WORLD OF LIGHT LABORATORY

LAB 2

Atomic Spectra

Introduction:

Atoms and molecules are much smaller than the wavelengths of visible light, making it impossible to see them individually, even with the best microscope that could conceivably be built. As a result, everything that we know about atoms and molecules has come from indirect measurements, usually on large numbers of them at once. Spectroscopy has proven to be a particularly powerful indirect technique. In spectroscopy, one finds what frequencies of light are able to resonate with the atom or molecule, thereby determining the object's natural resonant frequencies. This is analogous to the standing wave lab in which you found what frequencies of the audio oscillator were able to resonate with a string. In both cases, resonance enables energy to be transferred, whether between light and atoms or molecules, or between the oscillator and the string.

When light energy is transferred to an atom, it can only be absorbed or emitted in discrete amounts. This amount is the energy of a photon, given by the Planck relation, $E = hf$, where h is Planck's constant which equals $6.6\text{x}10^{-34}$ J·s and f is the light frequency. Due to this correspondence between frequency and energy, we often speak of the resonant frequencies of an atom as different energy levels. For example, if a hydrogen atom absorbs an ultraviolet photon of light, it will move from its lowest energy level, called its ground state, up to a higher energy level. Later on, it might release this energy as a different photon of ultraviolet light as it relaxes back to its ground state.

In today's lab, you will observe the energy levels of several types of atoms using a prism spectrometer. You will excite the atoms using an electric current through what is called a gas discharge tube and will measure the frequencies of the emitted photons with a prism spectrometer. You will calibrate your spectrometer using previously measured emission lines for mercury and helium and then use this calibration to determine the wavelengths of some hydrogen spectral lines.

Equipment:

Newton was the first person to disperse white light into its component colors using a prism, in 1665. Fraunhofer improved upon a simple prism by adding a few lenses and a slit, leading the first prism spectrometer in 1814. The spectrometers that we will use are very similar to the one that Fraunhofer invented. Ours are called Spencer spectrometers and are nicely described in a manual titled "The Use of the AO Spencer Spectrometer" by Roger Estey, published 1938 by the American Optical Company. The figure below is taken from that manual. Our spectrometers appear to be identical to the ones in that manual, and so probably date from a similar era.

These spectrometers are expensive instruments, so please take care of them. Much of the work in using a spectroscope is the tedious job of aligning and leveling its component parts, which has been done for you. You will only need to rotate the prism table and the telescope.

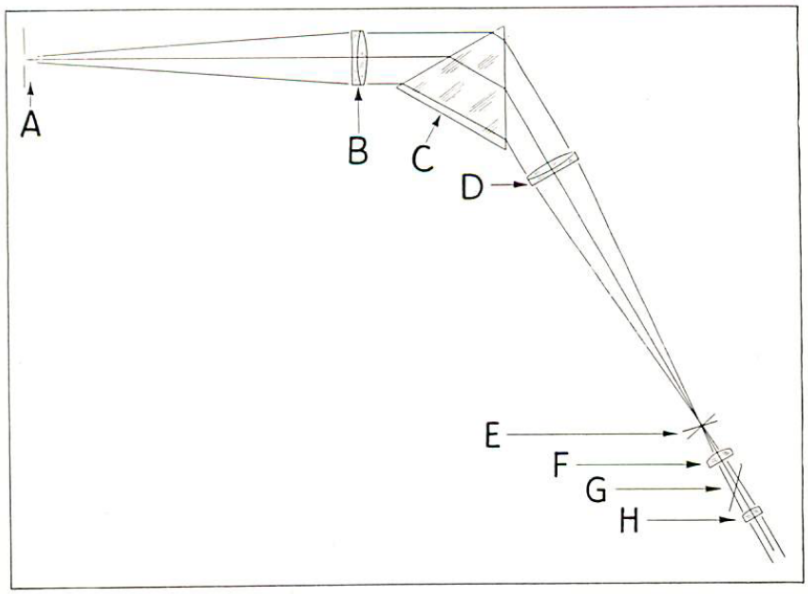


Fig. 7. Path of Rays through the Spencer Spectrometer. A—Slit; B—Collimator Objective; C—Dispersing Prism; D—Telescope Objective; E—Position of Cross Hairs; F—Eyepiece Field Lens; G—Semi-transparent Diagonal Mirror; H—Eyepiece Lens.

Collimator

Light to be studied enters an adjustable slit (A) and is made into a collimated beam by lenses (B).

Prism

The light is then dispersed into its component colors by the prism.

Telescope

After passing through the prism, light enters the telescope tube. The telescope converts the collimated beam into a real image at the crosshairs (E). The light then goes through more lenses in the eyepiece to enable you to see the image. The telescope should not require adjustment during the experiment.

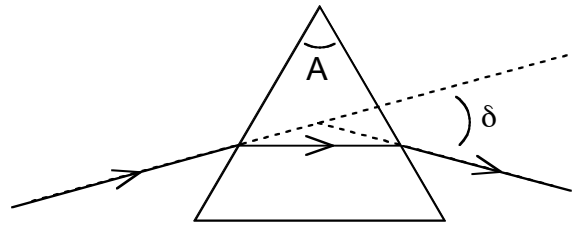
Prism Table and Graduated Circle

The prism table has been leveled by the three screws on its underside. Do not adjust these screws. The prism table and inner circle are capable of rotation about a vertical axis. The angle readings give the angle of rotation of the telescope relative to the prism table.

When a beam of light passes through a prism it will not emerge parallel to its former path but will be inclined to it; the angle thus formed (labeled δ in the figure below) is usually referred to as the angle of deviation. The angle of deviation of a prism varies with the angle of

incidence of the entering ray, but for one angle of incidence, the angle of deviation will be a minimum. This occurs when the ray passes through the prism parallel to the base of the prism. When the angle of deviation of the ray is minimum, δ_m the index of refraction of the prism is given by the equation

$$n = \frac{\sin\left(\frac{1}{2}\left(A + \delta_m\right)\right)}{\sin\left(\frac{1}{2}A\right)}$$



<u>Procedure</u>:

A. <u>Calibration of the Spectroscope</u>

Put a helium emission tube in the light source housing and turn it on. Place the spectroscope so the adjustable slit on the collimator is about 1 cm away from the emission tube. The light will then go through the prism where it is dispersed into its spectral components. The violet rays (shorter wavelengths) are deviated most, and the red rays (longer wavelengths) least. This is because the index of refraction of all ordinary transparent substances, including the glass prism, decreases with increasing wavelength of light used. By moving the spectroscope telescope back and forth some, you should be able to find some the helium emission lines. Refer to the above picture of a prism to get a sense of where you might want to look for the emission lines. Once you find the lines, move the spectroscope around some until they are as bright as you can get them. Then, don't move the spectroscope again for the rest of the experiment.

To get a reading for an emission line, align the telescope crosshairs so that they are exactly on the line. You may need to adjust the desk lamp. Then, read the "angular deviation" off of the spectroscope scale. To read the angular deviation, look through the magnifying glass. You will see that the inner scale is fixed while you rotate the telescope, but the outer scale changes. Find the '0' line on the inner scale. The angular deviation is the angle on the outer scale that this lines up with. The outer scale has large marks for every 1° and small marks for every 0.5°. Try to estimate the position of the inner scale '0' line on the outer scale, to 0.1° of precision.

The readout is the "angular deviation", which is the rotation angle of the telescope relative to some arbitrary angle. This is not very helpful, so your first task is to figure out the correspondence between the angular deviation and the light wavelength. Doing so is called calibration. To calibrate the spectroscope, you will graph the wavelength versus angular deviation for a number of spectral lines of known wavelength. We will use helium and mercury as calibration standards, using the wavelengths of prominent lines in the spectra of these elements given below. You should take readings for as many of the identifiable lines in mercury and helium as you can. Use the intensity values in the spectral tables to determine which colors correspond to which bands of the spectrum. Not all of the lines you see in the spectrum appear on the spectrum charts.

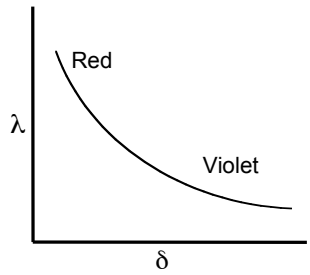
Helium Bright Line Spectrum

Color	Wavelength (nm)	Intensity	Deviation
Red	706. 5	10	
Red	667. 8	10	
Yellow	587. 6	10	
Green	501. 6	10	
Blue-green	492. 2	5	
Blue	471. 4	4	
Blue-violet	447. 2	10	
Violet	438. 8	3	
Violet	402. 6	4	
Violet	396. 5	4	
Violet	388. 9	6	

Mercury Bright Line Spectrum

Color	Wavelength (nm)	Intensity	Deviation
Red	690. 9	10	
Orange	615. 1	5	
Yellow	578. 0	10	
Green	543. 1	10	
Green	535. 4	4	
Blue-green	496. 0	5	
Blue-green	491. 6	5	
Blue-violet	435. 8	10	
Violet	404. 7	10	

Using Excel and the supplied template, plot your calibration data with wavelength as the *y*-axis and deviation (the measured scale reading) as the *x*-axis. Your calibration data should resemble the following.



Still in Excel, fit your data with a parabola,

$$\lambda = a\delta^2 + b\delta + c$$

This fit has no theoretical significance, but should fit your data reasonably nicely. In other words, it's an empirical interpolating function. This interpolated result is your calibration curve. It shows the relationship between angular deviation and wavelength, using emission lines with known wavelengths.

B. <u>Use of the Spectrometer to Measure "Unknown" Wavelengths</u>

Once the spectroscope has been calibrated, it can be used to determine the wavelengths of lines in the spectrum of an "unknown" source. In astronomy it is possible to identify various chemical elements in stars and obtain much other valuable information by studying the wavelengths in the spectra from the stars.

Insert a Hydrogen tube into the spectrum tube power supply and observe the spectrum. By looking carefully you should see four lines. Record the apparent colors and angular positions of the lines.

Using the calibration curve for the instrument, with your Excel file, determine the wavelengths of the lines.

C. Comparison with Theory

According to the theory of the spectrum of the hydrogen atom, the wavelengths should be given by the formula below, where $m = 3, 4, 5$, etc. Use this formula to calculate the wavelengths of these lines for each of these m values. Then, compare these numbers with your measured wavelengths. The hydrogen lines in the visible part of the spectrum are known as the Balmer series:

$$\frac{1}{\lambda} = R\left(\frac{1}{2^2} - \frac{1}{m^2}\right)$$

where R is the Rydberg constant, given by $R = 1.097 \times 10^7 m^{-1}$.

D. Qualitative observations on more spectral lines

Look at a neon, sodium, and nitrogen emission tubes in the spectrometer. What do you observe?

E. Lab report - **due Monday, April 20**

This lab explanation and worksheets are purely for your own use, and do not need to be turned in. Instead, turn in a more polished lab report, prepared using Microsoft Word or equivalent. It should have five clearly labeled sections: Introduction, Methods, Results, Discussion, and Conclusions.

Introduction

• Write a few sentences about why atomic (and/or molecular) spectra are important.
• Show a diagram of the hydrogen atom energy levels. Show energy level numbers for at least levels numbered 1 to 5. Include several arrows that represent emission transitions. Label them with the correct light wavelengths.
• Explain the diagram. In this explanation address the following topics: energy level quantization, atomic excitation, light emission, and photons.

Methods

• Briefly (3-4 sentences) explain what your experimental methods were. Note that this is not instructions for someone else to follow, but just a brief explanation of what you did.

Results

• Present your raw data in table format and present your calibration graph. The graph should include the best-fit line. It should be copied from Excel, not hand-drawn. Please keep the data tables relatively small, and shrink the graph down so that it takes less paper.
• Include some text which explains what the data table and graph show.
• Present your experimental results for the hydrogen emission line wavelengths.

Discussion

• Describe how well your data agreed with the theory.
• Present your calculation results for the hydrogen emission wavelengths.
• Why do you think the data did not agree with the theory better? In particular, what are some things that could have caused experimental errors in this lab? (Errors does not mean your mistakes; it means limitations from the equipment or the procedure.)
• Qualitatively compare the different atomic spectra. Why do you think they are different?

Conclusions

• Summarize the principle results that you found in this lab in 4-5 sentences. This is *not* about how much you learned, or how fun the lab was. It is about the scientific findings. Include the key qualitative results, and how well your experimental results agreed with theory. If someone else wants to get the gist of what you did with minimal reading, this is what they will read.

Lab report grading will be based about 50% on whether you included the required topics in your lab report, and about 50% on what you presented. Note that longer reports typically say more, and thus get higher grades.