THE SPECTROGRAPH:  
Colors of Light and Emissions of Light by Atoms

OBJECTIVE: To determine the wavelengths of colors and observe the spectral lines from different elements.

INTRODUCTION:  
LIGHT is a type of ENERGY and moves through space at a constant speed that we call $c$. We can imagine that the light energy can be carried in either of two ways: by WAVES or by PARTICLES.

LIGHT AS A WAVE

A "nice" wave has a wavelength ($\lambda$) and a frequency ($f$). FREQUENCY is simply how many crests pass a certain point per second. WAVELENGTH is simply how far one crest is from the next crest. The wavelength and frequency are related in a definite way:

$$\lambda \cdot f = v$$  \hspace{1cm} (1)

where $v$ is the speed of the wave. For light travelling in vacuum (and approximately for air also),

$$v = c = 3 \times 10^8 \text{ m/s} = 672 \text{ million mph}$$  \hspace{1cm} (2)

The frequency of the wave determines the color of the light. (In sound, which can also be thought of as a wave, the frequency determines the tone or pitch.) But because $c$ (the speed of light) is a constant, the color can also be specified by $\lambda$ (the wavelength) as well as $f$ (the frequency):

$$\lambda = \frac{c}{f}.$$  \hspace{1cm} (3)

LIGHT AS A PARTICLE

If light is thought of as a particle, the color of the particle (a particle of light is called a PHOTON) is determined by its energy. The energy of the beam of light of a certain color is simply equal to the energy of one photon (particle) of that light times the number of photons that constitute the beam. Thus, a brighter beam of red light has more photons in it than a dimmer beam of red light -- NOT more energetic photons for this would change the color of the beam.

THE CONNECTION BETWEEN WAVE AND PARTICLE

Since light can be thought of as either a wave or a particle, there must be some relation between a certain color of light considered as a wave and the same light considered as a particle. This relation is found between the frequency of the wave and the energy ($E$) of the photon:

$$E = hf$$  \hspace{1cm} (4)

where $h$ is a constant (called Planck's constant) for all colors and has the value of

$$h = 6.63 \times 10^{-34} \text{ Joules-sec}.$$
In some cases it is more convenient to think of light as being a wave, and in other cases it is more convenient to think of light as a particle. Remember that light is a real, physical entity and we are only describing its behavior by the use of the wave or particle concepts.

**WHITE LIGHT**

White light is light that consists of all the visible colors. (Because of the way the human eye works, we only need three colors to make a light appear white. But true white light has all the different colors.) If white light is shown through a prism, the prism will bend each individual color a little differently and hence will separate the white light into its component colors. You have seen this effect whenever the sunlight (essentially white light) shines through raindrops: the raindrops act like little prisms to separate the individual colors and a rainbow is formed. This effect can be explained very nicely using the wave idea of light. In this experiment we will not use a prism but will use a diffraction grating to separate the individual colors from the lights we wish to analyze. A diffraction grating doesn't look anything like a prism, but it accomplishes the same task.

**EMISSION OF LIGHT BY ATOMS**

To explain the absorption and emission of light by matter, the particle (photon) idea of light is used because of the nature of atoms. (All normal materials are composed of atoms -- the type of matter depends on the kinds and combinations of the basic atoms). All atoms have a certain minimum internal energy that depends on the type of atom and only to a lesser extent on the environment that the atom is in. If any atom gains energy above its minimum, it will tend to get rid of that extra energy by radiating the energy as light. (However, sometimes that light is not always visible light but may be infrared or ultraviolet, or even radio.) But an atom cannot gain or lose just any amount of energy. It can gain (absorb) or lose (emit) energy only in certain well-defined amounts which depend on the type of atom present. Thus, if an atom is illuminated in white light (recall white light has all the visible colors), all the light will not affect the atom -- only those bits of light (those colors) that have one of those special amounts of energy will be absorbed by the atom. Therefore the white light, after it has passed through many such atoms, will be deficient in those certain colors. If its spectrum (its "rainbow") is displayed, dark lines will appear indicating the absence of those colors.

On the other hand, if a certain type of atom has an excess of energy, it will emit that energy as light. But, since that extra energy is only in certain well-defined amounts, the light emitted will only be of certain energies, that is, certain colors. Hence, each type of atom has its own "signature" and if the light is broken into all of its component colors (that is, if its spectrum is displayed), the atoms which radiated that light can be identified. And if the atoms can be identified, the composition of the light-emitting body can be determined.

Any light can be broken into its component colors if it is passed through a prism or a diffraction grating. A simple type of spectrograph -- an instrument used to photographically record the spectrum of light -- can be constructed by placing a diffraction grating in front of the lens of a camera and then taking a time-exposed pictured of the light.

In this experiment we will observe the spectra from a mercury (Hg) lamp and a helium (He) lamp, and then make a simple spectrograph and use this to photograph the spectrum of the light emitted from each of the lamps. The mercury spectrum will then be analyzed to determine its different component wavelengths (colors). We will then use these as standards to determine
the wavelengths (colors) of the helium light. These experimentally determined wavelengths for helium will then be compared to listed values as a check.

PROCEDURE:
1. Take a diffraction grating (it looks like a clear slide) and hold it right next to your eye and look through it at each of the light sources. You should see the light source but should also see its spectrum (rainbow) off to both sides of the light.

2. Draw a picture of what you see using the diffraction grating: the color and spacing of the lines that you see for the mercury source and for the helium source.

3. If you have a camera function on one of your devices, you can actually take a picture of a spectra. To do this, simply attach a diffraction grating in front of the lens of the camera (just like you put the diffraction grating in front of your eye - your eye works very much like a camera except your eye keeps taking many pictures every second). We put both spectra on the same image by taking a double-exposure, i.e., taking one picture of the mercury and then taking a second picture of the helium using the same image. A paper copy of that image is provided in lab. You can view the color image at: facstaff.cbu.edu/jholmes/N111/Labs/HeHg.JPG. There is a link to this picture also on the lab web page.

4. Note that the picture looks approximately like what you saw when you looked directly through the diffraction grating, i.e., there is the central bright line and then other (colored) lines off to each side. Caution: the camera and the eye have different sensitivities in the different color ranges: the camera is less sensitive to the red end but more sensitive to the violet end. Can you match the lines on the photograph with the ones you saw (and drew) directly with the diffraction grating? Identify the color of each of the lines, and check with your instructor to make sure you are correct.

5. For the mercury spectrum, measure the distance between the same color lines, e.g., from the nearest violet line on the left to the nearest violet line on the right. Repeat for the other mercury lines. Do the same for at least six lines for the helium spectrum.

6. Construct a graph of the measured distance (from step 5 above) vs. the wavelength of the colors: the horizontal axis should be the wavelength axis and should go from about 390 nm to about 700 nm; the vertical axis should be the measured distance and should go from 4 cm to about 8 cm. Now plot your four mercury colors on this graph using the fact that the four mercury colors have the following wavelengths:

   - deep violet - 406 nm
   - violet - 435 nm
   - green - 546 nm
   - yellow - 578 nm

Draw the best straight line through these four points. Do the four points fall close to this straight line?
7. Now knowing the distance for the helium lines (from step 5 above), find the wavelengths for each of the lines (colors) using the graph: find the distance on the vertical axis, go horizontally on the graph till you reach the straight line you drew in step 6, and then go straight down until you intersect the horizontal axis and read the wavelength. Record these wavelengths for each of the lines and see if you can match these wavelengths up with those in the list below.

<table>
<thead>
<tr>
<th>HELIUM wavelengths (nm)</th>
<th>382</th>
<th>402</th>
<th>438</th>
<th>492</th>
<th>587</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>388</td>
<td>412</td>
<td>447</td>
<td>501</td>
<td>667</td>
</tr>
<tr>
<td></td>
<td>396</td>
<td>414</td>
<td>471</td>
<td>504</td>
<td>706</td>
</tr>
</tbody>
</table>

(Note: you will not see all these lines because some are brighter than others, and the film as well as your eye is more sensitive to some colors than to others.)

8. On the graph write the colors that correspond to the different wavelengths. Are the colors and wavelengths for mercury consistent with the colors and wavelengths for helium?

9. Is the camera image more sensitive to some colors than your eye is? Is your eye more sensitive to some colors than the camera image?

REPORT:
1. Include the graph you made in step 6 in the above procedure. Make sure you label both axes of the graph and include appropriate units for the scales for both axes.

2. Make sure you show the results of step 8 on the graph. From this you should recognize that there is a certain range of wavelengths that go with each color. In your report, give the range of wavelengths that are associated with each of the colors you worked with (violet, blue, green, and yellow).

3. Report your findings of your experimental results for the wavelengths of the helium lines (step 7 in the procedure), and compare them to the values given.

4. Answer the questions posed in step 9 of the procedure.