levorotatory or (-)]. The absolute configuration of the dextrorotatory form was finally confirmed in 1954 by special x-ray crystallography.



Reactions which produce optically active compounds often yield racemic mixtures. The recognition of this and the subsequent separation (resolution) of these mixtures are important in synthetic chemistry. The thalidomide tragedy of the 1950's is evidence of this fact. One optical isomer of the compound is useful in treating depression. The other causes fetal mutations and deaths [the drug was marketed to pregnant women as a racemic mixture]. The common drug naproxen (found in Aleve™) is another case in point. One enantiomer is an active antiarthritic drug. The other is a powerful liver toxin which must be removed from the product mixture. Preparative methods which result in only one enantiomer being produced are actively sought. The 2001 Nobel Prize in Chemistry was awarded for work involving chiral catalysts for producing only one isomer in a reaction.

Werner had no such luck. Chemists of the time *did* know that optical isomers behave identically with non-chiral reactants but differently with chiral agents. One of the more common pathways to the resolution of isomers was to choose a second optically active compound which would react with the molecules of the racemic mixture and give compounds (*diastereomers*) with different solubilities which could be separated by fractional crystallization. That is the technique used by Werner and in this experiment.

The preparation of $[\text{Co(en)}_3]\text{Cl}_3$ is similar to that of cobalt(III) ammine complexes. The cobalt(II) ion is oxidized by hydrogen peroxide in the presence of ethylenediammine, a weak base. Activated charcoal is used to ensure that all six coordination positions are filled [the charcoal appears to have a catalytic effect in this and similar syntheses]. The compound is isolated as a racemic mixture.

The resolving agent in this experiment is (+)tartaric acid:



The racemic solid is dissolved and treated with the tartaric acid. After an approximate pH adjustment, the mixture is left to cool. (+)[Co(en)₃][(+)-tartrate]Cl is less soluble and crystallizes out. (-)[Co(en)₃][(+)-tartrate]Cl remains in solution.

Both compounds are eventually converted to iodide salts [the tartrate is removed] and crystallized from solution with excess iodide ion. At that point they should exhibit the characteristic rotation of the complex ion [the diastereomers exhibit unique rotations based on the separate optically active centers in the compounds].

The Experiment

There are three parts to this experiment:

- identification of chiral unknowns and concentrations by polarimetry
- resolution of optical isomers of Co(en)_3^{3+}
- isolation and testing of $(+)\text{[Co(en)}_3\text{]I}_3$ and $(-)\text{[Co(en)}_3\text{]I}_3$

The following non-locker materials will be provided:

- glucose and fructose powders
- 6 M NaOH
- ? M sucrose solution
- adapted "polarimeter cells"
- polarimeter and light source
- standard thermometer
- metric ruler
- pH paper
- (+)tartaric acid
- solid NaOH
- concentrated aqueous NH_3
- ethanol
- solid NaI
- 2-propanone

The Chemicals

2-propanone (commonly known as *acetone*) is a volatile, highly flammable liquid with a characteristic odor and sweet taste. It is completely miscible with water, forming a low boiling azeotrope which speeds evaporation and drying (hence its frequent use in rinsing wet glassware and washing precipitates). It will attack many plastics including some synthetic fabrics such as rayon.

2-propanone is used as a solvent for fats, oils, resins, waxes, lacquers, and rubber cements. It is also used in paint and varnish removers (some formulations of fingernail polish remover contain acetone). Prolonged or repeated topical exposure may cause skin dryness. Inhalation may produce headache, fatigue, and in large amounts, narcosis. Serious poisoning is rare.

Ethanol or ethyl alcohol is a clear, colorless liquid with a pleasant odor and a burning taste. It absorbs water readily from the air and is miscible with water and many organic liquids. Most ethanol is used in alcoholic beverages in dilute form. It is also used in the laboratory as a common solvent, in pharmaceuticals, and as a common topical antiseptic. Nearly all ethanol sold as "alcohol" (not for drinking) has been *denatured* (including the ethanol in the lab). Denaturing in this context means adding some substance which does not markedly interfere with the behavior or properties of ethanol except to render it unfit for drinking. Most denaturants are toxic.

(+) *tartaric acid*, $C_4H_6O_6$, occurs in many fruits in free form and combined with potassium, calcium or magnesium. Practically all of the L-tartaric acid sold today is a by-product of the wine industry. During wine-making potassium tartrate forms. This salt is converted to calcium tartrate and then hydrolyzed to tartaric acid and calcium sulfate. The acid is diprotic and fairly strong for an organic acid ($K_1 = 1.04 \times 10^{-3}$). Tartaric acid is used in the soft drink industry, candy and baked products. It is also used in photography, tanning and ceramics. The acid is essentially non-toxic. Concentrated solutions are mildly irritating.

Sodium hydroxide is commonly known as lye or caustic soda. It is a very hygroscopic white solid (absorbs water from the air rapidly) and also absorbs CO_2 . It is very corrosive to vegetable and animal matter and aluminum metal, especially in the presence of moisture. Dissolving NaOH in water generates considerable heat.

Besides its use in the laboratory, sodium hydroxide is used in commercial drain cleaner preparations, to treat cellulose in the manufacture of rayon and cellophane and in the manufacture of some soaps. It is corrosive to all tissues and can be detected on skin by the "slimy" feeling associated with bases. It should be rinsed off thoroughly upon contact. It can damage delicate eye tissues and cause blindness.

Ammonia is a gas at room temperature. Laboratory solutions of aqueous ammonia have sometimes been erroneously called "ammonium hydroxide" although there is little evidence for the existence of that compound. Aqueous solutions of ammonia are basic.

Ammonia gas can be manufactured from industrial gases associated with the processing of "coke", a spongy form of carbon obtained from processing coal and essential in steel-making. In the Haber-Bosch process nitrogen and hydrogen from these industrial gas mixtures are combined at high temperature and pressure in the presence of a catalyst to form ammonia. The gas and its aqueous solutions are colorless with a very pungent odor (lower limit of human perception: 0.04 g/m^3). Mixtures of ammonia gas and air can explode when ignited under favorable conditions. At room temperature ammonia is soluble to the extent of 31% in water, only 16% in methanol. It is used in the manufacture of nitric acid, explosives, fertilizers and in refrigeration. In anhydrous liquid form it is a good solvent for many elements and compounds, notably the alkali metals which yield blue solutions when dissolved in liquid ammonia.

Inhalation of the concentrated vapor causes swelling in the respiratory tract, spasms and asphyxia.

Sodium iodide is white, odorless and deliquescent. It slowly turns brown when exposed to air due to oxidation that forms iodine. Its uses parallel those of potassium iodide. It is also used in medicine as an expectorant.

glucose, $C_6H_{12}O_6$, (or *dextrose*) occurs naturally in the free state in fruits and parts of plants. It is one of the components of cellulose, starch and glycogen. Crystallized from water below $50^\circ C$, the most common form is α -D-glucose monohydrate. One gram dissolves in about 1 mL of water at room temperature. Solutions tend to mutarotate as the α form is converted to the β form ($+112.2^\circ$ to $+52.7^\circ$). Complete conversion is immediate in basic solutions. 0.74 times as sweet as sucrose, glucose is used in treating dehydration and for nutritional purposes.

fructose, $C_6H_{12}O_6$, (or *levulose*) occurs naturally in a large number of fruits and honey. Sweetest of the sugars, aqueous solutions of the most common form, β -D-fructose, show mutarotation from -132° to -92° (immediate in the presence of hydroxide ion). The powder is freely soluble in water and is used to prevent "sandiness" in ice cream.

sucrose, $C_{12}H_{22}O_{11}$, or cane sugar (table sugar), is a disaccharide consisting of one glucose and one fructose unit. One gram dissolves in 0.5 mL of water. Sucrose does not show mutarotation but upon hydrolysis (catalyzed by acid) the optical rotation falls and becomes negative. The resulting mixture of glucose and fructose is thus called "invert sugar". Sucrose is used as a sweetening agent in food and in the plastics and cellulose industry. It is also used in the manufacture of some inks and transparent soaps.

Technique Discussion

The polarimetry exercises consist of identifying two white powders which are the isomeric sugars glucose and fructose, determining the concentration of a sucrose solution, and investigating the temperature dependence of the observed rotation, α .

The zero-point of the polarimeter should be determined using distilled water. Good technique for changing solutions in the cells includes several distilled water rinses followed by at least two small rinses with the solution to be measured.

Solutions of the isomeric sugars should be prepared which are sufficiently concentrated to give easily read rotations (the polarimeter scale has marks for every 2° and should be read carefully to the nearest 0.5°). Approximately 2-2.5 g in 10 mL of water should be sufficient for either solid.

The cells supplied with the polarimeter require volumes on the order of 40 mL to achieve a 1 dm path length; this requires more chemicals than we would like to use. Therefore you will use tall 10 mL graduated cylinders with holes drilled in the plastic bases to allow the light to pass through the solution. There is a small amount of distortion because the bottoms are not always perfectly flat and the cylinder is quite narrow but careful positioning of the cylinder in the light path can minimize this problem. Approximately 12 mL of solution can fit in the cylinder and gives a path length of over 1 dm. This means you will need to use less solid material to achieve a readable rotation

Since the scale on the polarimeter is marked for 0° to 360° it is not immediately obvious whether a solution exhibits a positive or negative rotation. For example, an apparent rotation of $+90^\circ$ might actually be -270° . The only way to distinguish one from the other is to change the amount of sample (either by dilution or by path length). If the observed rotation is $+90^\circ$, decreasing the sample amount will require moving the analyzer counter-clockwise to find the new minimum transmittance. If the rotation actually is -270° then decreasing the sample size will make it necessary to turn the analyzer clockwise to find the new minimum transmittance.

Both sugars have a tendency to slowly mutarotate in solution (i.e., the angles gradually change) so the measurements should be made as soon as the mixture is ready. The length of the solution column should be measured with a ruler. The temperature of the solutions should also be measured. After the initial measurement, add 1-2 drops of 6 M NaOH to each solution, mix thoroughly, and read the angle again.

Similar data is required to interpret the concentration of the unknown sucrose solution. After the room temperature measurement for sucrose is made, two additional readings should be made at temperatures significantly lower and higher than room temperature (do not boil the solution).

The synthesis of the racemic salt mixture $[\pm\text{Co}(\text{en})_3]\text{Cl}_3$ is detailed below. Because the procedure and techniques are very similar to the synthesis in the previous experiment, the instructor will perform the synthesis and the compound will be provided.

1. dissolve 3.0 g of $\text{CoCl}_2 \cdot 6 \text{H}_2\text{O}$ in 10 mL of distilled water
 2. in a 100 mL beaker, cool 7.5 mL of 4.7 M ethylenediamine over ice
 3. add 2 mL of 6 M HCl to the iced ethylene diammine solution
 4. keeping the mixture on ice, add the CoCl_2 solution, 0.5 g activated charcoal, and then **carefully** add 5 mL of 30% H_2O_2 , a little at a time, with swirling
 5. remove the solution from the ice and swirl for a few minutes until effervescence stops
 6. add 6 M HCl dropwise, as needed, to adjust the pH to 7.0-7.5
 7. boil *gently* to reduce the solution volume by approximately half; suction filter hot to remove the charcoal
 8. to the filtrate, add an equal volume of concentrated HCl, followed by 30 mL of ethanol
 9. cool in ice and suction filter; wash with 2 small portions of ethanol and air dry.
-

To resolve the isomer mixture into diastereomers:

1. add 1.3 g of (+)tartaric acid to 2.4 g of the racemic salt in a 50 mL beaker
2. add 10 mL of distilled water and 0.7 g NaOH
3. cover the beaker with a watch glass; heat gently (if needed), stirring, until the solids dissolve; adjust pH to just over 7 (slightly green pH paper) with additional 6 M NaOH, if needed
4. cover the mixture with parafilm and let cool overnight
5. collect the dark orange crystals by suction filtration; **REMOVE AND SAVE THE FILTRATE** which contains the (-)diastereomer.
6. wash the crystals with 10 mL of 1:1 water:acetone and then 10 mL acetone; air dry

The diastereomers must then be separated from the tartrate anion and precipitated as iodide salts. To isolate $[(+)\text{Co}(\text{en})_3]\text{I}_3 \cdot \text{H}_2\text{O}$:

1. place 1 g of the dark orange crystals from the previous procedure in a 50 mL beaker; break up large crystals
2. add 7.5 mL distilled water and 3 drops of conc. aqueous NH_3 ; stir *by hand*, crushing crystals if needed, and warm for a few minutes until the solid dissolves (hotplate "2"); **do not heat any longer than needed or the isomer will racemize**
3. stirring constantly, add 1.8 g NaI dissolved in 1.0 mL hot water
4. cool in an ice bath and collect crystals by suction filtration
5. wash with an ice-cold solution of 1.5 g NaI in 5 mL water; follow with washes of 5 mL ethanol and then 5 mL acetone; air dry

To isolate $[(-)\text{Co}(\text{en})_3]\text{I}_3 \cdot \text{H}_2\text{O}$:

1. dilute the reserved filtrate from the resolving step to about 15 mL
2. add 3 drops of conc. aqueous NH_3 and stir, warming *gently* to near 80°C until the solid dissolves
3. with stirring, add 4.3 g of NaI; cool in an ice bath
4. collect the impure solid $[(-)\text{Co}(\text{en})_3]\text{I}_3 \cdot \text{H}_2\text{O}$ by suction filtration; wash with an ice-cold solution of 1.5 g NaI in 5 mL of water
5. dissolve the crude compound in 17 mL of pre-heated water at 50°C ; filter off the undissolved racemate if needed
6. add 2.5 g NaI to the solution from step 5; stir to dissolve the NaI [a precipitate forms simultaneously]; cool
7. collect the crystals by suction filtration; wash with a few mL of ethanol, followed by acetone; air dry

The optical activity (and therefore the purity) of the products should be checked using the polarimeter. For both compounds, 0.5 g of solid should just dissolve in 15 mL of distilled water. More solution path length will give a larger observed angle. Examine the solutions immediately in case mutarotation or racemization begins. With deeply colored solutions such as these the zero-point sometimes appears broad. Viewing in subdued light helps. It is also wise to approach the point from both sides, noting where extinction appears to begin. The middle of the range boundaries should be taken as the correct angle. Repeat such difficult readings at least 3 times, each time starting with the dial far from the zero-point. The average of your three (or more) determinations should be reported as α . The specific rotation of $[(+)\text{Co}(\text{en})_3]\text{I}_3 \cdot \text{H}_2\text{O}$ is $+89^\circ$.

The Report

Your initial calculations should include:

1. The specific rotations of glucose and fructose based on the measurements with your solutions *after* adding NaOH [relative error]
2. The Molarity of the sucrose solution based on room-temperature polarimetry measurements
3. The "purity" of the resolved isomers based on polarimetry measurements and the specific rotation

Your conclusion to this experiment should include a brief discussion of the observed rotations of glucose and fructose (before and after mutarotation). The temperature effect on the specific rotation should also be briefly mentioned and its possible importance in the interpretation of your results. Describe the anticipated value for α if equal volumes of equimolar solutions of enantiomers were mixed. If the compounds were not completely resolved, how would this value change (if at all)?