Synthesis, Optical Resolution and Derivatization of Co(en)$_3^{3+}$

If you could analyze the light that travels toward you from a lamp, you would find the electric and magnetic components of this radiation oscillating in all of the planes parallel to the path of the light. However, if you analyzed light that has passed through a polarizer, such as a Nicol prism or the lens of polarized sunglasses, you would find that these oscillations were now confined to a single plane.

In 1813 Jean Baptiste Biot noticed that plane-polarized light was rotated either to the right or the left when it passed through single crystals of quartz or aqueous solutions of tartaric acid or sugar. Because they interact with light, substances that can rotate plane-polarized light are said to be optically active. Those that rotate the plane clockwise (to the right) are said to be dextrorotatory (Latin dexter, "right"). Those that rotate the plane counterclockwise (to the left) are called levorotatory (Latin laevus, "left"). In 1848 Louis Pasteur noted that sodium ammonium tartrate forms two different kinds of crystals that are mirror images of each other, much as the right hand is a mirror image of the left hand. By separating one type of crystal from the other with a pair of tweezers he was able to prepare two samples of this compound. One was dextrorotatory when dissolved in aqueous solution, the other was levorotatory. Since the optical activity remained after the compound had been dissolved in water, it could not be the result of macroscopic properties of the crystals. Pasteur therefore concluded that there must be some asymmetry in the structure of this compound that allowed it to exist in two forms.

Molecules that possess these right- or left-hand forms are said to be chiral (literally, "handed"). A pair of such objects that are mirror images of each are called enantiomers or optical isomers. If equal amounts of the two enantiomers are present in a sample, the optical effects of each cancel and the mixture is said to be racemic. In this experiment, you will synthesize a racemic mixture of a coordination compound and resolve, or separate, it into its two enantiomers.

Optical activity is usually associated with organic molecules containing asymmetric carbon.

However, optical activity is a general property that can be found in any molecule that cannot be superimposed on its mirror image. Inorganic molecules may be chiral based on asymmetric nitrogen, phosphorus or sulfur atom, but a larger number of chiral inorganic compounds do not have any asymmetric atoms. Instead, the chirality of these molecules is due to the overall
molecular symmetry, specifically the absence of an improper rotation axis. Optical activity in octahedral transition metals complexes is an extensively studied example of this type of chirality.

The resolution of the optical isomers of $\text{Co(en)}_3^{3+}$ (where en = $\text{NH}_2\text{CH}_2\text{CH}_2\text{NH}_2$) by Alfred Werner in 1912 was, in fact, instrumental in finally understanding the nature of the structure and bonding in all coordination compounds. The enantiomeric forms of $\text{Co(en)}_3^{3+}$ are shown below.

\[ \Lambda (+) \text{ enantiomer} \quad \Delta (-) \text{ enantiomer} \]

**Figure 1**

A polarimeter (Figure 2) is used to study optically active compounds.

**Figure 2**

Imagine a horizontal line that passes through the zero of a coordinate system. By convention, negative numbers are placed on the left and positive numbers on the right of zero. Thus, levorotatory compounds are indicated with a negative sign (−) and dextrorotatory compounds are with a positive sign (+).
The magnitude of the angle through which an enantiomer rotates plane-polarized light depends on four quantities: (1) the wavelength of the light, (2) the length of the cell through which the light passes, (3) the concentration of the optically active compound in the solution through which the light passes, and (4) the specific rotation of the compound, which reflects the relative ability of the compound to rotate plane-polarized light. For example, the specific rotation of the dextrorotatory isomer of glucose is written as $[\alpha]_D^{20} = +3.12$.

When the spectrum of sunlight was first analyzed by Joseph von Fraunhofer in 1814, he observed a limited number of dark bands in this spectrum, which he labeled A through H. We now know that the D band in this spectrum is the result of the absorption by sodium atoms of light that has a wavelength of 589.6 nm. The "D" in the symbol for specific rotation indicates that it is light of this wavelength that was studied. The "20" indicates that the experiment was done at 20 °C. The "+" sign indicates that the compound is dextrorotatory; it rotates light clockwise. Finally, the magnitude of this measurement indicates that when a solution of this compound with a concentration of 1.00 g/mL was studied in a 10-cm cell, it rotated the light by 3.12°. The magnitude of the rotations observed for a pair of enantiomers is always the same. The only difference between these compounds is the direction in which they rotate plane-polarized light. The specific rotation of the levorotatory isomer of this compound is –3.12.

In a typical experiment, monochromatic light (usually from a sodium lamp) is introduced to the sample. The light passes through the polarizing lens (prism). This light is then passed through a solution of an optically active compound, which results in a rotation of the plane of oscillation. A second polarizing lens (prism) is used in conjunction with a detector to find the angle of rotation. The specific rotation is determined from

$$[\alpha]_k^T = \frac{\alpha_{\text{meas}}}{lc}$$

Where:

- $\alpha_{\text{meas}}$ rotation measured by the polarimeter in degrees.
- $\lambda$ wavelength used to measure the rotation in nanometers.
- $l$ path length in decimeters (usually this is 1 dm = 0.1 m or 10 cm).
- $c$ concentration measured in g/mL.
- $T$ temperature (usually in °C) at which the measurement was made.

The slight temperature dependence on optical rotation can be corrected using:

$$[\alpha]_k^{20} = [\alpha]_k^T [1 + 0.0001(T - 20)]$$

The percent optical purity ($x$) of a material is the ratio of the measured specific rotation, to the standard pure specific rotation, $[(\text{std})$, where
\[ x = \frac{[\alpha]_h^T \text{ (meas)}}{[\alpha]_h^T \text{ (std)}} \times 100 \]

The percentage of the major enantiomer in a mixture of enantiomers can be calculated as:

\[ \% \text{ (major enantiomer)} = x + \frac{(100 - x)}{2} \]

Thus, if a sample is an equal mixture of (+) and (–) enantiomers, the measured rotation is zero and \( x = 0 \), so the \% (major enantiomer) = 50%.

Although it was known that \((+)\text{Co(en)}_3^{3+}\) must have one of the structures shown in Figure 1, it was not until 1954 that the absolute structure was determined to be the one on the left. The designation by the Greek letters \(\Lambda\) and \(\Delta\) are similar to the R and S descriptors used in organic chemistry. There is no correlation of \(\Lambda\) and \(\Delta\) with dextrorotatory or levorotatory.

In this experiment, you will oxidize aqueous \(\text{Co}^{2+}\) in the presence of ethylenediamine to give the inert \(\text{Co}^{3+}\) complex. \(\text{Co(en)}_3\text{Cl}_3\) is isolated as a mixture of the two optical isomers. They are then resolved as diastereomers (which have different chemical properties) by crystallization in the presence of the optically active anion \((+)\text{tartrate}\) (Figure 3).

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[(+)\text{Co(en)}_3][(+)\text{tart}]\text{Cl} \text{ is less soluble than \([-]\text{Co(en)}_3][(+)]\text{tart}]\text{Cl, and crystallizes from solution.}

[(+)\text{Co(en)}_3][(+)]\text{tart}]\text{Cl has } [\alpha]_D = +102^\circ.

In the last part of the experiment, you will use racemic \((\pm)\text{Co(en)}_3\text{Cl}_3\) to make a non-optically active derivative.

**General Considerations.** All of the reagents used are hygroscopic, so it is essential that the reagent containers be open to the atmosphere only as long as necessary.

**Part I. Synthesis of Tris(ethylenediamine)cobalt(III) Chloride, \([\text{Co(en)}_3]\text{Cl}_3\)**

In a 250-mL beaker, dissolve 6.0 g (25 mmol) of \(\text{CoCl}_2 \cdot 6\text{H}_2\text{O}\) in 25 mL of water while stirring with a magnetic stir bar. After the cobalt salt is fully dissolved, add 13.3 g (100 mmol) of ethylenediamine dihydrochloride \((\text{H}_2\text{NCH}_2\text{CH}_2\text{NH}_2\cdot 2\text{HCl})\). The solution will turn cloudy pink. Add 8.0 g (200 mmol) of sodium hydroxide \((\text{NaOH})\) pellets and continue stirring for several
minutes while the sodium hydroxide dissolves. The solution may appear bluish during this addition. When the NaOH dissolves, add 20 mL (20 mmol) of 3% hydrogen peroxide and the solution will turn a dark orange. Dilute the mixture to 50 mL (if necessary) and heat to boiling. Any cloudiness should disappear at this point. Allow a few milliliters of water to evaporate during the boiling step to concentrate the solution and improve the yield.

After about 10 minutes of gentle boiling, remove the stir bar and place the beaker in an ice/salt bath (below 0 °C). Let the beaker sit untouched for about 30 minutes. During this time, set up a filtration assembly with a Buchner funnel and filter paper. When the reaction mixture has been cooled for the specified amount of time, take the beaker from the ice, and quickly filter the orange needles that have formed. It is important to filter the solution while it is cold to improve the yield. Before rinsing the crystals, transfer the filtrate to an Erlenmeyer flask and cover with Parafilm. If necessary, you may be able to recover additional product from the filtrate by reducing its volume and re-cooling it. Remember that byproducts such as NaCl will also eventually precipitate, too (NaCl has a water solubility of 0.36 g/mL). Wash the solid in the Buchner funnel with ethanol and then ether. Pull air through the crystals until they are dry and record the yield. Discard the filtrate wash solution in the waste containers in the fume hood labeled “cobalt solution waste”.

*Note*: Save some of the Part I product (~1.0 g) for Part III and use the rest for Part II.

Part I product analysis: Yield, IR (KBr)

Part II. Resolution of Tris(ethylenediamine)cobalt(III) Cation
Synthesis of Co(en)$_3$[(+)-tartrate]Cl·5H$_2$O

If you do not have 6.0 g of the complex, use what you have and scale the other reactants appropriately.

Place 6.0 g (14.0 mmol) of (±)[Co(en)$_3$]Cl$_3$ in a 100-mL beaker and dissolve it in 20 mL of water with stirring. Add 2.6 g (17.4 mmol) of (+)tartaric acid to this solution and let it stir for about one minute. To the stirring solution, add 1.4 g (35 mmol) of NaOH. Gently heat the solution until all of the solids are dissolved. Remove the beaker from the heat, quickly remove the stir bar, and cover with Parafilm. Leave your beaker undisturbed in your bench until the next lab period. In order to only crystallize (+)Co(en)$_3$[(+)-tartrate]Cl·5H$_2$O, this process must occur slowly over time. If your crystals precipitate out too quickly, gently rewarm the solution and retry the crystallization.

When you arrive for the next lab period, set up a Buchner funnel for a vacuum filtration. Prepare 20 mL of a 1:1 (by volume) water: acetone solution and a 20 mL portion of pure acetone to rinse the product. Decant the dark orange solution into an Erlenmeyer flask, cover it with Parafilm (this solution should contain primarily your other (–)-enantiomer), and store it in your drawer.
Isolate the dark orange crystals of (+)Co(en)$_3$[(+)tartrate]Cl·5H$_2$O by filtration. Wash the crystals with the water/acetone solution and then pure acetone. Pull air through the product until it is dry and record the yield.

**Part II product analysis**: Yield (remember, this is wrt ½ of (±)[Co(en)$_3$]Cl$_3$), polarimetry (~0.05 g/mL)

**Part III. Synthesis of a Macrobicyclic Complex**:

![Chemical Structure]

In the hood, add separate solutions of 37% aqueous formaldehyde (50 mL) and aqueous ammonia (14 mL of concentrated NH$_3$ diluted to 50 mL) from two separatory funnels, at the same time over a period of 1 hour to a magnetically stirred aqueous suspension (20 mL) of 2.3 g Li$_2$CO$_3$ and 0.9 g of ±Co(en)$_3$Cl$_3$. Stir the resulting mixture for 15-20 minutes and gravity filter through fluted, fast filter paper.

Add a filtered (if necessary) solution of 2.5 g sodium diethyldithiocarbamate trihydrate (NaS$_2$CNEt$_2$·3H$_2$O) in 50 mL of distilled water to the filtrate and stir for 30 min.

Collect the red precipitate by vacuum filtration. Discard the aqueous filtrate in a waste container. Wash the precipitate with 3 x 50 mL portions of 20:80 CH$_2$Cl$_2$:hexane. The green solution should be discarded in an organic waste container. Suspend the red solid ([Co(sep)][S$_2$CNEt$_2$]$_3$) in 10 mL of acetonitrile and add concentrated HCl until the color change is complete. Gently heat the yellow mixture on a hot plate for a few minutes. Collect the yellow solid (Co(sep)Cl$_3$). Record the yield. Record and compare the IR to the starting complex.

**References** This experiment is adapted from: