SP212 Lab: Diffraction Gratings
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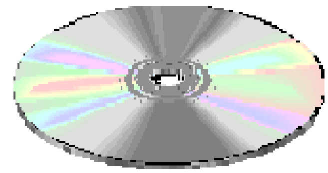
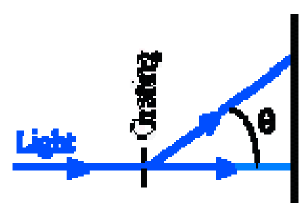


Diffraction Gratings

Introduction: A *diffraction grating* consists of a large number of equally spaced parallel slits. When light is incident on a grating, the light from each slit diffracts and will interfere with the light from the other slits. When the conditions for constructive interference for a given wavelength are satisfied, that color is enhanced and hence observed.
A CD has a spiral, grooved track (usually composed of pits). For a small region on the surface of a CD, the grooves create an approximately parallel pattern. Consequently, the light reflected from a small portion of the surface diffracts as if from approximately parallel sources. This results in the colored patterns you see when viewing white light reflected from a CD. Because of this, an ordinary CD is a *reflection* grating.
It is straightforward to construct *transmission* gratings, where the interference occurs due to transmitted light. A CD will also act as a transmission grating if the reflective coating is removed.
In this lab, we will first establish the properties of a laboratory transmission grating. We will then show that a CD behaves similarly both in transmission and reflection and we will make measurements to determine the distance between the grooves. Next, we will use the laboratory transmission grating to analyze the light emitted by hydrogen atoms and compare the results with that predicted by theory. Finally, we will study the light emitted by helium atoms and a "typical" light bulb.

Theory: If light of wavelength λ is incident on a grating along the perpendicular to the surface of the grating, constructive interference occurs when



$$\sin\theta = \frac{m\lambda}{d} \quad (m = 0, \pm1, \pm2, \pm3,...) \qquad (1)$$

where θ is the angle at which constructive interference occurs (relative to the perpendicular), *d* is the separation distance between the slits in the diffraction grating, and *m* is an integer called the order of the pattern.

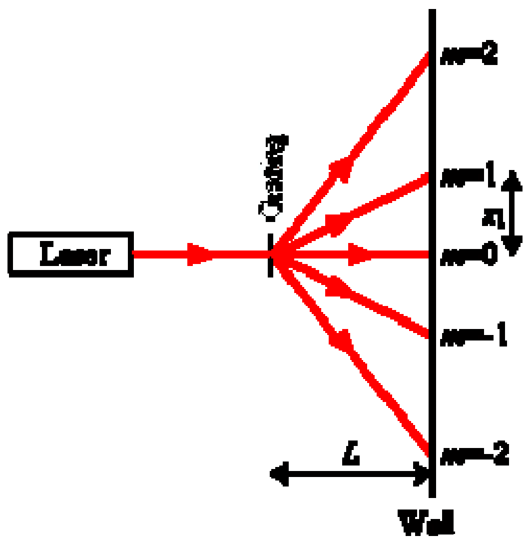
If light of a known wavelength is incident on a grating, *d* can be determined from measurements of the angles where bright light is observed. Conversely, if a grating of known value of *d* is used, the wavelength of the light can be determined from measured angles. We will use both approaches in this lab.

Laboratory Transmission Diffraction Grating Our first experiment is to determine the value of d for our laboratory transmission grating. The wavelength of the dominant, red light from a helium-neon laser is $\lambda_{\text{He-Ne}} = 632.8$ nm.

Warning! *Do not look into the laser beam or shine the laser beam into anyone's eyes. Permanent vision damage can result.*

Procedure

1. Set up the equipment as shown in the next diagram. (This diagram is a top view of the required setup.) The grating should be at the end of the table and the laser should shine through it so that spots are created on the wall. The diffraction grating should be parallel to the wall and the laser beam should be perpendicular to both the diffraction grating and the wall. The best way to verify your setup is to check the pattern on the wall. If the pattern on the wall is symmetric and oriented horizontally, then your setup is correct. If your pattern is symmetric, but oriented vertically, then you probably have the transmission grating rotated 90 degrees.



2. Measure the distance from the grating to the wall and record the value as $L_{\text{Grating-Wall}}$ in the space provided.

R1: $L_{\text{Grating-Wall}}$ = ______ ± ______ m

3. Measure the distances from the central maximum (the bright spot at $m = 0$) to each of the other points of constructive interference.

R2: Record the values as x_m in the next table (as an example, x_1 is shown in the preceding diagram).

4. Use the values of x_m and $L_{\text{Grating-Wall}}$ to calculate the values of θ.

R3: Record the values of θ in the table.

R4: Show a sample calculation of θ.

R5: Why are the third order constructive interference spots ($m = \pm 3$) not visible and therefore not included in the table? (Hint: Try calculating θ for the 3rd order spot.)

m	x_m (meters)	θ (degrees)	$d_{Grating}$ (meters)
+1	±	±	±
-1	±	±	±
+2	±	±	±
-2	±	±	±

5. Use eq. (1) to calculate the value of $d_{Grating}$ for each angle.

R6: Record the values in the table. Ensure your recorded values are in the units shown in the column headings.

6. Decide on your best value of d (average value, etc.) and record it as $d_{Grating,best}$ in the space provided.

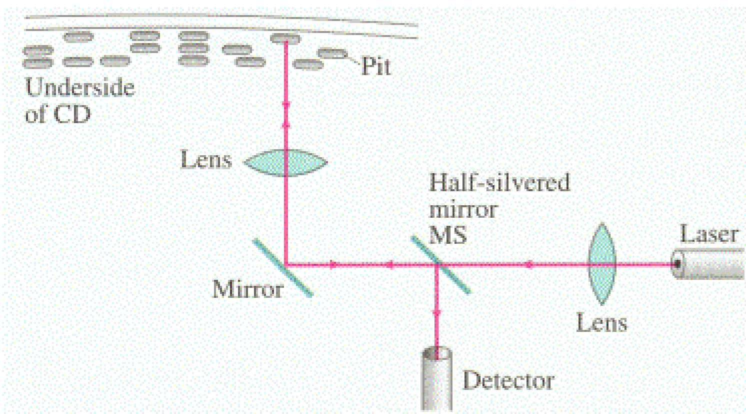
R7: $d_{Grating,best}$ = ± m

7. There may be an accepted value of d (or $1/d$) written on the grating. If there is an accepted value, record the value as $d_{Grating,accepted}$ in the space provided.

R8: $d_{\text{Grating,accepted}}$ = [ ] ± [ ] m

Save your Responses

Compact Discs The next sketch and following simplified explanation of the operation of a CD are taken from, *Physics*, D. C. Giancoli, Prentice Hall, New Jersey, 2000, page 1022. "The fine beam of a laser, focused even more finely with lenses, is directed at the undersurface of a rotating compact disc. The beam is reflected back from the areas between pits but reflects much less from pits. The reflected light is detected as shown, reflected by a half-reflecting mirror MS. The strong and weak reflections correspond to the 0s and 1s of the binary code representing the audio or video signal." (Interesting additions to this discussion are that the pit depths are chosen to give destructive interference thereby enhancing the weak reflections and there is a diffraction grating in the laser beam path where the diffracted light is used to track the spiral groove.)



The parallel arrangement of the pits, mentioned in the **Introduction** to this write-up, should be apparent from the sketch. The regions *between* the approximately parallel pits give rise to the approximately parallel sources of diffracted light that enable typical CDs to act as reflection gratings. However, a manufacturer of CDs (Dering Corporation, Lancaster, PA) has been kind enough to supply us with CDs that are not "mirrored", yet still contain digital information (the pits). Such incomplete CDs are sometimes used as packaging for CD-RWs. Our second experiment will be to use a non-mirrored CD as a transmission grating to determine the spacing between the rows of pits. Our third experiment will be to verify that a standard, reflecting CD also acts as a diffracting grating.

Procedure - Transmission

Note: The CD is not as efficient as the laboratory grating, so the spots produced by the grating (positions of constructive interference) will be more difficult to see. To make it easier to find the spots, start by placing a piece of white paper directly behind the CD so you can easily see each spot, and then "walk" each one out to the wall to find that spot on the wall.

1. Replace the laboratory transmission grating with the transparent CD. The CD and the wall should be parallel to one another and perpendicular to the laser beam

2. Shine the laser through the top of the CD. Now shine the laser through the left or right side of the CD.

R9: Give a qualitative explanation of the results. Explain which way the light diffracts (spreads) relative to the orientation of the grooves. Does the diffraction pattern occur parallel or perpendicular to the groove direction?

3. Measure the distance from the CD to the wall and record the value in the space provided.

R10: $L_{\text{CD-Wall}}$ = ______ ± ______ m

R11: Measure the distance from the central maximum (bright center spot) to each first order diffraction maximum and record these values as x_m in the table below.

m	x_m	θ (degrees)	d_{CD} (meters)
+1	±	±	±
-1	±	±	±

Save your Responses

R12: Use the values of x_m and $L_{\text{CD-Wall}}$ to calculate the values of θ and record the values of θ in the table above.

R13: Calculate d_{CD} and record the values of d_{CD} in the table above.

R14: How do the values of d_{CD} compare with $d_{Grating}$ from R7 or R8? Is the spacing of the grooves on the CD greater, less than, or comparable to the laboratory grating?

Our goal for the third experiment is to study the interference pattern from a standard CD.

Procedure - Reflection

1. Reposition the laser so that the laser beam reflecting off a reflective CD will strike a wall or the ceiling where you can see the pattern.

2. Position a standard CD so that it reflects the laser beam safely.

R15: Describe the results qualitatively.

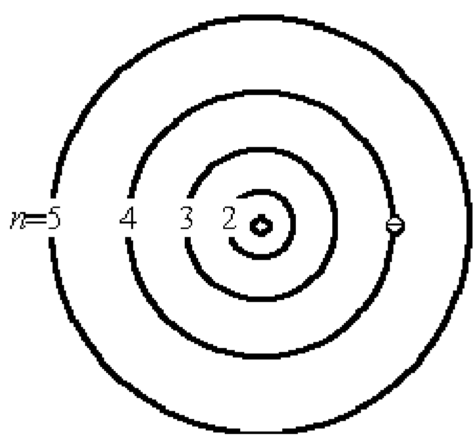
Save your Responses

Hydrogen The fourth experiment is to determine the wavelengths of (visible) light emitted from a hydrogen atom.

Theory The semi-classical theory known as the Bohr model of hydrogen is comprised of an electron circulating in orbit around a proton. As you may have heard, only certain orbits are allowed. The lowest energy state (orbit) of the electron is characterized by $n = 1$ and the orbit has a radius of

$$r_1 = 0.529 \text{ x } 10^{-10} \text{ m.} \qquad (2)$$

Higher energy states of the electron are characterized by $n = 2,3,...$ and the radii are $r_n = n^2 r_1$. An electron circulating in the $n = 4$ orbit is shown in the next diagram.

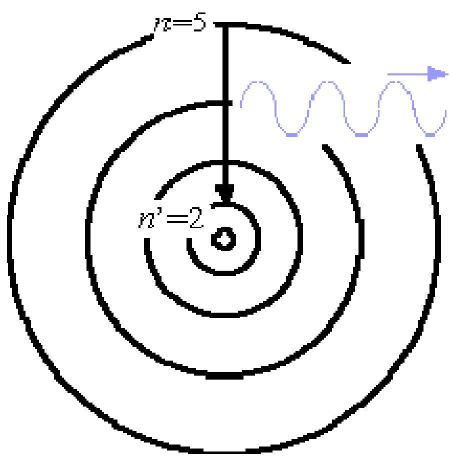


Further, if an electron transitions from a high energy level to a low energy level, the atom must emit energy. If the change in energy of the electron is in a special range, that energy takes the form of visible light. The Bohr theory enables us to predict the wavelengths of the light that are emitted from the hydrogen atom. For us, the important result of the theory is that for a one-electron atom (or one-electron ion) the wavelengths are given by

$$\frac{1}{\lambda} = \frac{Z^2 e^4 m}{8 \epsilon_o^2 h^3 c}\left(\frac{1}{(n')^2} - \frac{1}{(n)^2}\right) \qquad (3)$$

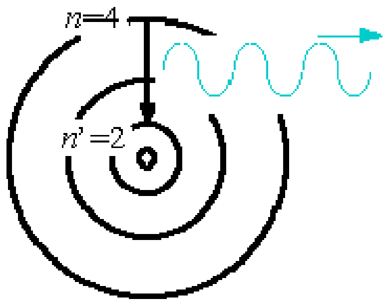
In eq. (3), n designates the orbit for the higher (initial) energy level of the electron and n' is the value for the lower (final) energy level. Z is the number of protons in the nucleus. For our experiment, $Z = 1$ since we will be studying hydrogen. The only parameter in eq. (3) that we have not studied this semester is Planck's constant, $h = 6.626 \times 10^{-34}$ J s . Planck's constant is a "universal" constant that is very important in modern physics. The point of all this is to show that the wavelengths of the light emitted from a hydrogen atom can be predicted using some of the quantities that we have been learning about this semester such as ϵ_o (the permittivity of vacuum), m (the mass of the electron), e (the charge on the electron) and c (the speed of light). This was a very important achievement of physics when it was formulated in 1913.

We will now use eq. (3) to predict the wavelengths of the light that should be emitted from hydrogen atoms. For each of the transitions shown below, calculate the predicted wavelength of light and record each result in the space provided. Show your calculation of the wavelength of light emitted for a $n = 5$ to $n' = 2$ transition.

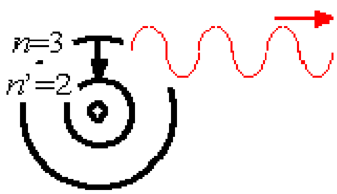


R16: λ_{52} = nm

R17: Calculation of λ_{52}:



R18: λ_{42} = [ ] nm

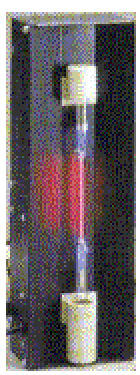


R19: λ_{32} = [ ] nm

[**Save your Responses**]

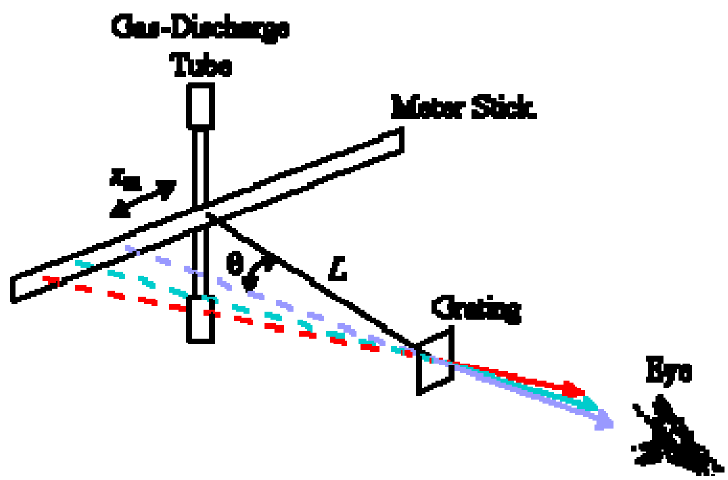
We will now attempt to observe this light and measure the wavelengths in order to verify the predictions of the Bohr model.

Experiment The hydrogen is contained inside a glass tube with an electrode at each end. This is referred to as a gas-discharge tube. A typical tube (and enclosure) is shown in the next image.



When a high voltage (the tube operates at about 5000 V) is applied across the electrodes (top and bottom of the tube), the hydrogen atoms inside the tube emit light. The reason they emit light is that free electrons in the tube acquire kinetic energy because of the voltage (i.e., the free electrons are accelerated by the corresponding electric field). Those electrons collide with atoms and transfer some or all of their kinetic energy to the hydrogen atoms so that electrons are either raised to higher energy levels (excited states) or become free. That the voltage (5000 V) is high enough may be obvious from the fact that the ionization energy of hydrogen is 13.6 eV. This implies that if an electron moves freely through a voltage of about 13.6 V, it can gain enough kinetic energy to eject an electron from an atom. Consequently, because of the voltage, there is enough energy available to place atoms into all possible energy levels. Visible light is emitted when the electrons with $n \geq 3$ transition to $n' = 2$.

We can use the laboratory transmission grating to separate the light into the individual wavelengths (colors), called a spectrum. This is, of course, based on eq. (1) since for a fixed slit width (d), constructive interference occurs at different angles (θ) for different wavelengths (λ). The easiest way for us to do this experiment is shown in the next diagram.



1. Set up the meter stick, hydrogen gas discharge tube and grating as shown in the diagram. Due to the extended length of the gas discharge tube, we will observe bright lines rather than spots. Also, rather than projecting these bright lines (which really aren't so bright) onto a wall, we will instead project the bright lines directly into your more sensitive eye.

2. Turn on the tube (be sure it's labeled hydrogen not helium!) and observe the hydrogen spectrum by placing your eye very close to the grating. If your setup is correct, you will see multiple color lines that appear to be emanating from locations along the length of the meter stick. (A distance between the meter stick and the grating of about 50 cm works well.) We will measure the distance between the grating and meter stick, L, and use the measurement scale on the meter stick to determine x_m. Because of the similar angles, these indirect measurements enable us to calculate the constructive interference angles for the hydrogen wavelengths that are being projected onto your retina.

Only the three most prominent (longest) wavelengths of light from the hydrogen atom are shown in the diagram. To be consistent with our textbook they are referred to as red, blue-green and blue. However, the blue line is more properly referred to as violet. The reason that it should be referred to as violet will be apparent from the color you perceive when viewing the spectrum.

3. Measure the distance from the grating to the meter stick and record the value in the space provided.

R20: $L_{\text{Grating-Meter Stick}}$ = ______ ± ______ m

R21: Measure the values of x_m for the various colors and record the values in the table below.

R22: Use the values of x_m and $L_{\text{Grating-Meter Stick}}$ to calculate the values of θ and record the values in the table.

4. If a value of $d_{\text{Grating,accepted}}$ is available (response R8), use it and the results in the table and eq. (1) to calculate the observed wavelengths, $\lambda_{\text{experimental}}$. If a value of $d_{\text{Grating,accepted}}$ is not available, use $d_{\text{Grating,best}}$ (response R7) in your calculations.

R23: Record the values of $\lambda_{\text{experimental}}$ in the next table.

R24: Show a sample calculation of $\lambda_{\text{experimental}}$.

Color	m	x_m (meters)	θ (degrees)	$\lambda_{\text{experimental}}$ (nm)	$\lambda_{\text{accepted}}$ (nm)
Red	+1	±	±	±	±
Red	-1	±	±	±	±
Blue-Green	+1	±	±	±	±
Blue-Green	-1	±	±	±	±
Blue-Violet	+1	±	±	±	±
Blue-Violet	-1	±	±	±	±

R25: "Accepted" values are 656 nm, 486 nm, and 434 nm. Record those values in the last column of the table.

Save your Responses

R26: Compare the experimental, theoretical and textbook values of the wavelengths associated with the hydrogen spectrum.

Note: While the Bohr model predicts the wavelengths of the light emitted from hydrogen very well, almost everything else about the theory is wrong (i.e., does not agree with experiment). Not long after the Bohr model, the Schroedinger wave equation was developed and it correctly describes many more features of the hydrogen atom. Interestingly, even though the Schroedinger wave equation is much more sophisticated, the predictions for the wavelengths of light are the same as for the Bohr model. Should you wish to learn more about these and other aspects of modern physics take SP 301.

5. The same three lines (red, blue-green, and blue-violet) should be observable in the second order hydrogen spectrum.

R27: Are those lines observable in second order?

☐ Yes ☐ No

Discuss:

6. As regards third order, if you don't look carefully, the blue-violet line appears to be missing. To understand the reason for this, calculate the angle where the third order blue-violet line should appear and calculate the angle where the second order red line should appear. Record both values in the space provided.

R28: $\theta(\lambda_{\text{third order blue-violet}}) =$ ______ $\pm$ ______ ^{o}

R29: $\theta(\lambda_{\text{second order red}}) =$ ______ $\pm$ ______ ^{o}

R30: Discuss how these calculations explain why it is difficult to observe the blue-violet line for the third order hydrogen spectrum.

Helium For the fifth experiment, replace the hydrogen tube with a helium tube. (After switching it off, let the hydrogen tube cool down for a few minutes before you touch it!) Then use the diffraction grating to observe the new spectrum.

R31: Give a qualitative description of the helium spectrum. (How many different lines do you see in first order and what colors do they have?)

Incandescent Light For the sixth experiment, replace the gas discharge tube with an incandescent light and use the diffraction grating to observe the spectrum of "white" light.

R32: Give a qualitative description of the spectrum caused by the incandescent light. (How many positive orders can you see in all, and which orders overlap?)

End of Lab Checkout Tidy up the work station.