PHY 124 Lab 9 - Atomic Spectra

The purpose of this laboratory is to study transitions between energy levels of the hydrogen atom by observing the spectrum of light emitted when the atoms make transitions from higher- to lower-lying quantized energy levels. To measure the wavelengths of the emitted light, you will use a transmission diffraction grating in a simple apparatus.

Important! You need to print out the 2 page worksheet you find by clicking on this link and bring it with you to your lab session. [http://www.ic.sunysb.edu/Class/phy122pk/labs/pdfs/phy124s13atomspeclab9worksheet.pdf]

If you need the .pdf version of these instructions you can get them here [http://www.ic.sunysb.edu/Class/phy122pk/labs/pdfs/phy124s13atomspeclab9.pdf].

Preparation

To prepare for this lab you should review Ch21 sheets 28' and 9 (about diffraction gratings), Ch25.3 sheets 31-38 (about "the early atom"), and Ch26 sheets 38-49 (about "the hydrogen atom") in the online notes for the PHY 122 workshops. You will also profit from reading Chap. 17.3 (about diffraction gratings, pp. 553-556) and Chaps. 29.3-29.5 (about the hydrogen atom, pp. 960-971) in Knight, Jones and Field, *College Physics: A Strategic Approach*, 2nd ed. (KJF2), the optional textbook for PHY 122. If you don't have a copy, you'll find one bolted to a table in the Help Room, A-131 physics building. A few copies are also available on closed reserve in the Math/Physics Library, level "C" of the physics building. The questions related to the above material in the online pretest for Lab 9 also helped to prepare you for this Lab.

Video

Equipment

- Optical bench with clamp and mount to hold diffraction grating
- Diffraction grating ("replica" transmission grating with 13,400 lines/inch)
- Ruler with battery-powered, light emitting diodes mounted on a meter stick
- Electric gas discharge tube with hydrogen gas (our light source)
- Small ruler to measure the distance "y" in Fig 2. accurately

Fig. 1 is just below here
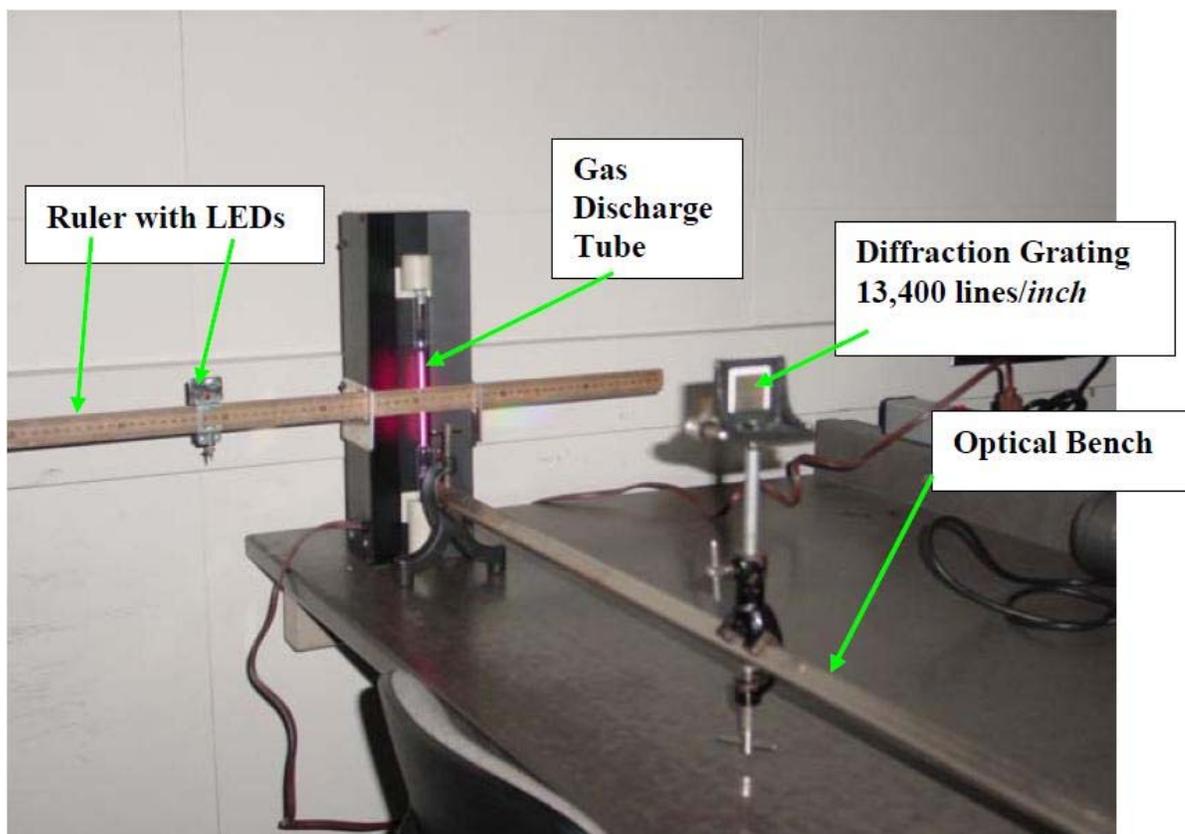
Introduction

A diffraction grating is a dispersive optical device with a spatially periodic structure that affects the reflection and/or transmission of electromagnetic radiation. If the spacing of periodic elements, e.g., lines or slits, is d, then the wavelength(s) λ of light diffracted by the grating can be determined from Eq. (21.7') in Ch. 21.3 sheet 28' of the online notes (equivalently Eq. (17.12) in p. 553 of Chap. 17.3 in KJF2):

$$d\sin\theta_m = m\lambda,$$
(9.1)

where $m = 0, \pm 1, \pm 2, \ldots$ counts the *order number*: $m = 0$ for non-dispersed, undeflected light; positive m for light dispersed to positive angles θ_m; and negative m for light dispersed to negative angles θ_m. You will use a transmission diffraction grating having $\frac{1}{d} = 13,400$ lines per inch to disperse several wavelengths of the electric discharge spectrum of hydrogen atoms. These spectral lines are emitted with intensities strong enough for you to see them with your eyes in a darkened room. The whole apparatus, called a spectroscope, consists of the light source, the grating, an optical bench and a meter stick. Two battery-powered, light emitting diodes (LEDs) mounted on the meter stick will be used to locate the position of the "spectral lines", which are the interference maxima (bright interference fringes, or "lines") for specific wavelengths and hence specific colors, under study. When, in a previous experiment, you used a (reasonably) monochromatic light source, the diffracted maxima (bright lines) and minima (dark lines) of different orders m all had the same color.

The name "spectral line" comes from the following. Usually what one observes in a spectroscope is diffracted (dispersed) images of a narrow "slit" through which light from the discharge tube must pass before it gets to the grating. Since these images look like colored "lines", the name was an obvious choice.

In your apparatus, there is no need for an external "slit" because the discharge tube itself is sufficiently narrow that it approximates a light-source-plus-slit.

David Rittenhouse [http://en.wikipedia.org/wiki/David_Rittenhouse], a self-taught inventor and scientist in Philadelphia, made the first man-made diffraction grating in 1786 by stretching ~50 hairs between two finely threaded machine screws. (Your previous experiment in PHY 124 used only one hair!) Rittenhouse's first transmission grating had about 100 hairs per inch. In Bavaria, Joseph von Fraunhofer, another self-taught inventor and scientist, perfected the technique with use of closely spaced, stretched metal wires and used his transmission gratings to discover and catalog hundreds of so-called Fraunhofer absorption lines [http://en.wikipedia.org/wiki/Fraunhofer_lines] in the solar spectrum. Indeed, helium (from the sun-god *Helios* in Greek mythology) was discovered via observation during a solar eclipse in 1868 of a previously unknown yellow absorption line in the solar spectrum. You can see this yellow line and a few others in the portion of the helium spectrum shown on the top of p. 940 of KJF2. (Helium wasn't detected and studied on earth until 25 years later.)

The geometry of the setup you will use to measure the angles of the optical rays pointing toward specific spectral lines of hydrogen atoms is illustrated in the figure below.

Fig. 2 is just below here
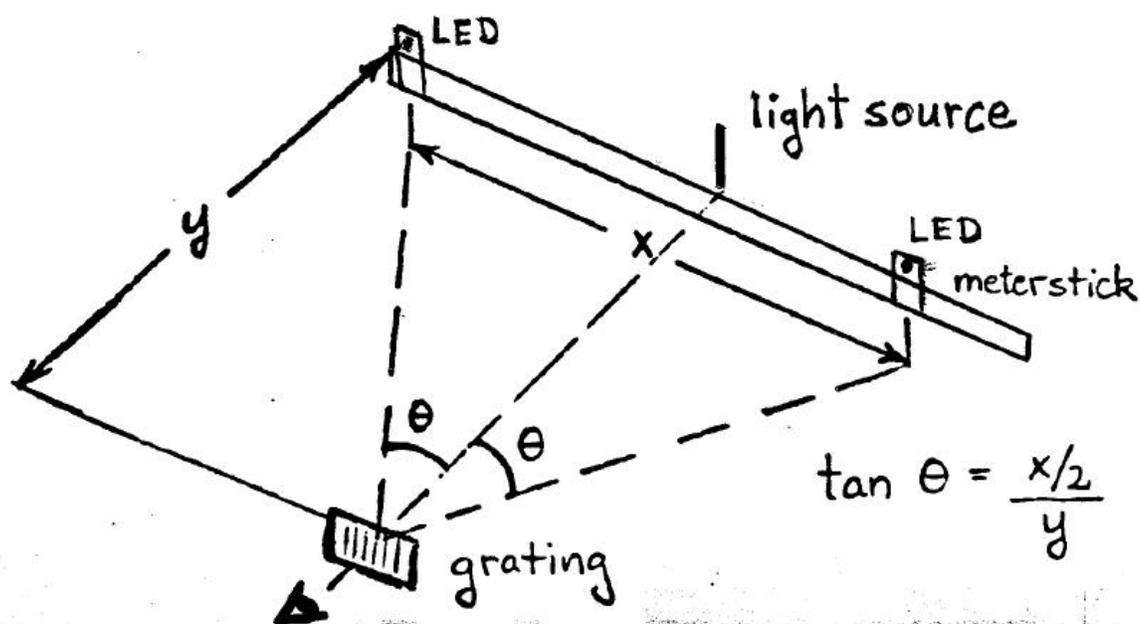
Each angle θ_m can be calculated from the distance x between interference maxima (bright lines) of the same order m and same wavelength λ (color), and the distance y between the grating and the ruler with the LEDs. You will use the trigonometric relation

$$\tan\theta = \left(\tfrac{x}{2}\right)/y = \tfrac{x}{2y}$$
(9.2)

Be careful when using this formula! Remember that you are measuring the distance x, but Eq. (9.2) requires you to use the distance $(x/2)$ because the distance to an interference maximum (bright spectral line) is always measured from the position of the central maximum, which is located at the light source itself.

Use Eq. (9.2) to determine each value of θ, and then use Eq. (9.1) to find the respective wavelengths λ for each spectral line.

Part I: Qualitative Use of the Diffraction Grating

The purpose of this part is to observe the interference orders m that are visible when you look through the transmission diffraction grating with your eyes.

The room has to be dark, so your TA will turn off the lights when all groups are ready to take data.

Turn the on the LEDs and the hydrogen discharge tube. Since the gas discharge tube loses effectiveness the longer it stays on, when you aren't actually observing spectral lines please turn off the electrical power to the tube! Since the LEDs are battery-powered, please turn them off when you're not actually using them.

Set the distance y between hydrogen discharge tube and diffraction grating to approximately 45 cm. (**Warning**: After reading the paragraph two below this one, realize that later you may have to readjust this distance y .) Make sure that the tube is in line with (centered on) the optical bench and that the plane of the transmission diffraction grating is perpendicular to the optical bench. Look through the grating at the tube. On both sides of the tube you will see several sharp colored spectral lines – a purple line, a blue-green line, and a red line.

Note: you may also see a line in the green-yellow region. If you do, ignore it because it comes from something contaminating the hydrogen gas in the discharge tube. You will also see a "continuum spectrum" as a rainbow having a much lower intensity than the bright spectral lines. This "continuum" likely comes from many spectral lines emitted by *hydrogen molecules* in the discharge tube. Molecular lines can be so closely spaced that they appear to be a continuous rainbow of color. Because hydrogen gas is a diatomic molecular gas, H_2, you shouldn't be surprised to see "spectral features" from them. The electric discharge dissociates most, but not all, of the H_2 molecules into hydrogen atoms, and, moreover, (excited) hydrogen atoms can "recombine" into excited molecules that emit light.

Focusing on the atomic hydrogen spectral lines, move your head slightly from side to side so that you can see the lines farther away from the center, i.e., at larger angles away from the optical axis along the optical bench. You should see at least 2 full orders (the m in Eq. (9.1)) on both sides of the axis. Make sure the conditions are such that the $m = 2$ order red line (the second repetition away from the optical axis of the bright red line) is "still on the ruler". If it's not "on the ruler", you won't be able to measure its position, which you need to do. If it's "off the ruler", think carefully how you must modify (change a distance in) your apparatus to get it "on the ruler". What distance should you change? If you do change that distance, you will have to repeat the measurements used to determine the angles for the spectral lines.

After choosing to concentrate on either the left side or the right side, ask your lab partner to position the LED light on each bright spectral line (i.e., each different color), one after the other. This can be done quickly and does not have to be done accurately now since the recorded positions will only be used to make an approximate sketch. On your worksheet, record the positions of the lines along with their colors and order number, and record the position of the gas discharge tube.

Make a sketch showing where each lines is located along the horizontal meter stick, with their approximate distances x from the discharge tube, and label their colors and their orders m. Explain the sequence of colors and orders in terms of equation (9.1).

Part II: Quantitative Study of the Hydrogen Spectral Lines

In the 1880s, the Swedish physicist Janne Rydberg devised a relatively simple, general formula for spectral lines of alkali metal atoms that gave the relationship between the "wavenumbers" (for a wavelength λ in cm, its inverse $1/\lambda$ gives the wavenumbers in units of cm^{-1}) and certain integers and constants determined empirically from observed spectra. It eventually led to a formula called the Rydberg formula [http://en.wikipedia.org/wiki/Rydberg_formula]. A Swiss school teacher, Johannes Balmer, noticed in 1885 a relationship, now called the *Balmer formula*, betweeen the wavelengths of the four visible spectal lines in the spectrum of the hydrogen atom. The equation given below re-expresses Balmer's formula in the formula Rydberg wrote down in 1888 that can be used to determine the R_H from the four visible (so-called Balmer lines [http://en.wikipedia.org/wiki/Balmer_series]) in the hydrogen spectrum:

$$\frac{1}{\lambda_n} = R_H \left[\frac{1}{2^2} - \frac{1}{n^2} \right] n = 3, 4, 5, \ldots.$$
(9.3)

There was no theoretical understanding of nor explanation for either one of these semi-empirical formulae until Bohr's theoretical work in 1913, which contributed to Bohr's winning the 1923 Nobel Prize in Physics. Since Rydberg's formula may be used to determine its value, R_H is called the Rydberg constant. The first four digits of its value are $R_H = 1.097 \times 10^7$ m^{-1}. The relative uncertainty in its current value from "precision measurements" is 6.6×10^{-12}. That puts the uncertainty in the 13th digit of its value! (You may well wonder how such precise measurements can be made. The answer is *with lasers used by very clever and persistent scientists.*)

Though not to 13 digits of precision (!), you are going to measure the Rydberg constant by plotting $\frac{1}{\lambda_n}$ vs. $\frac{1}{2^2} - \frac{1}{n^2}$.

The Lab 9 pretest asks you to calculate the value of d because you need it for the analysis of your data. You obtain the value of d from knowing that the number of grooves per inch for the diffraction grating is 13,400. Calculate the spacing in meters between the grating grooves to get your value of d . Be careful with units! Not only do you have to convert from inches to meters, but you also must notice that the units of grooves per inch is one over length, in *SI units*, m^{-1}.

Move the diffraction grating to ~ 60 cm from the discharge tube. This is the distance y in the earlier figure that defines the geometry of your setup. Record y accurately along with an estimate of its uncertainty.

Place your observing eye very close to the grating and keep that eye centered on it. You should be able to see the full first order spectrum on both sides ($m = +1$ and $m = -1$ for each color) by turning only your eyes and not moving your head. Have your partner place one LED at the position of a spectral line with a given color on the left side and the other LED at the position of the same-color spectral line on the right side of the discharge tube, both lines having the same value of $|m|$, viz., being of the same order. This means that you have observed and marked the position of the $m = +1$ and $m = -1$ spectral line having a given color. Record the position of the first order lines for all three colors, left and right of the tube, but be sure you're doing this now with more accuracy than you did in Part I, which was only "practice". Make sure each LED is placed so that the spectral line in question appears to pass through the center of the LED. Note that the uncertainties are substantial: something like 3 to 4 mm is appropriate, but you should make your own quantitative estimate.

Enter your readings and their uncertainties in the table on your worksheet.

Calculate the difference (left position – right position) and its corresponding uncertainty according to equation (E.6) in *Uncertainty, Error and Graphs*.

Calculate the angle θ from Eq. (9.2) above and the wavelength λ from θ using Eq. (9.1) and the value of d you determined above for your transmission diffraction grating.

Now you need to find the uncertainty for each experimental value of λ .

Propagate the uncertainty for experimental x and y values into the uncertainty for $(x/2y)$ according to equation (E.7) in *Uncertainty, Error and Graphs*. For the uncertainty in each value of λ , assume that it has the same relative uncertainty as the relative uncertainty in the experimental value of $(x/2y)$ used to determine it.

Now convert experimental values of λ into values of $1/\lambda$.

Since the relative uncertainties for λ and $1/\lambda$ are the same (and are the same as the relative uncertainty for $(x/2y)$, to find the absolute uncertainty in a given $1/\lambda$ value you need to take the relative uncertainty in the corresponding experimental value of $(x/2y)$ and multiply it by $1/\lambda$.

Enter your values for $1/\lambda$ and their respective uncertainties into the table below and click submit.

n=3 1/λ= [＿＿＿＿] m^{-1} Δ(1/λ)= [＿＿＿＿] m^{-1}
n=4 1/λ= [＿＿＿＿] m^{-1} Δ(1/λ)= [＿＿＿＿] m^{-1}

n=5 1/λ= [_____] m^{-1} Δ(1/λ)= [_____] m^{-1}

[submit]

The computer plots $\frac{1}{\lambda}$ vs. $\frac{1}{2^2} - \frac{1}{n^2}$.

From the slope of your plot, find an experimental value for R_H. Compare your value for R_H and its uncertainty to the value just below Eq. (9.3) that is given to four significant figures. Are they consistent, i.e., is the difference between your experimental value and the value given below Eq. (9.3) less than the uncertainty you estimate for your measurement? If it is, maybe you want to consider a career in "precision measurements". You could be the one to push the experimental uncertainty for the Rydberg constant into the 14th digit. That would be something to be proud of!