**10 The Spectrophotometer and Atomic Spectra of Hydrogen**

**Introduction:**

When heated sufficiently, most elements emit light. With a spectrometer, the emitted light can be broken down into its various colors or wavelength components and its “spectrum” is observed. A gaseous element (a vaporized solid or liquid) will typically emit light only at certain characteristic wavelengths or colors. In a spectrometer, such a discrete spectrum appears as a series of colored lines.

![Figure 12.1: Line Spectrum](image)

A particular set of lines or wavelengths is characteristic of a certain element and can be used as a “fingerprint” for identifying an element.

Light from a hot solid source has a continuous spectrum, which in the spectrometer will appear similar to a rainbow. The simplest form of this type of spectrum is that produced from a cavity inside a hot body. It is called a blackbody spectrum. Such a spectrum extends over a considerable range of wavelengths. The dominant frequency region of the spectrum is proportional to the $4^{th}$ power of the temperature of the emitting body. The frequency region of sun light is determined by the 6000K temperature of the solar exterior. The solar spectrum peaks in the center of the human eye’s sensitive frequency range. Incandescent light bulb filaments, on the other hand, operate at roughly 3,000K, near the melting point of tungsten, and produce blackbody spectra that peaks at a lower, infrared frequency. Only the upper, visible tail of the spectra is useful for illumination. Since only 5% of the emitted energy is visible, incandescent bulbs are only 5% efficient.

Fluorescent lamps used an electrical discharge through mercury vapor to produce the characteristic line spectra of mercury. Light from the very intense ultra violet line is absorbed by a fluorescent coating on the lamp walls and re-emitted as visible light along with the visible lines of mercury. Since most of the emitted light is visible, fluorescent lamps are more efficient (about 20%). Other newer gas discharge lamps are 40 to 50% efficient.

Light emitting diodes or LED’s also emit continuous spectra although not as broad band as black body spectra. The light comes from the recombination of electron-holes pairs and is of a frequency roughly given by $(eV)/h$, where $V$ is the voltage drop across the diode, $e$ is the electron charge, and $h$ is Planck’s constant.
Equipment:

The spectrophotometer uses a diffraction grating to produce a spectrum of the light source. The diffraction grating has about 600 lines (or slits) per millimeter. It works the same as a double slit except the maxima produced are much sharper than for the double slit. The double slit formula is

\[ n\lambda = D \sin \theta \]

For this equipment \( D = 1 \text{mm} / 600 \) and is thus \( D = 1660 \text{ nm} \). In the experiment, the angle of the light sensor will be varied and this allows a separation of wavelengths resulting in the spectra of the light source. We expect to observe a spectra on each side of \( \theta = 0^\circ \) corresponding to \( n = 1 \) and perhaps a second spectra corresponding to \( n = 2 \) but you will not measure it.
Observe the operation of the spectrophotometer. Light from the source passes through a slit and a collimating lens and is then incident on the diffraction grating. A light sensor mounted on a rotating platform measures the spectrum produced by the diffraction grating. An angular motion sensor connected to the platform measures the rotation of the platform. The angular motion sensor turns through 600 for every degree that the rotating platform makes.

Both of the sensors will be connected to the Science Workshop and you will load a file called 'spectrophotometer.ds', which has the correct formula to convert the input from the angular motion sensor into a wavelength measurement. It is important to note that the angular motion sensor is set to zero each time the "START" button is pressed and thus the rotating platform must be in the zero position each time data taking is started.

Each time you take data you must make sure that the light source is lined up with the slit and the lens is adjusted to produce the best spectra. It may be necessary to adjust the slit near the light source or the light sensor.

**CAUTION:** Hydrogen and other atomic gas tubes require high voltage. You must not touch the tube holder and the holder should be unplugged if your instructor tells you to change the tubes. Also the tubes get hot, so exercise caution.

### Theory of Atomic Spectra

One of the milestones in development of our understanding of the atom was the discovery of the empirical Balmer formula relating the wavelengths of light from dilute hydrogen gas to certain integers. The formula may be written:

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

where:
- \(\lambda\) = the wavelength of light
- \(R\) = the Rydberg constant, 1.097 x 107 m\(^{-1}\)
- \(n\) = an integer, 3, 4, 5, ….

### Part 1: Emission Spectrum

1. Connect the rotary motion sensor and the high intensity light sensor.
2. Use a mercury tube as the light source and the 600lines/mm diffraction grating.
3. Set the light sensor gain to ten using the switch on the light sensor. You will then need to do a second scan with the gain on one hundred in order to see the violet. Correct your intensity measurements for this gain change.
4. Start DataStudio and load the 'spectrophotometer.ds' file.
5. Because the rotary motion sensor zeros itself when you press start, line up the sensor with bright central maxima.
6. Press start! Sweep through the full range of motion of the light sensor arm in one direction and press stop.
7. Open up a graph of light intensity vs. wavelength.

8. Use the smart tool to measure the wavelength and intensity of each line in the hydrogen spectrum for positive and negative angles. Calculate the theoretical wavelengths using the Balmer formula. Use Excel to create a table like the one below.

9. Comment on your results. Do the experimental and theoretical (Balmer) wavelengths match? Does intensity decrease as wavelength decreases? (This is expected because lower wavelength means higher energy and fewer hydrogen atoms are excited to the higher energy states.)

<table>
<thead>
<tr>
<th>Color</th>
<th>Intensity</th>
<th>Quantum</th>
<th>Experimental</th>
<th>Balmer</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Number n</td>
<td>Wavelength ( \lambda ) (nm)</td>
<td>Wavelength ( \lambda ) (nm)</td>
<td></td>
</tr>
<tr>
<td>Violet</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue green</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Part 2: Blackbody curve and absorption**

In this section you will record the spectrum of small incandescent lamp, which should be close to that of a blackbody. Unfortunately, the detector system is not ideal for this measurement. You should see continuous spectra, but it will not have the expected shape of a blackbody that you have studied.

You will also record several absorption spectra, which result when light of certain wavelengths is absorbed by some material placed between the light bulb and the light sensor. If the absorbing material were a gas of hydrogen atoms, you would see dips in the continuous spectra where some of the hydrogen lines occurred. This is not possible in today's lab, but we will study absorption caused by a food dye and also a special filter that is designed to absorb everything but a very narrow part of the spectrum.

Start with the same setup as Part 1, but substitute a light bulb for the atomic spectra tubes.

1. Set the light sensor gain to ten using the switch on the light sensor.
2. Mount the food dye cell as indicated by the instructor.
3. Turn on the light bulb. Because the rotary motion sensor zeros itself when you press start, line up the sensor with bright central maxima.
4. Press start! Sweep through the full range of motion of the light sensor arm in one direction. Comment on the observed spectra. At what wavelength is the absorption maximum?

5. Place a filter in the slot directly in front of the light sensor and sweep the arm back to zero.

6. Press start! Sweep through the full range of motion of the light sensor arm in one direction. Comment on the observed spectra. At what wavelength is the transmitted light maximum?