Ruby crystals and the first laser
A spectroscopy experiment

Introduction:
In this experiment you will be studying a ruby crystal using spectroscopy. Ruby is made from sapphire (Al$_2$O$_3$) which has been doped with chromium ions, Cr(3+). There are three sets of experiments that you will conduct to learn about some of the optical properties of a Ruby crystal. You will combine the results of these experiments with library research about how a Ruby laser works connecting the optical properties of the crystal with the lasing properties of the crystal. This experiment is based on an experiment developed by Don Heiman at Northeastern University.

Part I: How a Ruby Laser works
Use a Modern Physics textbook to explain how a Ruby laser works. Be sure to describe the energy levels that are used in the laser. Make a sketch of the energy levels in the Ruby laser. Talk about population inversion and how that is related to the number of energy levels. One of these energy levels is metastable. What does metastable mean? Which level is metastable? Why is this important for the lasing action?

Part II Absorption length and index of refraction
1. For this experiment, you will begin by setting up the apparatus as shown in the picture below. Use the Spectroscopy handout and your lab notebook to refresh your memory on the operation of the USB 2000 spectrometer and Logger Pro software.

![Diagram of apparatus setup](attachment:setup_diagram.png)

Figure 1 shows the setup of the apparatus used to measure the Transmission through the Ruby Crystal. The ruby is removed from the setup to determine the reference spectrum and dark spectrum. Then it is placed in the apparatus to measure the transmission spectrum.
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2. Measure the transmission spectrum of the ruby crystal. Be sure that the transmission is at 100% before you insert the crystal. Also make sure that the edges of the holder are not obscuring the light.

3. Measure the absorption spectrum of the ruby crystal.

4. Using Appendix A, calculate the Reflection, R, using the value of T at the maximum transmission. At maximum transmission, we are assuming that the absorption is zero ($\alpha$=0).

5. Next you can calculate the approximate index of refraction from the flat part of the transmission spectrum. We assume the absorption is zero ($\alpha$=0) in this region and all of the light is transmitted or reflected. (See Appendix A.) Find an accepted value for the index of refraction of sapphire (or ruby), and compare it to the value you determine here.

6. Using your transmission spectrum and your value for R you can plot the absorption coefficient as a function of wavelength where

$$\alpha(\lambda) = \frac{1}{L} \ln \left( \frac{(1-R)^2}{T} \right)$$

and L is the sample thickness. Be sure to show where this equation comes from in your lab notebook starting from Appendix A. Smooth out the noise in this spectrum.

7. Find the "absorption length", $1/\alpha$, using your plot from (6) by determining $\alpha$ at the main absorption peak. Why is this called a length?

Part II Ruby Fluorescence Spectrum

1. In this experiment you will measure the wavelength of the Ruby R-line. Begin by setting up the optical breadboard as shown in figure 2 below. DO NOT turn on the laser without talking to your instructor. In this setup the laser bounces off of the front surface of the ruby sample. The backscattered light is collected by a lens that focuses the light onto the optical fiber. The fiber is connected to the USB2000 spectrometer. The lens has a focal length of 2.54 cm. The laser is a green diode laser module of wavelength 532nm.
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Figure 2 shows the setup of the apparatus to measure the ruby fluorescence.

2. You need to align the optical elements.
   a. First, get your instructor to help you to turn on the laser and discuss laser safety with you.
   b. Next, use the mirror mount to direct the green laser beam so that it bounces off of the face of the ruby crystal. Make sure the laser isn't bouncing off the mirror and going out the door.
   c. The alignment of the fiber, lens and backscattered light from the ruby, is made more straightforward by having each optical element attached to a rail. This way they are aligned in one dimension.
   d. To align the system in the other two dimensions, disconnect the optical fiber from the USB spectrometer and attach it to the white light source. Turn on the white light source. Adjust the height of the posts so that the white light spot overlaps with the green light.
   e. Block the green light, and move the fiber holder and lens back and forth along the rail so that the light from the fiber is focused onto a small spot on the ruby crystal.
   f. Finally unblock the green laser diode module and make sure that the green light overlaps with the white light using the adjustments on the mirror mount.
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3. Now you can measure the ruby fluorescence and the green laser line. You will need to reattach the optical fiber to the USB2000 spectrometer. You will need to optimize the integration time and subtract the dark counts. You should collect one spectrum that does not truncate either the laser line or the ruby R-line. You should take another spectrum that maximizes the Ruby R-line without cutting it off.

4. Determine the wavelength of the green laser line and the R-line.

5. Compute the photon energy of each line.

6. Include a plot that overlays the absorption spectrum from experiment I with the spectrum collected here and an overlay of the transmission spectrum from experiment I with the one collected here.

7. Why are we using a green laser?

Part III Lifetime of the Ruby R-line
In this last experiment, we will measure how long the electrons stay in the excited state before they make the R-line transition.

1. The optics setup is similar to the experiment in part II, only now instead of measuring the spectrum, we will measure how long the R-line decay lasts. To do this we replace the fiber holder with a photodiode. You should also add a long pass filter somewhere after the ruby crystal and before the photodiode. The long pass filter removes the laser light and only allows wavelengths above 600nm to pass.

2. CAUTION: Once again, do not turn on your laser until you talk to your instructor. There are two different green diode laser modules.
   a. If your module is colored green, it requires 5 Volts of power. First set the power supply to 5 volts, then turn it off. Next attach the red wire to the red “+” terminal and the black wire to the black “-” terminal.
   b. If your laser is Black, it will plug directly into the wall socket. DO NOT turn on the power yet.
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3. Next turn on your oscilloscope. Attach the Photodiode to CHN 2 using a BNC cable. Attach one BNC cable to from the TTL output on the function generator to CHN 1 on the oscilloscope. Turn on the function generator and set the frequency so that the period is between 30 and 50 msec. (The function generator reads Hz, not msec). Make sure that CHN1 and CHN 2 are DC coupled.

4. Double check the power supply for your laser and turn it on. Attach the White (or Yellow) wire from the laser diode module to the red screw terminal on the function generator. If everything is adjusted properly, you should see the green light flashing slowly on and off with the period that you set in (3).

5. Adjust the Time and voltage knobs on your oscilloscope until you see one period of a square wave from Channel one and an exponentially decaying signal from Channel 2.

6. Determine the lifetime from your data. When the time = the lifetime, or $t = \tau$, we know that $\exp(-t/\tau) = \exp(-1) = 0.36$. Using the oscilloscope’s “measure” feature and the cursers, you can determine the time it takes for the signal to fall to 36% of its original value. This time is the lifetime. You may be able to use the program FREEVIEW on the computer to capture an image of the oscilloscope screen for your notebook (and possibly a formal report.)
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7. Finally, compare the lifetime you determine from your data to the accepted lifetime of the R-line which is 3.6 msec.

Part IV  
Be sure to discuss how the parameters that you determined in this experiment, the wavelength and energy of the R-line, the wavelengths absorbed by the ruby, and the lifetime of the R-line help a Ruby laser work.


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Appendix A
When light is incident on an interface, some light is reflected and some light is transmitted and some light is absorbed so that

\[ I = I_0 (1 - R)^2 \exp(-\alpha L) \]

where \( I \) is the intensity of light that passes through a sample, \( I_0 \) is the incident light intensity, \( R \) is the Reflection as a function of wavelength, \( \alpha \) is the absorption coefficient as a function of wavelength, and \( L \) is the thickness of the sample. We can understand this equation if we first consider what happens in the absence of absorption. In the figure below, incident light is reflected off of two interfaces.

The relationship between the transmitted and reflected light at the first interface, in the absence of absorption, is

\[ T + R = 1 \]

or \( T = (1 - R) \)

Here \( T \) is the transmission and \( R \) is the reflection. In other words, the incident light is either transmitted or reflected. If the light encounters another interface, the relationship becomes

\[ T = (1 - R)^2 \]

(1)

The Reflection is related to the indices of refraction where

\[ R = \left(\frac{n_t - n_i}{n_i + n_t}\right)^2 \]

at each interface. Since \( n_i = 1 \), this equation for our sample becomes

\[ R = \left(\frac{n_t - 1}{n_t + 1}\right)^2 \]

(2)

Using equations 1 and 2, one can solve for the index of refraction, \( n \), as a function of the Transmission, \( T \).
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Appendix B
When light is absorbed by the crystal, Chromium ions jump to an excited state. This excited state has a very short lifetime, so they almost immediately relax to a lower metastable state with a lifetime of $\tau$. Since we are turning the laser light on and off, we are populating the metastable state, and then we are allowing it to depopulate as the Cr ions make a transition to the ground state and emit the ruby fluorescence. The number of excited ions at a time $t$ is given by the following equation:

$$N(t) = N_0 \exp\left(-\frac{t}{\tau}\right)$$

where $N_0$ is the number of excited ions initially, and $N$ is the number left after a time, $t$. The lifetime of the state is $\tau$. 