Physics 214 - Lab 3

Atomic Spectra

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NAME: _____

LAB PARTNER(S): _____

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LAB SECTION: _____

TA: _____

DATE: _____
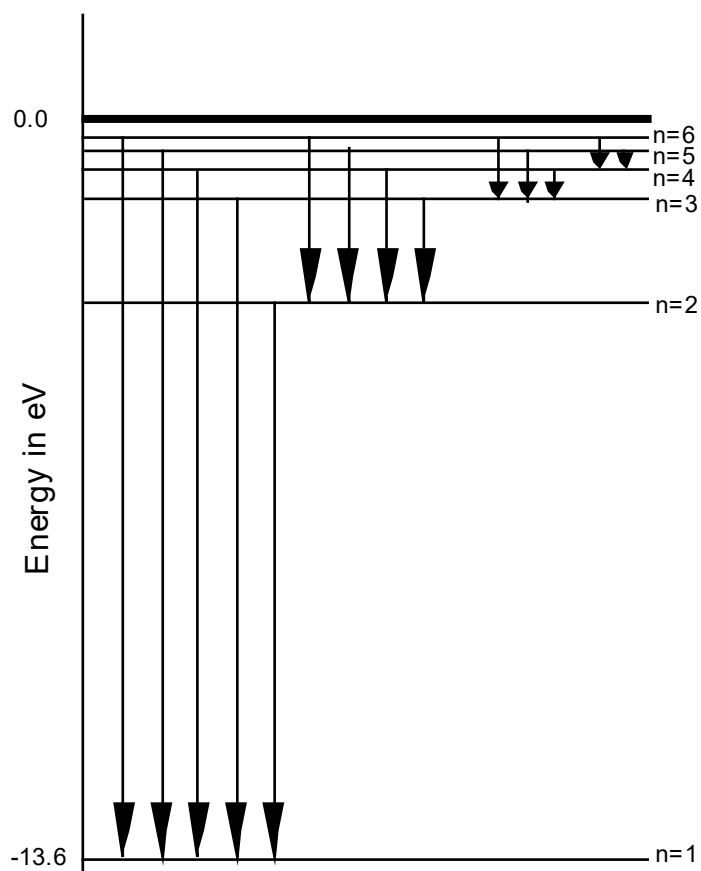
Energy Levels and Transitions in Hydrogen

<u>**Equipment List**</u>

Physics 214 – Experiment 4: Atomic Spectra

Equipment listed assumes "per station", unless otherwise noted.

<u>Needed for all the Investigations</u>
- Colored pencils
- Desk lamp
- Spectrometer with 7500 slit/cm diffraction grating

<u>Investigation 1: Decoding Light</u>
- Sodium light source

<u>Investigation 2: The Hydrogen Atom</u>
- Hydrogen gas discharge lamp light source

<u>Investigation 3: Spectra from Different Sources</u>
- Unknown gas discharge tube light source, labeled with a number. The gas should be helium, krypton, or mercury.
- Fluorescent tube light source

<u>Setup Notes:</u>
- Computers are not used for this lab.

Physics 214 – Lab 3

Atomic Spectra

Investigation 1: Decoding Light

Purpose   • To learn how a diffraction grating can be used to separate different wavelengths of light
• To learn how to use a spectrometer to determine the spectrum of colors from a sodium lamp

Preview: • Observe the spectrum from a diffraction grating.
• Learn to make a quantitative association between wavelength of light and angle of deviation of light through a diffraction grating spectrometer.
• Investigate the spectrum emitted by sodium vapor.

Activity 1-1:   Learning About Diffraction Gratings

1.   Warm up the sodium lamp.
•   Turn on your sodium lamp right now. It takes a few minutes to warm up, and you will be using it soon…

   In this lab we will use the diffraction grating to measure the wavelength of light from a variety of sources of visible light. Figure 1 shows a diffraction grating, and indicates the relationship between angle and the position of intensity maxima. Note that all rays of any wavelength interfere constructively at the center. This point is called the *zeroth-order maximum*.

In general, the relation d sinθ = mλ, m = 0, ±1, ±2, ±3, …. corresponds to constructive interference with *m* = 0 at the center of the screen, and *m* = ±1 is the *first-order maximum*, as shown in Figure 1. Thus, at the first-order maximum, d sinθ = ±1λ. If we know the slit spacing *d*, then from the first bright spot that appears away from the origin, we can calculate the wavelength of light that forms a constructive interference bright spot at that angle.
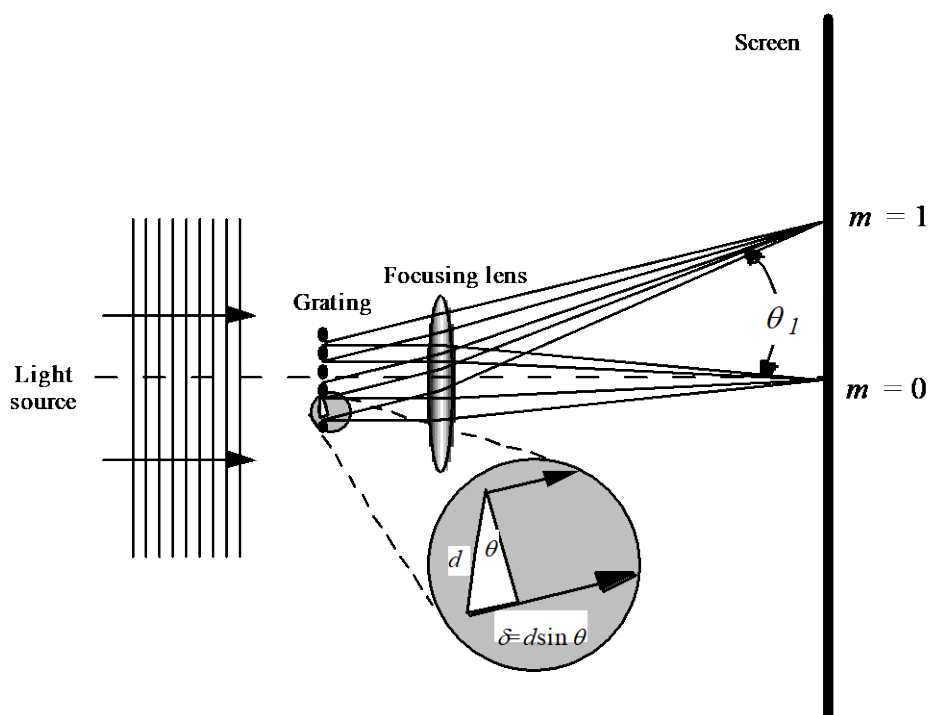
Figure 1. A view of a diffraction grating. Bright spots appear for $m = 0$ and $m = 1$ where constructive interference occurs.

Calculations and Predictions:

You are given a diffraction grating with 7500 lines per cm. You illuminate the grating with 589.3 nm wavelength yellow light. You observe a bright spot along the central axis ($m = 0$) and at several other places (where $m \neq 0$) away from the axis on a screen.

1) What is the slit spacing? $d = $ _____ [m]

2) At what angle will the first-order maximum be found?

$$\theta_1 = \text{_____} \text{[degrees]}$$

☐☐☐   (Make sure you use enough significant figures to get at least two decimal places accuracy for the angle of the first maximum.)

The instrument you will use to distinguish spectral emission lines of different wavelengths is known as a diffraction grating *spectrometer*. You will use it to analyze the emission lines from low-pressure, gaseous samples of various atomic elements contained in sealed glass tubes – known as gas electric-discharge tubes. A strong electric potential is placed across electrodes at the ends of the tubes. The voltage generates an electric current (of electrons) flowing through the gas. Some of these electrons collide inelastically with the atoms in the gas, sending those atoms into excited states. The atoms then emit light as they fall from their excited states. Since the energy levels of the atom are quantized, the light emitted is of fixed and characteristic frequencies.

IMPORTANT: Do _not_ put your fingerprints on the grating and do _not_ burn yourself on the various gas discharge lamps!!!
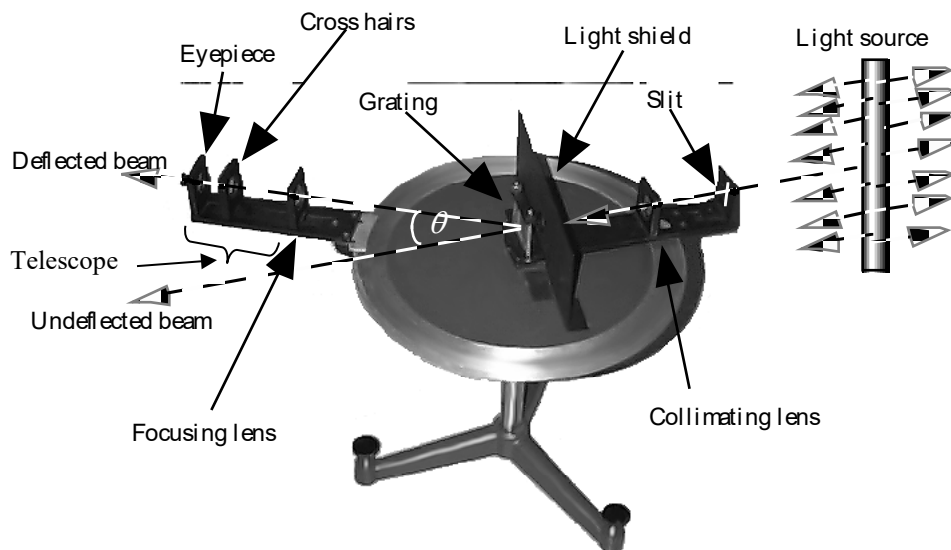

Figure 2. The spectrometer

2. Set up the diffraction grating spectrometer apparatus.
- Figure 2 is a diagram of the diffraction grating spectrometer that you will be using. Position your sodium lamp so that its light passes through the slit and the collimating lens.
- Adjust the position of the cross hairs so that they are in focus when viewed through the eyepiece; you might want to use the desk lamp to illuminate them.
- Line up the telescope with the slit and collimating lens and adjust the position of the focusing lens until the slit as viewed through the eyepiece gives a sharp image. If you cannot get it into sharp focus, you may have to move the position of the slit slightly.

You will measure the angle of deviation of light passing through the grating using the angular scale scribed along the outside edge of the circular spectrometer plate. In order to accurately measure between the marks of the scale, we make use of a *vernier scale* attached to the telescope device.
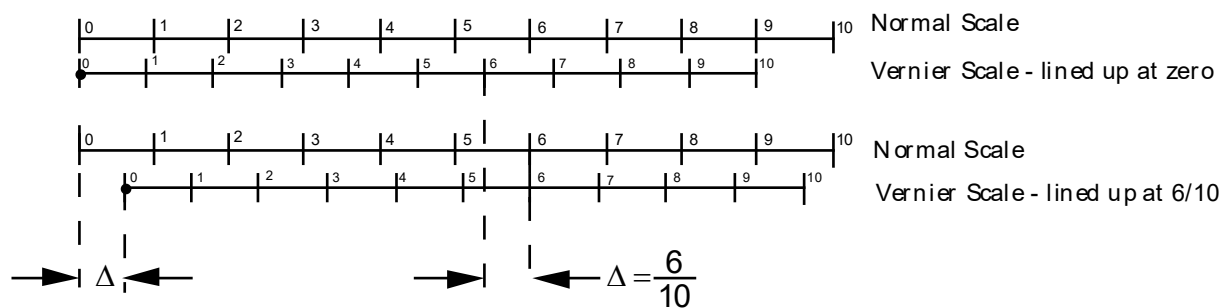
Figure 3. The Vernier Scale

As shown in Figure 3, measurements are made using two scales—a normal scale and a shorter vernier scale. The spacing of the marks of the vernier scale is 9/10 of the normal scale. As is depicted, if the vernier scale is moved an amount Δ, each of the marks is also moved Δ, and the one that lines up with the mark on the normal scale indicates how large Δ is. Since the sixth mark on the vernier lines up with a mark on the normal scale in Figure 3, we know that $\Delta = 0.6$. The vernier is used to measure fractions of the markings on the regular scale with much better accuracy than would be possible by estimating or by subdividing the regular scale with finer markings.
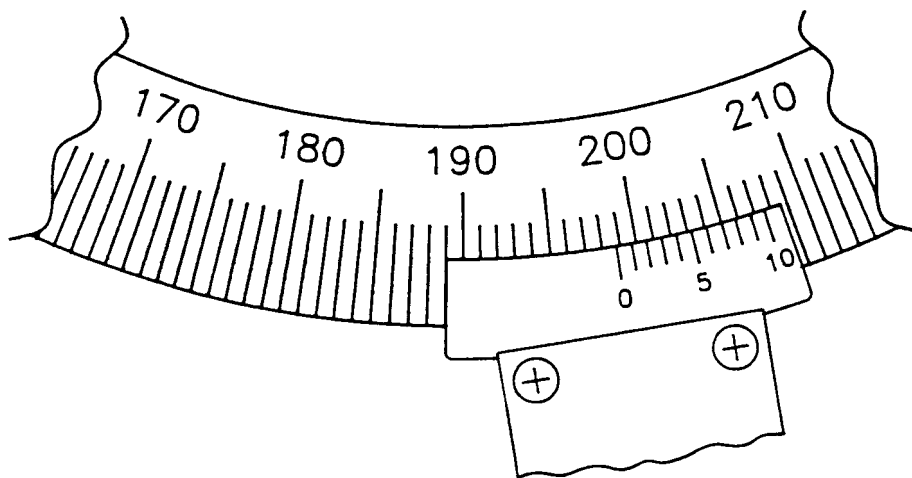

Figure 4. Reading the vernier scale on your spectrometer

Q1: What angle is indicated by the scale in Figure 4? Remember, the reading is taken from where the 0 on the vernier is located, and the fractional reading is taken as shown in Figure 3.

_____

Ask your TA to verify that you properly understand reading a vernier scale.

We will measure the angular position of the first-order maximum on *both* the right and left sides of the zeroth-order maximum, thereby eliminating the need to know the offset of the vernier scale with respect to the "straight-through" beam associated with the zeroth-order maximum, resulting in a more accurate measurement. As depicted in Figure 5, we will measure θ_L and θ_R, calculate the average of these two angles. This offset cancels in the averaging process!

3. Measure some angles:

• Check that the plane of the diffraction grating is parallel with the slit face.
• Begin with the telescope aimed directly at the undiffracted (i.e., straight through) beam. If necessary, carefully adjust the position of the sodium light source so that you achieve maximum brightness through the slit.
• Now inform the lab TA that you are ready to have the room lights turn off. They will be off for the remainder of this lab. Use your desk/table lamp to help you illuminate/read the vernier scale on the diffraction grating spectrometer.
• Move the telescope to the right until you observe the first-order yellow spectral line. It is actually a *pair* of very closely spaced lines, but you will probably not be able to discern them. Why? (Hint: think about finite source width…)
• Measure and record below the position of the first-order yellow spectral line as read off the vernier scale, on the right, $\theta_R^{\text{Vernier}}$.
• Now measure and record below the position of the first-order yellow spectral line as read off the vernier scale, on the left, $\theta_L^{\text{Vernier}}$.

Note that: $\theta_R = \theta_R^{\text{Vernier}} - 180.0° = $ _____ [degrees], and

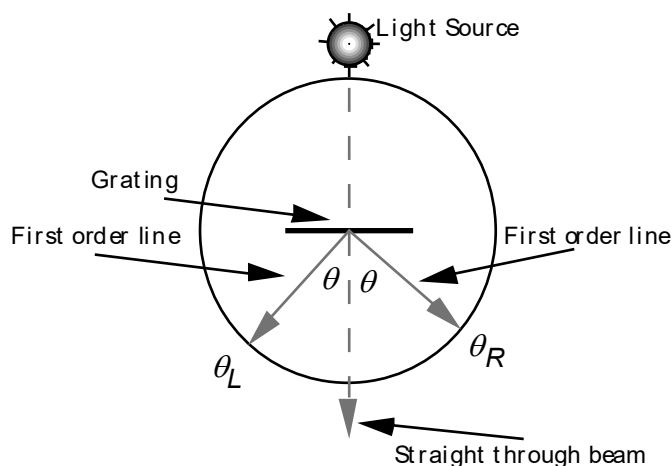$\theta_L = 180.0° - \theta_L^{\text{Vernier}} = $ _____ [degrees].

Figure 5. Measuring angles

4. Calculate the (average) value of the deflection angle, θ for the first-order yellow spectral line of sodium:

$$\theta = {}^1/_2\,(\theta_R + \theta_L) = {}^1/_2\,(\theta_R^{\text{Vernier}} - \theta_L^{\text{Vernier}}) = \underline{\hspace{1cm}} \text{ [degrees]}$$

5. Please turn off the sodium lamp now.

Q2: Given the average value of the sodium doublet wavelength, $<\lambda> = 589.3$ nm, does the measured angle θ agree with the angle predicted by the d sinθ = mλ formula? Compute a percentage difference, 100(data-theory)/theory.

_____

_____

Investigation 2: The Hydrogen Atom

Purpose: • Learn how quantum mechanics describes the quantized energy levels of the
hydrogen   atom.

Preview: • Predict the wavelengths of light produced by various level-to-level transitions in
this atom.
• Using the spectrometer and a hydrogen lamp, measure the emission spectra in the
visible region and compare it to theory

Activity 2-1:   The Quantized Energy Levels of the Hydrogen Atom

In a hydrogen atom, the electron can occupy only certain states, which are termed the allowed
states. The energies for the electron in the allowed states are given by:

$$E_n = \frac{-13.6}{n^2} \ [eV]$$

with $n = 1$ corresponding to the ground state, $n = 2$ the first excited state, and so on. The
negative sign ensures that lower quantum numbers have lower energies, and that unbound (i.e.
free) electrons have positive energies. (These are the energies predicted by the Bohr model. The
energies agree with experiment even though the Bohr model is not correct in detail. The full
quantum theory developed later also leads to the same expressions for the allowed energies in a
correct quantum description of the hydrogen atom.)

Calculations: Calculate the first **six** energy levels for the hydrogen atom. These will be used
below to compute the spectral lines.

$E_1 = $ _____ [eV]

$E_2 = $ _____ [eV]

$E_3 = $ _____ [eV]

$E_4 = $ _____ [eV]

$E_5 = $ _____ [eV]

$E_6 = $ _____ [eV]

 In these orbits the motion of the electron is stable. It does not lose energy by radiating
electromagnetic waves. When the electron jumps from one orbit to another, it emits or absorbs
a photon whose energy equals the difference in energy levels of the atom. The energy of the
photon is given by:

$$E_\gamma = hf = hc/\lambda$$

where $h = 6.626 \times 10^{-34}$ J·s, $c = 2.998 \times 10^8$ m/s and $hc = 1240$ eV-nm.

Observations of emitted photons do not, of course, correspond to electron energy levels directly but to *differences* in electron energy levels:

$$E_\gamma = \Delta E = E_{n_i} - E_{n_f} = -13.6 \left(\frac{1}{n_i^2} - \frac{1}{n_f^2} \right) \ [eV]$$

For example, for a transition of an electron from the $n = 3$ (2nd excited state) to the $n = 1$ (ground state), the photon energy, E_γ = the electron energy difference, $\Delta E = E_3 - E_1 = 12.09$ eV. Check this value with your calculation(s) above.
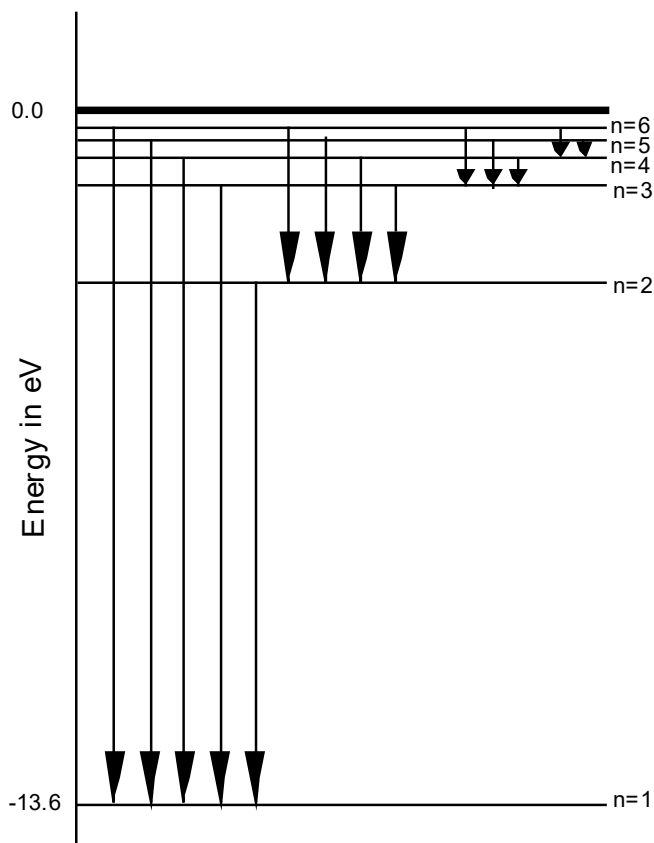

Figure 6. Hydrogen energy levels

Thus, a photon of energy $E_\gamma = 12.09$ eV has a wavelength, λ of

$$\lambda = \frac{hc}{E_\gamma} = \frac{hc}{\Delta E} = \frac{(6.626 \times 10^{-34} \, \text{J} \cdot \text{s})(2.998 \times 10^8 \, \text{m/s})}{(12.09 \, \text{eV})(1.602 \times 10^{-19} \, \text{J/eV})} = \frac{1240 eV - nm}{12.09 eV} = 102.6 \text{ nm}$$

Alternatively, dividing the above formula for E_γ by hc gives the following relation:

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

where $R = 1.097 \times 10^7$ m^{-1}, known as the Rydberg constant. Note that this formula gives the reciprocal of the wavelength, $1/\lambda$, in m^{-1}.

Predictions:

For hydrogen, calculate some of the energies and wavelengths of some of the transitions that correspond to the lines drawn in Figure 6. For each one, indicate if it is in the ultraviolet (UV) or the infrared (IR) region of the electromagnetic spectrum; if it is in the visible region, record the color. (See Figure 7 for a chart of the visible spectrum.)

Region of EM spectrum

Transitions to the $n = 1$ (ground state):

$n_i = 2, n_f = 1$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

$n_i = 3, n_f = 1$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

$n_i = 4, n_f = 1$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

Transitions to the $n = 2$ (1st excited state):

$n_i = 3, nf = 2$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

$n_i = 4, n_f = 2$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

$n_i = 5, n_f = 2$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

$n_i = 6, n_f = 2$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

Transitions to the $n = 3$ (2nd excited state):

$n_i = 4, n_f = 3$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

$n_i = 5, n_f = 3$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

$n_i = 6, nf = 3$ $E_\gamma = $ _____ [eV] $\lambda = $ _____ [nm]   _____

The hydrogen atom transitions in the UV light region are collectively known as the Lyman series; the transitions in the visible light region are collectively known as the Balmer series and the transitions in the IR light region are collectively known as the Paschen series, in honor of the physicists who first discovered them.

Q3: Which of the above transitions are in the visible portion of the electromagnetic spectrum? (List each transition in the form $n_i \rightarrow n_f$, such as "$5 \rightarrow 4$." For each such transition, draw on Figure 7 (on the following page) the corresponding emission line with an appropriately colored pencil.
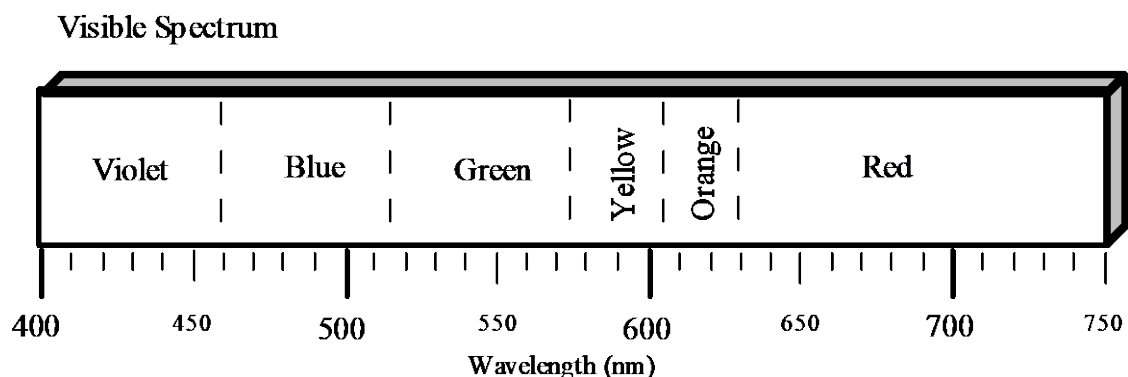
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Figure 7. The visible spectrum

Activity 2-2: Measuring the Hydrogen Atom Emission Lines

Using the technique you developed in Investigation 1, calculate the predicted angles at which the first-order diffraction maxima will appear in your diffraction grating spectrometer, corresponding to the first four hydrogen atom emission lines that are in the visible part of the electromagnetic spectrum.

Predictions:

Predict the angle(s) of deviation, θ of the first-order diffraction maxima associated with the first four *visible-region* (Balmer-series) spectral lines for hydrogen, from the relation $d \sin\theta = \lambda$. (Use the line spacing, d from your first calculation.)

	H-Atom Transition	Predicted Angle, θ [degrees]
1.)	_____	_____
2.)	_____	_____
3.)	_____	_____
4.)	_____	_____

Experimental Procedure:

1. Set up the light source: Set the hydrogen light source directly in line with the collimator slit and ensure the slit as viewed through the eyepiece is in sharp focus.

2. Find the *first-order* hydrogen emission lines: Look for the four spectral lines that were predicted to be visible by slowly rotating the telescope until each is in line with the cross hairs. Note that there should be a red, a blue-green, and two violet lines. The second violet line might be extremely difficult to see since it is almost outside the range of human vision. The lab room must be kept very dark and your eyes dark-adapted to observe this line!

3. Record your measurements in the following box: Record the two angles θ_L and θ_R for each of the four visible light emission lines for hydrogen. Use your procedure from Investigation 1 to find the (averaged) deviation angle θ for these spectral emission lines; record them in Table 1.

Your data and calculations:

Transition	Predicted angle, θ [degrees]	θ_R [degrees]	θ_L [degrees]	θ [degrees]

Table 1. Predicted and measured deviation angles for the four visible lines in the hydrogen spectrum

Q4:   Did your predictions agree with your observations? If not, why?

_____

_____

Investigation 3: Spectra from different sources

Purpose: • How to determine an element from its spectrum.
                      • How the spectrum from a source is dependent on the way the light is generated.

Preview: • Identify an unknown element by means of spectrometry.
                      • Examine spectra from other sources, including fluorescent and incandescent
bulbs.

Activity 3-1:   An Unknown Gas Tube…

    We will now turn away from our Earth-bound laboratory and take a moment to contemplate the stars. One of the most important questions in astronomy and astrophysics is, "What are the stars made of?" Knowing the composition of a star can tell us much about its origin, such as how old it is and from where it might have come.

    How does one find out things about stars that are thousands of light years away from us? From our previous investigation, we know what the emission spectrum of hydrogen looks like. What about other atoms? It turns out that each species of atom produces different and unique spectral lines. In essence, we can "fingerprint" atoms by examining their emission spectra.

    It is important to note that atoms can *absorb* the same wavelengths of light that they *emit*. The hot interior gases of a star emit a continuous spectrum of light, but the cooler surrounding gases have discrete spectra. Astronomers usually look for places in a star's spectrum where the light is "missing" – this is known as the <u>absorption</u> spectrum. These "dark" lines, or regions of the electromagnetic spectrum where light is <u>absent</u>, indicate the narrow spectral lines of light absorbed by the star's atmosphere. For example, if hydrogen was present in a star's atmosphere, we would notice four dark bands in the star's spectrograph at exactly the same places where we saw the four bright bands of the Balmer Series (transitions to n = 2).

    In order to find out what something is made of, we simply measure the spectrum of the light that is emitted from that object and match its spectral lines with known spectral lines from the catalog of all atomic spectra. Thus, for a star, although we cannot see inside it, we can determine what elements are present in its atmosphere, and that information can give us some clues about what is inside the star. Here on earth, optical spectroscopy is an invaluable tool for chemistry, biology, medicine, engineering, and physics.

    It is now *your* turn to do some investigations. At your station is a gas discharge tube containing an *unknown* gas. Your task is to *identify* the gas by measuring the spectral lines present and comparing them to a "table" of spectral lines associated with known elements.

Experimental Procedure:

1. Set up the unknown gas discharge lamp/unknown gas sample:
*   Find the number on the unknown gas discharge lamp/light source.
*   Position the unknown sample discharge tube in front of the slit of the diffraction grating spectrometer in the same way that you placed the hydrogen gas discharge sample.
*   Plug in the unknown sample light source and make sure that the light from this tube is going straight through the slit. You can check this using the eyepiece and by making sure that the light coming from the slit and passing through the lenses is as bright as possible.
*   Record the number of your source. Unknown source number = _____

2. Take some data:
*   Using the same method as before, swing the eyepiece to the first-order set of spectral lines to the right of the center position.
*   Position the cross hairs on one of the *brightest* lines of the spectrum. If the line is blurry or too close to other lines, you may need to have another group member verify that the cross hairs are on the correct line.
*   Record the color of the line and measure & record its angle, θ_R in Table 2 below. Use the vernier scale to obtain good precision in the angle measurement!
*   Swing the eyepiece to the first-order set of spectral lines just to the left of center and find the spectral line that has the same color as the one you just observed on the right. Record its angle, θ_L on the same line in Table 2.
*   Repeat this process for several (3-4) brightest lines in the spectrum.

In a real application, you would want to measure as many spectral lines as possible, in order to uniquely identify the composition of the unknown gas.

3. *Please turn off and unplug the unknown sample light source as soon as you have completed all of the angle measurements!!!*

4. Analyze the data:
*   For each spectral line of data, calculate the angle θ by from the average of θ_R and θ_R.
*   Using the formula $d \sin\theta = \lambda$, calculate the wavelength for each spectral line (in nm).

Line #	Color	θ_R [degrees]	θ_L [degrees]	θ [degrees]	λ [nm]
1					
2					
3					
4					

Table 2. Data from an unknown source

5. Look at the data in a new way:
• In the blank box in Figure 8, draw one line for each wavelength you have measured.
• Compare the spectral lines of your unknown element with the lines of the known elements shown in Figure 9 (on page 18), and try to determine the identity of your unknown sample. (One good trick is to superpose your spectrum on the others, and hold them up to the light. You should have enough lines to have _complete_ confidence about your conclusion; you may need to measure a couple more spectral lines, if they are present.)
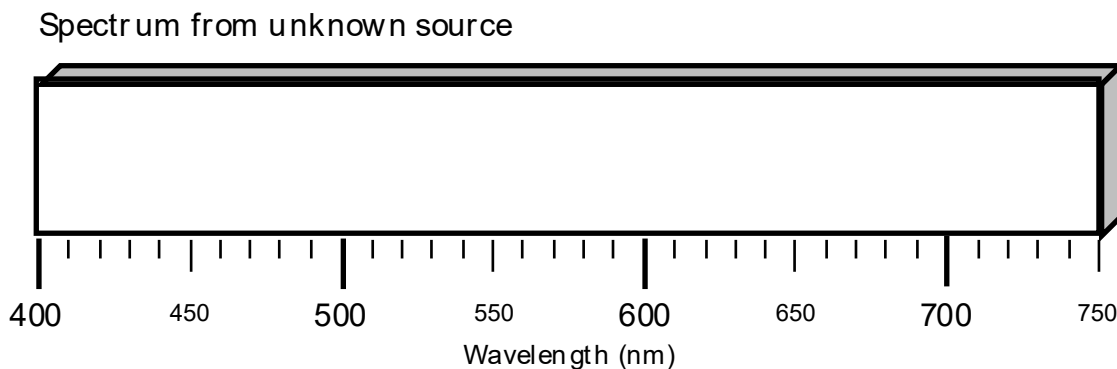
Spectrum from unknown source

Figure 8. The unknown element's spectrum

6. See how you did:
• We determined our unknown light source to be the element: _____.
• Ask your TA what the element in the unknown light source was. Record the element below.

       Our unknown light source was actually the element: _____.

Q5:   Were you able to determine the element in the source correctly? What characteristics allowed you to identify the source? How did you know it wasn't one of the other elements?

_____

_____

_____

_____

Q6:   What would you have observed if there were more than one element emitting in the lamp?

_____

_____

_____

Activity 3-2:   Fluorescent and Incandescent Lights

   Thus far, you have observed the spectra of various atomic gases in various gas discharge lamps. What would we expect if we analyzed the light spectrum of a common fluorescent light?

Prediction: The emission spectrum of a fluorescent light bulb will be made up of (circle one):
A.) Discrete lines, such as those seen in hydrogen gas emission spectra.
B.) A continuous band of colors, like a rainbow, or:
C.) Some combination of (A) and (B).

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1. Test your prediction using a fluorescent light bulb:
• Carefully move the source from the previous activity away from the spectrometer slit, and place the fluorescent tube fixture as close as possible to the slit.
• Use the spectrometer to scan through the spectrum. You need not record any quantitative measurements, but make sufficient observations to support or refute your above prediction!

Q7:   Did your observations agree with your prediction? Point out any differences.

_____

_____

_____

Q8:   Most fluorescence tubes contain small amounts of mercury vapor at low pressure. Based on your spectral analysis, what evidence can you give to support this statement?

_____

_____

_____

Fluorescence is the process of converting high[er] frequency electromagnetic radiation to lower frequency radiation. For example, an atom absorbs a UV photon, and emits another in the visible light region. A fluorescent tube is coated on the inside of the glass with thin layer of material possessing a very large number of discrete quantum states with transitions in the visible part of the spectrum. It can absorb a UV photon and emit numerous visible photons as it de-excites.

Q9: With the knowledge that one of the electron transitions in a mercury atom results in the emission of an *ultraviolet* photon, summarize how a fluorescent light can give white light, an apparently continuous spectrum.

_____

_____

_____

Q10: How does the spectrum from an incandescent bulb (a normal light bulb with a heated tungsten filament) compare with the other spectra that you have observed? (Look at it with your spectrometer.)

_____

_____

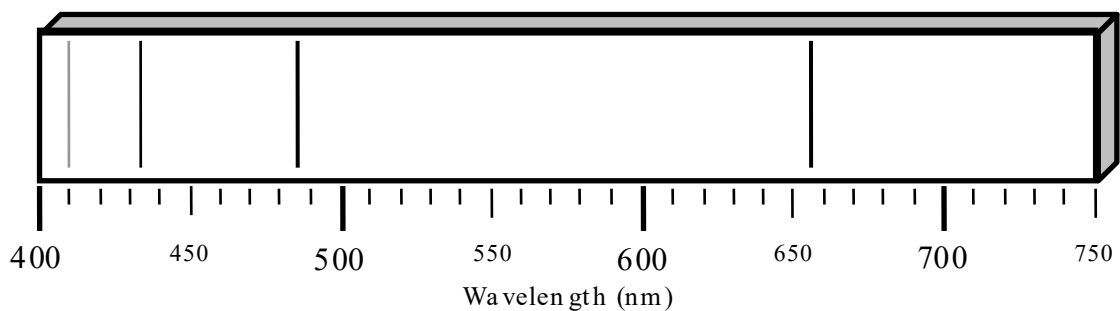_____

Atomic Hydrogen

Wavelength (nm)

Figure 9. Examples of the emission spectra from several atomic sources.
Only some of the brightest lines are shown. Darker lines are brighter.

Helium Gas

Wavelength (nm) (nm)

Mercury Vapor

Wavelength (nm)

Krypton Gas

Wavelength (nm)