# Spectra from transitions in atoms and lighting

Safety: This experiment uses a Mercury Light source and a laser. Mercury light source emits Ultraviolet light. You should always have the ground glass shield in front of it and do not look directly into the source as it is harmful to your eyes. Also do not <u>under any circumstances</u> look into the laser. To check if it is "on" shine it on a wall or a piece of. Do not feed the angry sea bass.

In this lab you will look at six (or more) different sources of visible light. All but one will be due to a quantum energy transition in an atom or a semiconductor, the other will be the continuous blackbody spectrum, because things that have temperature radiate. Also, this lab will introduce you to the basics of optical spectrometry. It including the operation and calibration of a pre-packaged diffraction grating + CCD (charged coupled device, with pixels like a digital camera), whose principles you also meet in unpackaged form in the photoelectric effect and e/h lab.

Set up operation and check the calibration of the device

First you need to check the spectrometer calibration and its band pass. This is done using the first setup of apparatus where the laser is mounted if front of a white diffuser cavity and the diffuse light is projected onto a ground glass screen viewed by a collimator connected to the spectrometer, as shown in Figure 1. The collimator is terminated in an optical fiber leading to a spectrometer with a CCD (charge coupled device) detector whose output is displayed on the laptop.

Gr. glass

Diffuser

Collim.

hν

Laser

Ground
Glass

H$_2$ light
source

Fiber

Spectrometer

Display
Screen
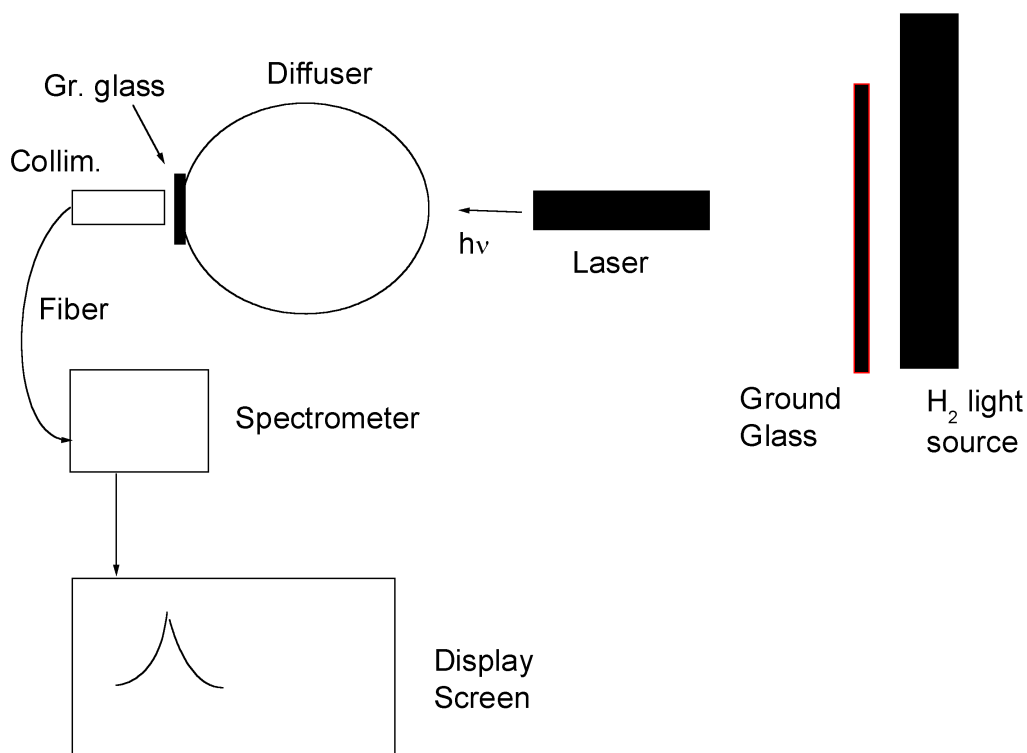
Optical spectrometer consists of a grating mounted between two reflecting concave mirrors. One mirror takes the light of all wavelengths from the optical fiber (connected to the spectrometer entrance slit) and projects it as a parallel beam onto the grating. The grating behaves like a multiple slit interference device (consisting of ~10^4 slits or reflective "rulings" per centimeter). The grating disperses the light into many (colors) wavelengths where the constructive interference is at different angles for different colors. Instead of projecting it onto a wall, like in a class demo, mirrors are used and its projected onto a linear array of CCD pixels. The second mirror focuses a particular λ onto individual CCD elements measuring the intensity at a particular λ. This information is fed to a computer that displays the spectrum on the screen, pixel by pixel. You can take the data in table form and transfer it to your own spreadsheet or favorite software to make nice figures.

Calibration of the spectrometer:

a) Turn on the data acquisition (DAQ) computer and set the integration time to 50 ms.

b) Make sure the Helium-Neon laser is aligned with the entrance port of the diffusing cavity, and turn on the laser. You should see the ground glass screen of the diffuser light up red with laser light whose wavelength is the characteristic 632.8 nm helium transition used for this laser.

c) The readout on the screen of the laptop should show a peak at 632.8 nm if the spectrometer is properly calibrated. If the peak is small increase the integration time to 100 ms so the peak is as tall as possible but NOT flat at the top. Being flat at the top means the device is "saturated" and you are not able to make accurate measurements.

d) You can record the data and display it on expanded scale around 630 nm, or read it off the "histogram" on the left of the plot.   The expanded line is lot sharp but displays a Gaussian shape about the average wavelength. The half-width of the line is its band pass. Using your data determine the average λ and the band-pass $\pm \Delta\lambda$ for the spectrometer. Is the average λ offset from the expected 632.8 nm? If so this is the offset correction for all your measurements.

Hydrogen and Mercury spectra.

Stop the data acquisition, and turn off and unplug the laser, and prepare for hydrogen and mercury spectra,

1.   Place the Hydrogen light source in front of the fiberoptic end.   **Do not stare at the hydrogen light source. Even though hydrogen gas discharge in this source is contained in a glass envelope it still emits near UV light in the 330 - 400 nm range that is outside the visible spectrum**

2.   You might imagine that you can scan this spectrum by hand, which is what all the old folks remember doing in their youth. Anyway, save a record of the hydrogen spectrum, adjusting the integration time and distance between the source and optical fiber as needed.

3.   Remove the hydrogen source and do a preliminary analysis of the spectrum, following the narrative below.

4.   Mount the mercury light source with the ground-glass shield. Record and save a spectrum for this one. There may be additional energy in the red and infrared. Adjust the distances and integration time to ensure you have a good record of the ultraviolet, blue, green, and yellow lines.

Hydrogen spectrum:

One objective of the experiment is to identify the wavelength and the corresponding energy of each Hydrogen line. The energy of the spectral line in eV is given by:

$$\varepsilon = hc/(\lambda e)$$

Where h is Planck constant, c is the speed of light, and e is the magnitude of the electronic charge. The energy of each line corresponds to the electron transition energy for Bohr's Atom given in eV by:

$$\varepsilon = 13.6(1/n_f^2 - 1/n_i^2)$$

Where n_f and n_i stand for the final and the initial energy quantum number in Bohr's Atom. For your write-up please look up the derivation of this equation in the treatment of Bohr's Atom in your textbook, and summarize it. Beware, you will simultaneously be learning something more fundamental than what led to the Bohr atom, so also consider how the nature of the predictions are different, and how delightfully naïve Bohr was.

Using you data answer the following questions.
a)   What is n_f and n_i for each of your lines?
b)   Are all the lines you observe attributable to a quantum theory of the hydrogen atom (like Bohrs, or the full one later in your text)? If not Why not? How do you know?
c)   Are any of the lines of the hydrogen spectrum broader than the laser line? To what can you attribute this broad line width? Look up the subject of Doppler broadening of a line and how temperature of the source affects the width of a spectral nine.
d)   Hydrogen spectrum should consist of discrete nines and a continuum. Do you observe a continuum? Why?
e)   What is the broad portion of the observed spectrum attributed to?

Notes on the relationship between photon emission and electron energy levels:

The Bohr theory for Hydrogen atom applies Newton's second law and Coulomb's law to the motion of electron about a massive nucleus assuming circular orbits for the electron and using the fundamental quantization principle for the angular momentum of electrons given by:

$$mVR = nh/2\pi$$

Where m is the mass of electron, V is its speed, R is the radius of its circular orbit, n is a running integer 1, 2, 3…

This picture, though totally naïve, yields accurate reproduction of the Hydrogen emission spectrum. You are simultaneously learning the full standing-wave quantum model for the hydrogen atom. But, ok, use the Bohr model for today, his was a standing wave too actually, just a little sillier than the real 3D one. Dress in period costume if you like how quaint it is. The model rests on the fact that electron moves around the nucleus with centripetal acceleration (mV^2/R) held by the centripetal force between charges given by F= $-Ze^2/(4\pi\varepsilon_0 R^2)$, where -e denotes the charge of the electron and the nucleus has charge Ze. The atomic number Z =1 for the Hydrogen nucleus. Taking the condition of quantization of the angular momentum into account the result yields discrete energy levels for the electron given in electron-Volts (eV, 1.6×10^{-19}J) by:

$$E_n = -Z^2(13.6)/n^2 \quad (eV)$$

Experimental observation of accelerated charges shows that they radiate energy unless they are in the stable or "ground" (the lowest available) energy state. Thus electrons in an atom that are excited to higher energy orbits by thermal collisions radiate energy as photons when they return to the stable ground state. The energy radiated upon electron transitions between the orbits is "quantized" because the allowed energy states are discrete as shown by the above equation (see any Modern Physics book, such as Beiser in the lab room). As a result, photons emitted by a heated gas yield a spectrum with discrete energies. The spectrum is distinct for each atom thus the spectrum serves as a "finger print" we can use to identify a glowing gas. For Hydrogen the energy of the emitted photons is given by E = hc/λ. In MKS system of units hc/λ is given by:

$$hc/\lambda = Z^2(13.6)((1.6\text{x}10^{-19})(\ 1/n_i^2 - 1/n_f^2)$$

Where λ is in meters, h is the Planck's constant, c is the speed of light, and n_i and n_f denote the initial and the final "energy level quantum numbers" respectively.

Mercury Spectrum:

Quantum mechanics can treat in analytical closed-form only the hydrogen and the helium atom. Good precision can be had using numerical solutions to differential equations. However, things become more complex for other atoms because the inner electrons "screen" the nucleus. But even though a first principles derivation of the observed spectral lines is challenging, using these other spectra is interesting. Lets consider the application to modern lighting.

Using the mercury lamp, measure the spectra of all the lines the spectrometer is able to see. Some are in the ultraviolet, and some may be in the infrared. The visible mercury lamp colors are the same ones you used in the photoelectric effect e/h lab.

Blackbody Spectra, suns, stars, and artificial lighting:

Evolution of animal and plant species on this planet has resulted in your brain thinking that blackbody spectra is "natural" . And you should be awake and alert when you are surrounded by full-spectrum sunlight, but sleepy and restful when you are not. For surprisingly separate reasons, you are conditioned to think that energy-efficient lighting is good for your bank account and for society's attempts to appropriately manage non-renewable resources. And if you like this sort of thing, multiple Nobel prizes have been given for understanding and exploiting these things. Lets join!

Set up the spectrometer to view an incandescent light bulb without saturation. Probably the bulb should be 15 to 20 cm away, again adjust the integration time to get a spectrum. Open one of your textbooks to the section describing blackbody radiation. Use that information to estimate the temperature the filament of the lightbulb.

Earlier, we calibrated the frequency axis of the spectrometer.   We used the intensity axis to identify peaks, but didn't measure the intensity itself. Comparing the expected blackbody spectrum to the one you measured, does it look like the intensity response needs calibration too ? Describe the problem you see, if any.   In fact, I think we dropped this unit, so it's a little messed up because of that. You don't have to actually do it, but speculate how you might go about obtaining a correction.

If you are able to get a spectrum from the sun, now would be a good time to do it.   If you are an astronomy enthusiast, remind yourself how blue stars and red stars are different from our sun's yellow. If you are a camping enthusiast, remind yourself how glowing yellow campfire coals different from dim red coals are different from coals that are warm to your hand but don't seem to give off visible light.

Now, lets save some energy. What you are seeing with this lightbulb is inherently wasteful. We have three other light bulb technologies that are better. Overhead fluorescent lights, invented in the 1930s, have been used in businesses and schools not long after. Another is a compact fluorescent bulb, an innovation from the late 1970's "oil crisis". The final one is a LED (light emitting diodes) bulb, which was not possible until the invention of the Blue LED in the 1990s.   Each of these involve a source of light and a patented (white-colored) coating, and each requires a blue or UV color.   Get the spectra for those. Probably you want to pick off any peaks in the spectrum, plus other qualitative information, and save the spectra to a file for later analysis and plotting. Interpret the spectrum and explain how they produce relatively "natural" light with less energy.

It should be obvious now what fundamentally makes the light in the fluorescent bulb. You should some name-brand search engine to get a quick story for how light emitting diodes are really also just providing photons from electron transitions to a lower energy state, but differently than mercury atoms.

In your lab report, tell the story of the hydrogren atom and how a spectrometer works. Then tell the story of these achievements in lighting design, using the spectra you obtained to make things quantitatively clear.