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Laboratory Exercises

About the Laboratory Component -

The scheduled laboratory periods may be used for lab exercises, as question sessions before the exams, or if necessary as additional lecture time. A student who misses a lab will be given an opportunity to perform a substitute exercise during the semester at a time arranged with the consent of the instructor. The average of the lab grades will count as 25% of the student's final course grade, unless the course instructor indicates otherwise. *Lab partners will be assigned and rotated several times during the semester.*

The student will keep a notebook (*e.g*. Ampad #26-251) of all laboratory work. Notebooks will be written neatly and clearly, and in *ink*. All laboratory objectives, equipment lists (include model and serial numbers), procedures, techniques, data, results, and conclusions will be written in the notebook (see below for guidelines). The notebook will then form the outline for any formal reports required. *No loose sheets may be used as scrap*. Any errors or changes must be struck out *with a single, light stroke* with the corrected value written nearby. *No pages are to be removed*, and the *information is not to be recopied* later into a 'cleaner, neater' notebook. Graphs printed by computer or drawn on loose leaf graph paper should be *glued or stapled* into the book, *one graph per page*. The instructor will examine and sign each notebook before it leaves the laboratory classroom; it is the student's responsibility to ensure that this is done. *Never disassemble your apparatus until your notebook has been checked!* While all this may seem rather AR, the student must realize that, at the least, a notebook must be capable of reminding the author of his procedures and results in case he must repeat them or if his work is questioned, and at the other extreme could be the factor determining who gets credit for a patent or other discovery. A good self test if enough information has been included is to ask whether a friend at some other school could duplicate the experiment using just the notebook and lab manual.

Construct a table similar to the one below on the first page of your notebook.

Lab #	Date	Title	Instructor’s Initials
01			
02			
03			

The grade for the lab portion of the course will be based on formal reports (due typically one week after the exercise) and the notebook checks. If a laboratory exercise is performed, but no report is submitted, the signed notebook is your proof that you did the lab. Notebooks and formal reports will follow the general format given below, although some sections may be combined if it seems better to do so.

- Student Name - Title - Date - Names of Partners

- Objective of Experiment - The objective is often to verify some relationship which was presented in class. In these cases, a brief discussion of the concept is required, along with an outline of how this experiment will support (or disprove) it.
- Description of Experimental Apparatus - A labeled schematic sketch is often enough for the reports. Artistic renderings of the apparatus are not necessary. Notebooks should include model and serial numbers, scale settings, *et c*.
- Procedure(s) – If the procedure corresponds exactly with that given in the lab manual, then write 'The procedure in the manual was followed exactly.' Any deviations from the given procedure should be included in the report. The goal is that the available information should be specific enough that another student taking PHYS I could reproduce the experiment. In particular, any steps with may be considered novel or unusual should be documented in detail.
- Data (if appropriate) - For reports, it is a judgment call as to how much raw data are included. Often, data can be presented in the form of a graph more efficiently than as columns of numbers. *In the notebooks*, however, all data should be recorded in some way, if at all possible. *All measurements must be accompanied by an estimate of the uncertainty in that measurement*. It may be that the student will not be asked to propagate the uncertainty through to the result, but at least the necessary information will be available.
- Results - Results often call for comparison of the student's answer to some accepted value; generally a *per cent difference* can be calculated, or a check can be made to see if the accepted value is within the uncertainty of the experimental result. Other times, a particular relationship among variables may be found by graphing. Results should be clearly indicated.
- Conclusions - This can often be combined with the results section. Did the experiment support whatever hypothesis was discussed? What mathematical relationship connects two or more variables? What are the implications of these results? Were there any problems with the experiment that could be corrected?

The reports should be typed, although figures may be hand-sketched while graphs should be constructed with Excel or some similar package. Reports do not need to be overly long; just include what's necessary. The language should be clear, concise, and natural, without the pretentious use of synonyms (*e.g.*, 'use' and 'utilize' do *not* mean the same thing.). Do not blame poor results on 'human error' unless there is a reaction time effect or something similar; poor experimental technique should not be explained away, it should be corrected before you leave. Now, on occasion, it may be that an apparatus will not yield good results, either because the equipment is worn or broken, or because the experiment is truly ill-conceived. We can only assure the student that the instructor has performed each experiment and obtained reasonable results.

In addition, note that there will be no food or drink allowed in the lab room, no cell phone activity, and that appropriate dress is required (no sandals, occasionally, long pants are required). Lab groups will be assigned and will comprise no more than four students. Attendance at and participation in laboratory exercises is mandatory; students more than a few minutes late to lab will be asked to perform a make-up instead. Students are responsible for returning the lab equipment to its original state. Students must sign into the lab and be certain to have the instructor sign notebooks before leaving. Violations of these and other general classroom policies may result in ejection from the classroom under the College's Code of Conduct.

Lab 401 – Reflection and Refraction

OBJECTIVE

To confirm the laws of reflection and refraction (Snell's Law)

BACKGROUND

In this laboratory exercise, the optical phenomena (*reflection* and *refraction)* that are the basic means by which most optical devices work are investigated. The *law of reflection* states that the *angle of incidence* of a *light ray*, as measured from a *normal* to the reflecting surface, is equal in size to the *angle of reflection*, measured in the same manner (see Figure 1).

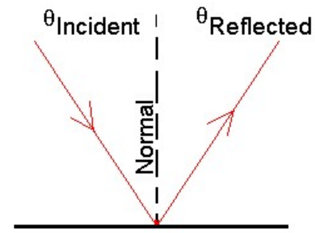


Figure 1 - Reflection

The *law of refraction* (*Snell's Law)*, in its modern form, states that the angles formed by a ray (relative to a normal) passing from one material to another meet this condition:

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where n_1 and n_2 are each the *index of refraction* of the respective materials. The index of refraction of a material is the ratio of the speed of light in vacuum to the speed in the material ($n = c/v$) and is equal to the square root of the material's *dielectric constant*, κ

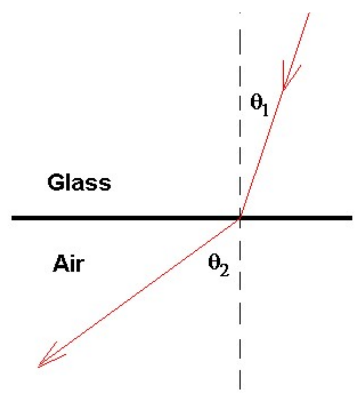


Figure 2 - Refraction

PROCEDURE and ANALYSIS

I REFLECTION

1. Mount the Light Source Box near one end of the magnetic rail. Place the Slit Plate on the front of the Light Source with the slits vertical. Place the Parallel Ray Lens on a magnetic holder and mount it on the rail, approximately 9 cm in front of the Source. Place the White Angle Table on the tilted bracket and mount that at about the middle of the rail. Adjust the position of the lens and the bulb in the light source until several parallel rays fall across the white angle table. Next, place the Slit Mask over the slit plate so that only one ray emerges. Lastly, adjust everything so that the one ray is incident along the 0^o line of the angle table and so that it is as thin as possible.

2. Place the flat side of the mirror so that it aligns exactly along the ±90^o line.

3. Rotate the angle table by ten degrees at a time and record the incident and reflected angles. Which is your independent variable and which is the dependent variable? Graph the values in such a way as to obtain a straight line. Is the Law of Reflection valid?

II REFRACTION

1. Remove the mirror and replace it with the Cylindrical Lens. Place the flat side of the lens toward the light source and align it exactly along the $\pm 90^o$ line. Adjust the table and slits so that the incident ray comes in exactly along the 0^o line.

2. Rotate the table by five degrees at a time and record the incident and refracted ray angles. Which is your independent variable and which is the dependent variable? Graph the values in such a way as to obtain a straight line. Is Snell's Law valid? How is the index of refraction of the plastic represented on the graph? What is the index of refraction, n, for this particular plastic? The manufacturer's accepted value is 1.5.

III TOTAL INTERNAL REFLECTION

1. Set up the cylindrical lens as in Part II, except have the flat side of the lens away from the light source, so that the light will emerge from the plastic at the flat surface. Slowly, rotate the lens until the refracted ray appears to emerge parallel to the flat surface. Record the critical incident angle. Calculate the index of refraction again. Compare this value with the one obtained in Part II by calculating a *per cent* difference. This is not very accurate; do your best.

IIII DIFFRACTION

1. You will return to diffraction with much more detail in a later exercise. For now, this is an experiential exercise. Remove the cylindrical lens from the angle table and adjust the apparatus again so that only one ray falls on the table. Remove the parallel ray lens and replace it with the diffraction grating. The grating is an array of many very narrow slits.

2. Describe, in words or perhaps with a sketch, what you see. How many 'rays' are there now? How are the rays different?

V POLARIZATION

1. Remove the angle table and its bracket. Remove the diffraction grating, but leave the magnetic holder in place. Put two more holders on the rail, one perhaps two inches away from the original holder, and the other perhaps two or three inches further down. On the last holder, place the white screen.

2. Note how bright the light appears to be on the screen. Now place one polarizer on the first holder so that 0^o is up in the notch. Once again note the brightness of the light on the screen and describe it in words.

3. Place the second polarizer on the middle holder so that its 0^o mark is in the notch. Again, qualitatively describe the brightness of the light you see.

4. Now, rotate the second polarizer in 10^o increments. Describe what happens to the brightness of the light seen on the screen after each rotation. At what angle does the screen go dark? What happens as the angle continues to increase? Find the angles for which the transmitted light is brightest (tough to do exactly) and darkest (much easier).

Lab 402 – Thin Lenses

OBJECTIVE

To confirm the Thin Lens Equation and investigate several types of aberrations.

BACKGROUND

Lenses are categorized according to what effect they have on light passing through them, namely *converging* and *diverging* lenses. These categories may be further subdivided according to the curvatures of the two surfaces:

Converging (f > 0)	**Diverging (f < 0)**
meniscus))	meniscus))
plano-convex |)	plano-concave |(
double-convex ()	double-concave)(

The following is a summary of the properties of *thin lenses* with which you should become familiar. More detail on each topic is found in the textbook. Keep in mind that the effects of real lenses are more complicated.

A. The relationship among the *object distance*, *o* (the distance from lens to object), the *image distance* *i* (the distance from lens to image), and the *focal length* of the lens, *f*, is

$$\frac{1}{o} + \frac{1}{i} = \frac{1}{f}$$

The object distance is positive for objects in front of the lens and the image distance is positive for objects behind the lens. The focal length is positive for a converging lens, and negative for a diverging lens.

B. The *magnification* is the ratio of the image size to the object size (h_i/h_o); this can be shown to be equal to the ratio of the image distance to the object distance:

$$m = \frac{-i}{o}$$

If the magnification is the positive, the image is *upright*; if it is negative, the image is *inverted*.

C. *Chromatic aberration* is a variability in the focal length of a lens due to *dispersion,* the property that the index of refraction varies with wavelength. For most glasses, the index of refraction is larger for blue light than for red light; this then causes the focal length of a converging lens to be shorter for blue light than for red.

D. *Spherical aberration* is an imperfection in the focal properties of a lens due to the fact that rays passing through the outer portion of the lens are bent more than those that pass through the central portion; the focal length for such rays is therefor shorter than that for rays passing through the center of the lens.

E. *Coma* is an aberration affecting incoming rays not parallel to the optical axis. Such rays do not converge, thereby blurring the image formed.

F. *Astigmatism* is a defect in which the focal length of a lens is different for rays passing through the lens in different planes.

PROCEDURE

A. Converging Lens

1. Place the light source at one end of the optical rail. Clip the object slide to the front of the light source. Set up the optical bench using the 75mm converging lens as in Figure 1. Look through the lens and find the image. Approximately, where does the image appear to be?

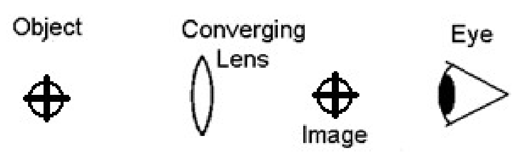


Figure 1 - Looking at the Image through a Converging Lens

2. Attach the screen holder with screen to the optical rail (Figure 2). The frosted side of the glass screen should face the lens so that the image will form on the front surface, but you may still observe it from the backside. Locate the image on the screen and record the following information: object distance (measured from the plate with the arrow-shaped hole, not from the center of the lamp), image distance, image real or virtual, object size (measure the length of one of the arrows), image size (same), and image upright or inverted.

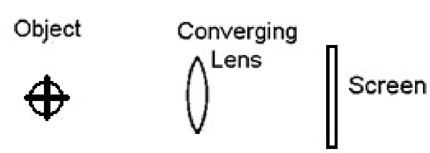


Figure 2 - Projecting the Image onto the Screen

3. Compute and record the focal length f_C of the converging lens.

4. Compute and record the magnification of the image (from h_i/h_o). Calculate a predicted value for the magnification based on the object and image distances and do a percent difference between the predicted value and the actual value.

5. *Construct a ray diagram using the object distance and image distance in Step 1. Determine the focal length and magnification from your diagram and compare with values found in Steps 3 and 4 by performing *per cent* difference calculations.

6. Using the same object distance as in Step 1, place a red filter in the light path. Focus the image of the screen and record the image position. Compare this value with the original image position. Repeat this step using a blue filter; record the image position. Comment on how chromatic aberration affects the image position.

7. Using the same object distance as in Step 1, place a circular disc over the center of the lens. Re-focus and record the image position. Replace the disc with an *aperture*, refocus, and again record the image position. What can you conclude about spherical aberration?

B. Diverging Lens

NOTE: The image of a real object formed by a diverging lens is always virtual. A virtual image cannot be focused on the screen; it can, however, be seen by eye if you sight through the lens at the object. It is always upright, reduced in size, and appears to 'hang' in mid-air between the object and the lens. There are a number of ways to determine the position of a virtual image.

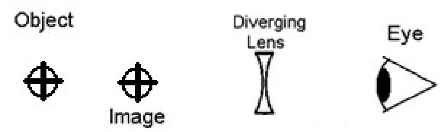


Figure 1

1. Remove the screen and replace the converging lens with a diverging lens. Can you see an image through the lens (Figure 3)? Describe its approximate position.

2. Mount the Virtual Image Locator on another magnetic holder so that it is above the opening in the holder. Place the locator at the approximate position of the image (Figure 4). Now, you will make use of an effect known as *parallax*; move your head left and right, watching the arrow on the locator and the image as seen through the lens. Most likely, the arrow and the image will shift back and forth differently. Adjust the location of the arrow locator until the arrow and image move together, *i.e.*, they are in the same spot. Record the location of the image. Calculate the focal length of the diverging lens and compare with the given value with a *per cent* difference.

   Note that this is a difficult task. Try to do as well as you can, then ask your instructor to check it.

Lab 403 - Interference

OBJECTIVE

Determine the wavelength of the light from a gas laser using interference.

BACKGROUND

Interference is an effect that directly supports the wave nature of light. When coherent light from two (or more) sources arrives at a particular point, the waves can add *constructively* (always in phase), *completely destructively* (always out of phase), or somewhere in between. In this exercise, you will make use of a gas laser[1] as both sources of light by passing the light perpendicularly through a double slit; the two resulting sources are therefor exactly in phase with one another. The light then continues on until it hits a screen. If the two beams are *in phase* on arrival at a particular spot on the screen, then the waves add constructively and a bright spot is seen. If the beams are 180° out of phase (and of the same intensity), a dark spot will appear. As derived in class, the condition for these two cases are

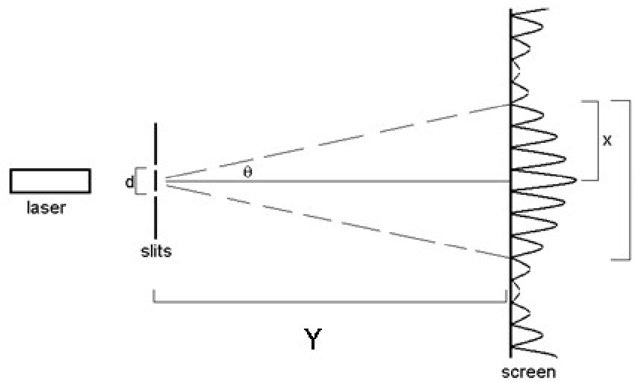


Figure 1 - Interference of Light Set-up

$$d\ sin\theta = m\lambda \quad (constructive) \qquad\qquad d\ sin\theta = \left(m + \tfrac{1}{2}\right)\lambda \quad (destructive)$$

Now, because the slits themselves are not infinitely thin, as was assumed in the derivation, there is also a diffraction effect. This appears in the interference pattern as an alternating decrease, then increase in the brightness of the spots.

Let's simplify the relationship for destructive interference, since the angles are small. The sine of theta should be about the same as the tangent of theta, which is x/Y, so that

$$\begin{aligned} d\ tan\theta &\approx \left(m + \tfrac{1}{2}\right)\lambda \\ 2d\ tan\theta &\approx (2m+1)\lambda \\ d\ \frac{2x}{Y} &\approx (2m+1)\lambda \\ X &= \left(\frac{Y\lambda}{d}\right)N \end{aligned}$$

[1] If you laser light is red, it is probably a *HeNe laser* with a wavelength of 632.8 nm.

In this expression, X is the distance along the screen between a dark spot on the left side of the central maximum and the corresponding dark spot on the right side (X = 2x), while N is the number of bright spots between the dark spots, *i.e.*, m = (N-1)/2.

PROCEDURE:

1. ***<u>Be very careful to avoid looking at the laser light!</u>***

2. Cover the screen with white paper. Mount the laser, slit plate, and screen on the optical rail. The plate should be about 6 cm from the laser, but the screen should be as far as possible from the slits while still showing a clear interference pattern. Measure this distance from slits to screen, Y. Watch out for reflected laser light!

3. The slits to be used are D and E. Align the laser and slits so that a clear pattern is seen on the screen.

4. For Slit Set D, measure the distance X from a dark spot on one side of the central maximum to the corresponding dark spot in the other side. Count how many bright spots appear between the marks; this is N. It might be easier to mark the spots with a pencil and measure the distance after removing the paper from the screen. Repeat for as many dark spot pairs as possible.

5. Repeat for Slit Set E.

ANALYSIS

Separately for each slit set, plot X against N in such a way as to obtain a straight line and perform a least-squares best fit. What is the physical meaning of the slope of the best fit line? What is the value you obtain for the slit separation, d for each set? Check your results with your instructor.

Lab 404 – Atomic Spectra

OBJECTIVE

To measure the wavelengths of several optical transition lines of mercury.
To verify the theoretically derived condition for maximum constructive interference from multiple slits.

META-OBJECTIVE

To investigate the properties of diffraction.

BACKGROUND

A diffraction grating provides an example of interference using many sources. In this case, light from a single source is passed through many slits (not just two as in a previous lab). As discussed in class, there are many interference maximums, but the very brightest interference maximums occur when the following condition is met:

$$m\lambda = d \sin \theta_m$$

where

m is the order of the maximum (waves from adjacent slits are in phase but the distance traveled to the screen differ by m wavelengths),
d is the separation between two successive lines or slits on the grating (usually on the order of a few wavelengths),
λ is the wavelength of the light, and
θ_m is the angle at which the m^{th} maximum occurs.

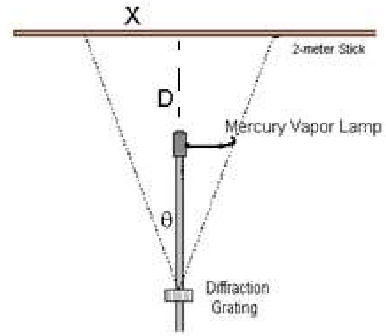
In this experiment, you will determine the wavelengths of the four principal lines in the emission spectrum of the element mercury.

PROCEDURE

1. Note the slit spacing d of your grating. It will probably be written as the number of lines *per* millimeter. Convert this to nanometers *per* line.

2. Mount the diffraction grating in its magnetic holder at one end of the optical bench. Position the optical bench so that that end hangs slightly over the edge of the table in such a way that it will be comfortable to look through the grating. Mount the mercury lamp at the other end of the optical rail. Adjust the heights of the grating and lamp to be approximately the same. Mount the two-meter stick on its stands and blocks well behind the optical rail (see Figure 1); be sure that it is reasonably well centered and perpendicular to the optical bench. Record the distance between the grating and the meter stick as D (you may use the horizontal distance).

3. Turn on the lamp by plugging it in. Mercury has a number of ultra-violet lines, so avoid looking directly at the lamp; looking at the lamp through the glass grating should present no problem. Look through the grating to observe the diffraction maximums; you should see a violet line (405 nm), a blue line (436 nm), a green line (546 nm), and two yellow lines (577 & 579 nm), then the pattern should repeat. You should be able to see two complete orders and part of the third order on each side of the mercury lamp. Adjust the grating so that the lines are sharp and clear and appear in a horizontal line.



4. Measure the apparent positions (X_{Left} and X_{Right}) of as many first order lines as you can. Partner A should look through the grating at a given line so that the line appears near the meter stick. Partner B will move the edge of a sheet of white paper along the meter stick until A says that the edge and the line under observation are aligned. Partner C will then shine the flashlight onto the stick and record the position of the paper's edge. Be sure to make measurements of the lines on each side of the lamp. Measure the locations of as many lines as you can. Simply record the positions of the lines on the meter stick; do not bother to measure the distance from the center. This will be taken care of in the next step.

ANALYSIS

1) Calculate X, the difference of the apparent positions of the corresponding lines on each side divided by two ($X = (X_{Right} - X_{Left})/2$); this process helps to reduce errors by averaging the distances of the lines from the central axis. Find and record the angles between each line and the optical axis (Hint: what is the relationship among X, D, and the angle θ?).

2) Calculate and record the wavelength of each line. Compare your values to the values given above in Part 3 by computing a percent difference. As an aside, the wavelengths of these lines can be measured with *spectrometers* to within a few parts *per* thousand.

Lab 501 – Speed of Electro-magnetic Waves

OBJECTIVE

To determine the speed of an electromagnetic pulse and confirm that the speed matches the known speed of light.

META-OBJECTIVE

To provide practice with the oscilloscope.

BACKGROUND

You may remember that, in Physics I, we developed the wave equation for a transverse pulse on a string along the x-axis:

$$\frac{\partial^2 Y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 Y}{\partial t^2}$$

where Y(x, t) is the displacement of the string from its equilibrium position and v is the speed of the pulse or wave. In the 1840s, Fizeau and Michelson independently measured the speed of light to be approximately 3×10^8 m/s. In the 1860s, Maxwell made use of the laws we discussed in E&M (Gauss's laws for electricity and for magnetism, Ampère's law, and Maxwell's corrected version of Faraday's law of induction) to predict the existence of electro-magnetic waves. For example, the following analogous equations can be derived:

$$\frac{\partial^2 E}{\partial x^2} = \varepsilon_o \mu_o \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \varepsilon_o \mu_o \frac{\partial^2 B}{\partial t^2}\,.$$

The implication here is that the speed of these waves in a vacuum (symbol c) should be

$$c \equiv v_{Vacuum} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \cong 3 \times 10^8 \text{ m/s}\,.$$

We might then jump to the conclusion that light is an electro-magnetic wave.

In this exercise, you will measure the speed of light and the speed of an electromagnetic wave using the time-of-flight method as described in class.

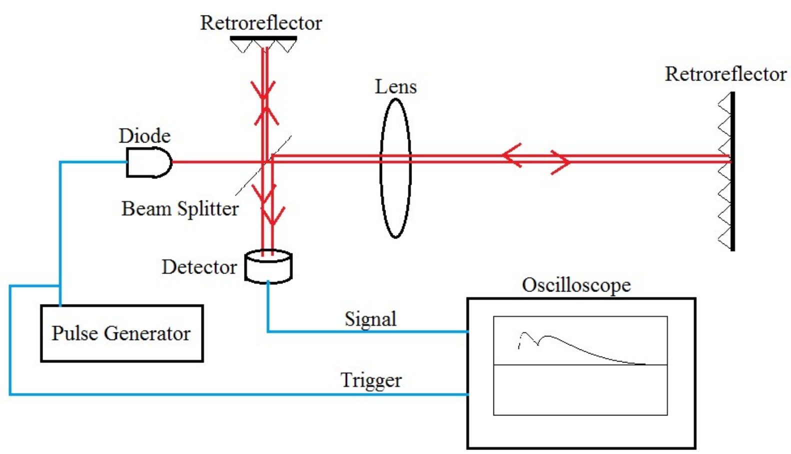
Oscilloscope Calibration

PROCEDURE

Since the accuracy of the time measurement is critical, the time-base of the oscilloscope must be calibrated. Connect the function generator directly to the scope input and set it to SQUARE WAVE, 50Ω output, and adjust the frequency to as close to 1 MHz as possible. Connect a cable directly from the output to Channel One of the scope with a T and a 50Ω terminator. Adjust the scope until something resembling a square wave appears on the screen; you will need to be able to see two such pulses. Adjust the VARIABLE SWEEP on the time base until corresponding points on adjacent pulses lie on the grid lines. For example, if the time base is set to 0.2 µS per division, the 1 MHz pulses should be exactly five boxes apart. Once the variable sweep adjustment is made, do not touch it again.

Speed of Light

PROCEDURE



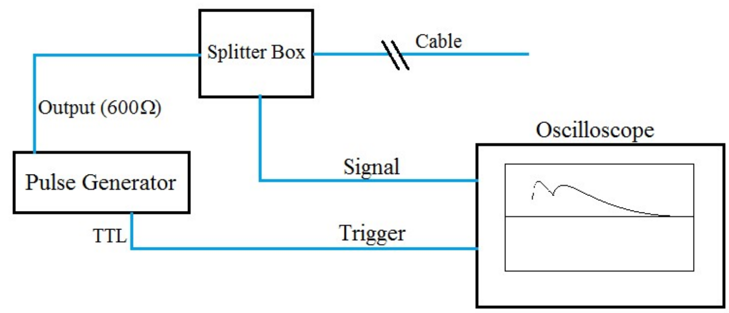
The speed of light apparatus comprises electronics that produce a series of short pulses, which are used to trigger the oscilloscope and power a diode. The light from the diode is split into two parts; one is diverted to a *photodetector* and the rest is collected by a lens and *collimated*, or made parallel. The light travels across the room to a *retroreflector*. This special type of mirror ensures that the light is reflected back along its original path regardless of the actual angle of incidence. The lens collects this returning light and directs it into the detector, which in turn converts the light to an electrical signal. When viewed on an oscilloscope, both of the pulses are visible. The time between the two peaks is the time of flight of the light.

Since more data points are better than fewer, do the following: place the retroreflector approximately 10m from the emitter, but measure the distance carefully. Obtain the double pulse signal and measure the time of flight, t. Repeat for increments of 8 or so meters until the distance is about 45 m (5 data points). Remember that the distance the light actually travels is twice the separation between the emitter and the retroreflector.

ANALYSIS

Construct a graph (t *vs* d). What does the slope of this graph represent? Calculate the speed of light in air. Compute a *per cent* difference between your experimental value and the theoretical value of 2.997×10^8 m/s.

Speed of an Electromagnetic Wave



In this part of the exercise, an electromagnetic pulse will be generated with a square wave produced by a function generator and a differentiating circuit. The output of the circuit will be zero when the input is high or low, and will be positive or negative when the square wave rises or falls. The pulses are sent simultaneously to the Y-input of an oscilloscope and down a 75Ω coäxial cable. When the pulse reaches the open end of the cable, it is reflected without inversion back to the oscilloscope, and a second pulse will appear on the screen. The time difference between these two pulses will be used to determine the speed of the pulse. This time will be much less than the time between generated pulses.

Now, the velocity that you will measure will be a bit less than the expected speed of light. The pulses generated here travel not though vacuum, but along a coäxial cable with a dielectric material separating the conductors. Think back to our discussion of capacitors in Physics II. We showed that

$$C = \frac{\varepsilon_o A}{d} \text{ (empty capacitor)}$$

$$C = \frac{\kappa\varepsilon_o A}{d} \text{ (capacitor with dielectric)},$$

that is, we replaced ε_o with $\kappa\ \varepsilon_o$. Therefore, perhaps, naïvely, we might predict that the velocity of a wave in a dielectric should be

$$v_{\text{Dielectric}} = \frac{1}{\sqrt{\kappa\varepsilon_0\mu_0}} = \frac{c}{\sqrt{\kappa}}. \text{ (Eq. 1)}$$

We'll see later that $\sqrt{\kappa}$ is what was previously known as the *index of refraction*, n, of the material.

So, in order to predict the speed of EM waves in the cable, the dielectric constant of the insulating layer between the conductors must be found. Again referring to an exercise from Physics II, you may remember that the capacitance of two coäxial cylinders of a great length L is given by

$$C = \frac{2\pi\kappa\varepsilon_o L}{\ln\left(\frac{r_{Outer}}{r_{Inner}}\right)}. \quad \text{(Eq. 2)}$$

For RG6/QS cable, r_{Outer} = 2.286mm and r_{Inner} = 0.512mm.

PROCEDURE

1) Determine the dielectric constant of the insulator. Connect the leads of a capacitance meter to the center conductor and the ground connection. Record the value indicated. Use Eq. 2 to calculate the dielectric constant, κ. Use Eq. 1 to calculate the expected speed of the EM pulse.

2) Connect the cable, function generator, oscilloscope, and differentiator box as shown. Connect the 75Ω termination resistor to the other end of the cable. This should ensure no reflection from that end of the cable.

3) Set the function generator to SQUARE WAVE, 600Ω output, ~100kHz, Amplitude at about 12 o'clock. All other functions should be disabled.

4) Adjust the 'scope until a positive pulse of width ~ 0.1 μS is seen on the left edge of the screen. Adjust the HOLDOFF knob so that you can just see the peak of this pulse. Remove the terminator from the far end of the cable (this allows a reflection) and adjust the 'scope settings again until a second positive pulse is also seen (with no negative pulses in between the two).

5) Measure the time for the pulse to travel down and back up the cable. Repeat the measurement after adding another length of cable to the end. Add a third, then a fourth cable and repeat.

ANALYSIS

Construct a graph similar to the one for light, and find the speed of the electromagnetic wave. Compute a *per cent* difference between your experimental value and the theoretical value you calculated above.

LAB 502 – Properties of Electro-magnetic Waves

OBJECTIVE

To demonstrate that electro-magnetic waves have the same properties as light and gain confidence that light is an electro-magnetic wave.

META-OBJECTIVE

To learn that "quick-and-dirty" experiments are often sufficient to prove very important relations in Physics (see *e.g.* the Compton Effect).

BACKGROUND

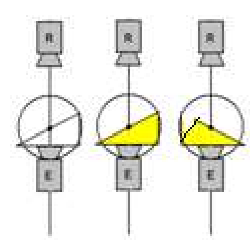
In this experiment, you will make measurements only to the accuracy necessary to convince yourself that EM waves follow the laws of reflection, refraction, diffraction, and polarization. With the exception of polarization, you will simply look for transmission peaks and show that these peaks correspond to what is predicted by optics. The EM waves in this exercise are microwaves of frequency 10.5 GHz. Although the power output is roughly 10^{-4} that of a microwave oven, please try to avoid placing body parts in the beam.

PROCEDURE and ANALYSIS

1) Calculate the wavelength in vacuum (or air) of an EM wave of frequency 10.5 GHz.

2) Place the emitter and receiver on the goniometer rails. Check that the angles on the dials on the mounts for each read the same position. Place a metal plate on the magnetic holder on the center; be sure that the surface of the plate is located exactly above the center of the rotating table. Rotate the reflecting plate to an incident angle of 20°. Move the receiver about until the signal is maximized and measure the angle of that location; the **difference** of this angle and the incident angle is the angle of reflection. Repeat for many angles, then plot the reflection angles against the incident angles. Is the law of reflection upheld?

3) Adjust the arms of the goniometer so that the receiver and emitter are facing one another. Place the empty Styrofoam prism on the table (be sure that the hypotenuse of the empty space is located above the center of the rotating table) and move the emitter up to the prism so that the microwaves are entering it at 0°. Gently swing the receiver back and forth until the position of maximum signal is found; it should be straight ahead from the emitter. Now, fill the prism with plastic beads. Repeat your investigation. Swing the detector back and forth to find the direction of peak intensity. Is the



position roughly consistent with refraction at an interface? Reverse the prism and repeat. Again, is the result consistent with refraction?

4) Remove anything between the emitter and receiver and again place them facing each other. Your instructor will now quickly demonstrate that microwaves are polarized by rotating a slotted metal sheet between the devices. Plot the receiver's signal as a function of angle (every 5°) and verify that these EM waves follow the Law of Malus:

$$I(\theta) = I_o cos^2\theta \ .$$

Construct a graph.

5) Place a double slit barrier on the center table. The slits should be about one inch wide and several inches apart. Predict at what angles diffraction maximums will appear. Gently swing the receiver around and look for these angles experimentally. Compare your experimental results with the theory. Are EM waves diffracted?

CONCLUSION

Make an argument for or against the notion that light waves are EM waves.

Lab 503 – Millikan Oil Drop Experiment

OBJECTIVE

To determine the elementary charge of an electron and demonstrate that electric charge is quantized.

BACKGROUND

The Millikan 'Oil Drop' experiment showed that the charge is *quantized*, that is, it only occurs as an integer multiple of some given fundamental value. The experiment is extremely tedious to perform, so you will make use of Millikan's own data.

The essentials of the experiment are given here. A small spherical drop of oil of radius r is given an electric charge q (by either adding or removing some small number of electrons through exposure to a radio-active source) and then allowed to fall through air while between two charged metal plates. Since the drop is so small, it achieves its *terminal velocity* (due to drag from the air) in a very short time. As may have been discussed in Physics 1, the magnitude of the *drag force* D acting on the drop moving at speed v is given by a 'corrected' *Stokes's Law*:[1]

$$D = \frac{6\pi\mu r}{1 + \frac{b}{Pr}} v \qquad (\text{Eq. } 1)$$

where μ is the *viscosity* of the air, P is atmospheric pressure, and b = 8.2×10^{-3} Pa m. The other possible external forces include the weight W of the drop, a buoyant force B on the drop due to the air, and an electric force F_E:

$$W = gm = g\frac{4\pi}{3} r^3 \rho_{OIL}$$

$$B = g\frac{4\pi}{3} r^3 \rho_{AIR}$$

$$F_E = qE = \frac{q\Delta V}{d}$$

where ρ_{OIL} is the density of the oil, ρ_{AIR} is the density of the air, q is the charge on the drop, and ΔV and d are the potential difference and physical separation between the metal plates. A particular drop is chosen and viewed through a microscope. With the electric field off, the drop falls distance y in time t_F at constant speed $v_F = y/t_F$. Making use of Newton's Second Law, we then have that

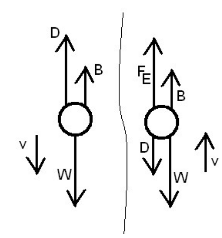


Figure 1 - Forces on a falling drop (left) and on a rising drop (right)

$$\Sigma F_i = +B - W + D_f = ma = 0$$

[1] Pasco manual 012-13093D p2.

$$g\frac{4\pi}{3}\,r^3\,\rho_{AIR} - g\frac{4\pi}{3}\,r^3\,\rho_{OIL} + 6\pi\mu r\left(\frac{1}{1+\frac{b}{Pr}}\right)\frac{y}{t_F} = 0 \quad (Eq. 2)\,.$$

Unfortunately, the viscosity requires a correction factor because the drops are smaller than Re-arrange Eq. (2) to get the radius r; we need to do this because there is no easy way to measure r.

$$g\frac{4\pi}{3}\,r^3\,(\rho_{OIL} - \rho_{AIR}) = 6\pi\mu r\left(\frac{1}{1+\frac{b}{Pr}}\right)\frac{y}{t_F}$$

$$g\frac{2}{3}\,r^2\,(\rho_{OIL} - \rho_{AIR}) = 3\mu\left(\frac{1}{1+\frac{b}{Pr}}\right)\frac{y}{t_F}$$

$$r^2\left(1+\frac{b}{Pr}\right) = \frac{9\mu y}{2g\,t_f\,(\rho_{OIL} - \rho_{AIR})}$$

$$r^2 + \frac{b}{P}r - \frac{9\mu y}{2g\,t_f\,(\rho_{OIL} - \rho_{AIR})} = 0$$

Solving the quadratic equation:

$$r = \sqrt{\left(\frac{b}{2P}\right)^2 + \frac{9\mu y}{2g\,t_f\,(\rho_{OIL} - \rho_{AIR})}} - \frac{b}{2P}\ .$$

Then, the electric field is turned on and the same drop is watched while it rises distance y in time t_R at constant speed $v_R = y/t_R$. Newton's Second Law now looks like this:

$$\Sigma\,F_i = +B - W - D_r + F_E = ma = 0 \quad (Eq. 3)$$

$$g\frac{4\pi}{3}\,r^3\,\rho_{AIR} - g\frac{4\pi}{3}\,r^3\,\rho_{OIL} - 6\pi\mu r\left(\frac{1}{1+\frac{b}{Pr}}\right)\frac{y}{t_R} + \frac{q\Delta V}{d} = 0$$

We can eliminate the drag function by combining Eq. 3 with Eq. 2:

$$g\frac{4\pi}{3}\,r^3\,(\rho_{OIL} - \rho_{AIR})t_F = 6\pi\mu r\left(\frac{1}{1+\frac{b}{Pr}}\right)y$$

Substitute:

$$-g\frac{4\pi}{3}\,r^3\,(\rho_{OIL}-\rho_{AIR})-\;g\frac{4\pi}{3}\,r^3\,(\rho_{OIL}-\rho_{AIR})\frac{t_F}{t_R}+\frac{q\Delta V}{d}=0$$

$$q=\frac{4\pi d}{3\Delta V}\,r^3\,g(\rho_{OIL}-\rho_{AIR})\left(1+\frac{t_F}{t_R}\right)$$

$$q=\frac{4\pi}{3}\left(\sqrt{\left(\frac{b}{2P}\right)^2+\frac{9\mu y}{2g\,t_f\,(\rho_{OIL}-\rho_{AIR})}}-\frac{b}{2P}\right)^3 g(\rho_{OIL}-\rho_{AIR})\left(1+\frac{t_F}{t_R}\right)\frac{d}{\Delta V}\quad (\mathrm{Eq.}\,4)$$

OK, then. Note that only the last two terms will change from trial to trial, so long as the temperature is constant.

Here are some values you will need:

Plate separation, d	1.60 x10^{-2} m
Distance to fall or rise, y	1.010 x10^{-2} m
Density of oil at 25°C, ρ_{OIL}	896.0 kg/m^3
Density of air at 25°C, ρ_{AIR}	1.184 kg/m^3
Viscosity of air at 25°C, μ	1.862 x10^{-5} Ns/m^2
Atmospheric Pressure	1.01×10^5 Pa
Gravitational Field Strength	9.8017 N/kg

Procedure

Your instructor will assist you in setting up the apparatus. Once you have found a suitable oil drop, use the hand switch to apply and disengage the electric field. Time the drop as it crosses the reticle lines. Choose only either PLUS and OFF or NEGATIVE and OFF.

Program an Excel sheet to calculate from Eq. 4 the charge values for each of the data sets given. Plot the resulting values of the charge to shown the quantization effect, and then estimate the value of the fundamental charge.

Lab 503a – Millikan Oil Drop Experiment (dry)

OBJECTIVE

To determine the elementary charge of an electron and demonstrate that electric charge is quantized.

META-OBJECTIVE

To provide practice with Excel.

BACKGROUND

The Millikan 'Oil Drop' experiment showed that the charge is *quantized*, that is, it only occurs as an integer multiple of some given fundamental value. The experiment is extremely tedious to perform, so you will make use of Millikan's own data.

The essentials of the experiment are given here. A small spherical drop of oil of radius r is given an electric charge q (by either adding or removing some small number of electrons through exposure to a radio-active source) and then allowed to fall through air while between two charged metal plates. Since the drop is so small, it achieves its *terminal velocity* (due to drag from the air) in a very short time. As may have been discussed in Physics 1, the magnitude of the *drag force* D acting on the drop moving at speed v is given by *Stokes's Law*:

$$\mathrm{D} = 6\pi\mu\mathrm{rv} \quad (\mathrm{Eq.}\,1)$$

where μ is the *viscosity* of the air. The other possible external forces include the weight W of the drop, a buoyant force B on the drop due to the air, and an electric force F_E:

$$W = gm = g\frac{4\pi}{3}r^3\rho_{OIL}$$

$$B = g\frac{4\pi}{3}r^3\rho_{AIR}$$

$$F_E = qE = \frac{q\Delta\mathrm{V}}{d}$$

where ρ_{OIL} is the density of the oil, ρ_{AIR} is the density of the air, q is the charge on the drop, and ΔV and d are the potential difference and physical separation between the metal plates. A particular drop is chosen and viewed through a microscope. With the electric field off, the drop falls distance y in time t_F at constant speed $v_F = y/t_F$. Making use of Newton's Second Law, we then have that

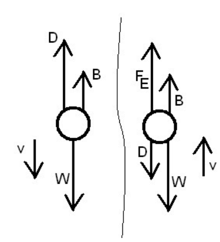


Figure 1 - Forces on a falling drop (left) and on a rising drop (right)

$$\Sigma F_i = +B - W + D = ma = 0$$

$$g\frac{4\pi}{3}r^3\rho_{AIR} - g\frac{4\pi}{3}r^3\rho_{OIL} + 6\pi\mu\mathrm{r}\frac{\mathrm{y}}{\mathrm{t_F}} = 0 \quad (\mathrm{Eq.}\,2)$$

Re-arrange Eq. (2) to get the radius r; we need to do this because there is no easy way to measure r:

$$r = \sqrt{\frac{9\mu y}{2t_F\, g\, (\rho_{OIL} - \rho_{AIR})}}$$

Then, the electric field is turned on and the same drop is watched while it rises distance y in time t_R at constant speed $v_R = y/t_R$. Newton's Second Law now looks like this:

$$\Sigma F_i = +B - W - D + F_E = ma = 0$$

$$g\frac{4\pi}{3}r^3\rho_{AIR} - g\frac{4\pi}{3}r^3\rho_{OIL} - 6\pi\mu r\frac{y}{t_R} + \frac{q\Delta V}{d} = 0$$

Now, substitute the expression for r above into Eq. (3) and solve for q:

$$q = 18\pi d\left(\frac{\mu^3 y^3}{2g(\rho_{OIL}-\rho_{AIR})}\right)^{\frac{1}{2}}\left(\frac{t_R+t_F}{t_R\, t_F^{\frac{3}{2}}}\right)\frac{1}{\Delta V} \quad \text{(Eq. 3)}$$

Note that only the last two terms will change from trial to trial, so long as the temperature is constant.

Here are some values you will need:

Plate separation, d	1.60×10^{-2} m
Distance to fall or rise, y	1.010×10^{-2} m
Density of oil at 25°C, ρ_{OIL}	896.0 kg/m^3
Density of air at 25°C, ρ_{AIR}	1.184 kg/m^3
Viscosity of air at 25°C, μ	1.862×10^{-5} Ns/m^2

Program an Excel sheet to calculate from Eq. 3 the <u>charge values</u> for each of the data sets given. Plot the resulting values of the charge to shown the quantization effect, and then estimate the <u>value of the fundamental charge</u>.

Lab 504 – Microwave Simulation of X-Ray Diffraction

OBJECTIVE

To determine the lattice spacing of a simulated crystal.

BACKGROUND

X-Ray diffraction is a powerful analytic technique that gives insight into crystalline structure, atomic spacing, and the determination of the masses of atoms. The structure of DNA was determined primarily on the basis of X-Ray diffraction measurements.

X-Rays are typically produced in a vacuum tube by accelerating electrons to high velocities (in a manner similar to that in a cathode ray tube) toward a metal target. As the electrons impact on the metal, they must decelerate and, as was discussed in Physics II, they therefor emit electromagnetic radiation of high energy called *Bremsstrahlung* (braking radiation). If enough energy is present, these electrons can also knock other electrons in the metal target out of their atoms, at which point a third electron already in the atom will fall to replace the removed one, thus emitting X-Rays with energies (or wavelengths) characteristic to the metal of the target. Figure 1 shows a schematic diagram of the output of such a tube. In this example, the Kα lines corresponds to an electron falling from the n=2 orbit to the n=1 orbit, Kβ corresponds to the n=3 to n=1 transition. Use of suitable absorption filters will reduce the output of the tube to essentially one emission line, such as the Kα. For a copper target, the wavelength of the Kα line is 1.54Å.

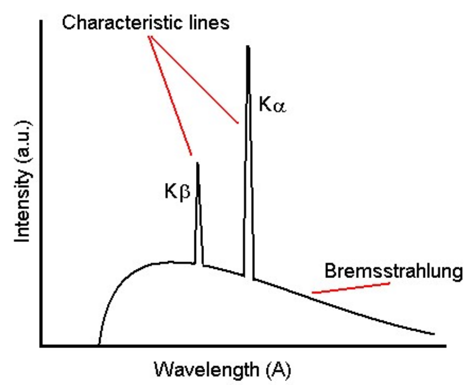


Figure 1 - Bremsstrahlung and characteristic emission lines

X-Rays can be detected by a number of means: fluorescent screens, film, and various types of solid-state counters.

Crystals come in one of fourteen basic arrangements; we will discuss only the *simple cubic lattice* (Figure 2). Consider a cubic cell of side length a that has one atom at each of the eight corners (or more correctly, an eighth of an atom at each corner, since each atom is at the corners of eight adjacent cells).

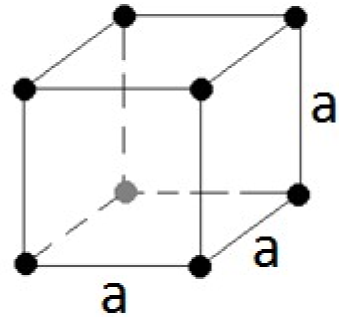


Figure 2 - The simple cubic lattice structure

When X-Rays are incident on these crystals, the rays are diffracted, much as visible light is diffracted by a grating; each atom becomes a new source of radiation. In some directions, the emitted X-Rays will interfere constructively and a bright beam will emerge from the crystal. In other directions, they will interfere destructively.

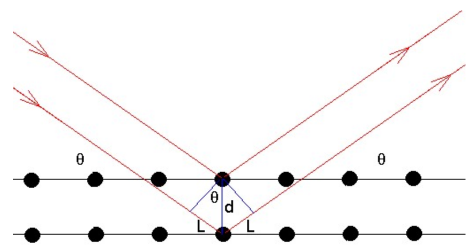


Figure 3 - Constructive interference for the (100) plane.

Consider two planes of atoms in the crystal that are separated by distance d (Figure 3). In class, we discussed how the first requirement for constructive interference suggests that the incoming and outgoing angles theta should be equal. In Figure 3, we see a 2-d schematic of a crystal with the diffraction planes running parallel to one set of sides of the cubic cell. X-Rays incident from the left are assumed to be in phase with each other. In order to get a bright 'reflection' from the two planes, the rays at the right must also be in phase. The lower beam travels a longer distance than the upper beam does, specifically, 2L = 2 d sinθ. In order for the beams to remain in phase, 2L must equal an integer number of wavelengths, so

$$2\ \mathrm{d}\ \sin\theta = \mathrm{m}\lambda, \quad (\mathrm{m\ a\ positive\ integer})$$

Of course, the same relationship must hold for any two adjacent planes.

To confuse matters a bit, realize that there are a number of different planes that could cause this interference effect, each with its own plane spacing, d. Figure 4 shows two of these 'planes' for a two dimensional lattice. Planes are described using *Miller indices*, each set of (h k l) indicating a vector perpendicular to the plane of interest. For example, the black plane in the top of Figure 4 is the (100) plane, in the lower, the red is the (110) plane. The lattice parameter a is the same in each diagram. The spacing d between adjacent planes of a given orientation (h, k , l) in a cubic cell of side length a is given by:

$$d = \frac{a}{\sqrt{h^2 + k^2 + l^2}}$$

Combining the relationships above, we see that interference maximums should appear when

$$sin\theta = \frac{m\lambda}{2}\frac{\sqrt{h^2 + k^2 + l^2}}{a}$$

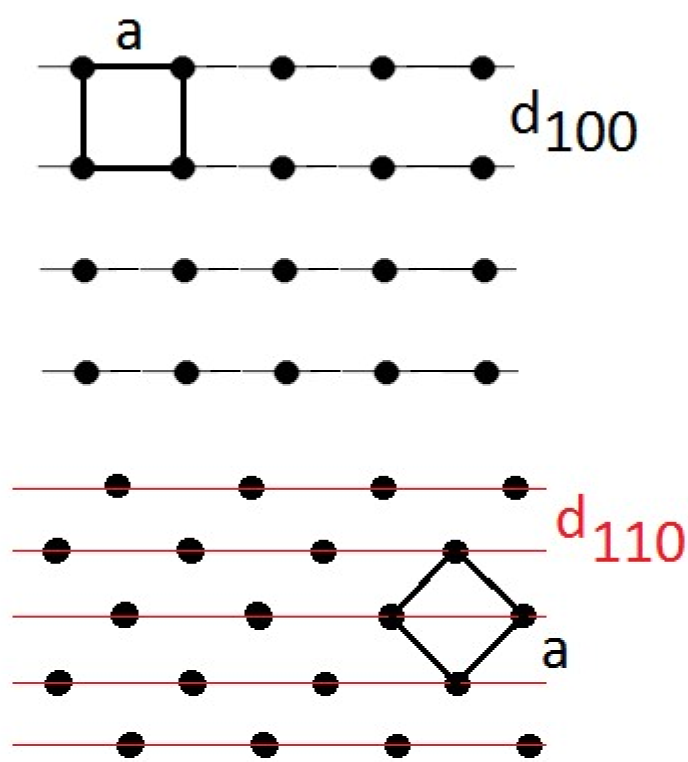


Figure 4

The apparatus is shown schematically in Figure 5.The source of X-Rays is shown on the left and is usually fixed. The sample itself is mounted on a rotating stage so that the incident angle θ of the X-Rays can be varied. The detector is mounted on a *goniometer* that swings though twice the angle of rotation of the sample; this is to keep the detection angle equal to the incident angle. As a result, the data are recorded as a function of 2θ, rather than θ.

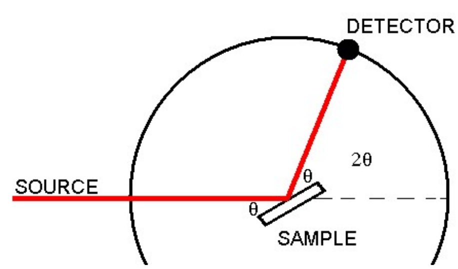


Figure 5

In this simulated experiment, you will use micro-waves of wavelength 2.86 cm. The crystal will be replaced by a regular three-dimensional arrangement of ball bearings embedded in Styrofoam. With these data, you will determine the 'lattice parameter,' a.

PROCEDURE

1) Orient the "crystal" such that the (110) plane is examined. Place the cube very carefully such that it is at a 45° angle from the 0° marking on the rotating table.

2) For angles between 0^o and 60^o, measure the diffracted beam in one degree intervals. Plot a graph and look for diffraction peaks. Calculate the lattice parameter, a. Compare to a directly measured value with a percent difference.

3) *Repeat for the (100) orientation. Using the **actual** measured lattice parameter, identify each peak.

Lab 505 – The Compton Effect (dry)

OBJECTIVE:

To verify the result derived by Compton, thereby confirming that photons behave as particles and have momentum.

META-OBJECTIVE

To learn about curve fitting.

BACKGROUND

Even in the classical picture of light, it is well-known that electro-magnetic waves carry momentum. The Poynting vector **S** is given by

$$\boldsymbol{S} = \frac{1}{\mu_o} \boldsymbol{E} \times \boldsymbol{B}$$

and the radiation pressure is given by

$$P_{Rad} = \frac{< \boldsymbol{S} >}{c}$$

According to J.J. Thomson, these waves should be scattered from particles such as electrons in a classical manner by causing electrons to oscillate at the frequency of the light, thus re-radiating the light at the same frequency as that as which it was absorbed. Compton, on the other hand, assumed that the X-Rays behave as relativistic particles (photons) that collide elastically with the electrons, much as two pool balls might collide. The scattered photon transfers energy to the electron, and is thereby shifted in wavelength by an amount that depends on the final direction of the X-Ray. A moderately long derivation (done elsewhere) results in this relationship:

$$\lambda_{Scattered} = \lambda_{Incident} + \frac{h}{m_e c} (1 - cos\varphi)$$

where m_e is the rest mass of the electron and φ is the *scattering angle*, the angle between the initial and final paths of the X-Ray.

In a separate paper, Compton scattered X-Rays from the Kα line of a molybdenum target (wavelength $\lambda_{Incident}$ = 0.711Å) from a graphite (carbon) target. Scattered X-Rays were measured at 45°, 90°, and 135° from the direction of the incident rays. The wavelengths of the scattered rays were measured by diffracting them from a calcite crystal (rhombohedral structure, distance between planes d = 3.036Å). The results are presented in the worksheets at the end of this lab (data are also in the PHYS III Excel worksheet).[1] It should be clear that there are two peaks, one that shifts and one that does not. The shifting peak corresponds to Compton scattering from the outer electrons of the carbon atoms, while the unshifted peak corresponds to 'classical' scattering (with no wavelength change) from the more tightly bound inner electrons of the atoms.

PROCEDURE

1) Fit the data in each graph (45°, 90°, and 135°) to a double Gaussian curve.[2] Determine the central angle for each peak. You will use either data in an Excel spreadsheet or you will use a set of worksheets, depending on your instructor's wishes.

2) Using your knowledge of X-Ray diffraction, determine the wavelength corresponding to the center of each shifted peak.

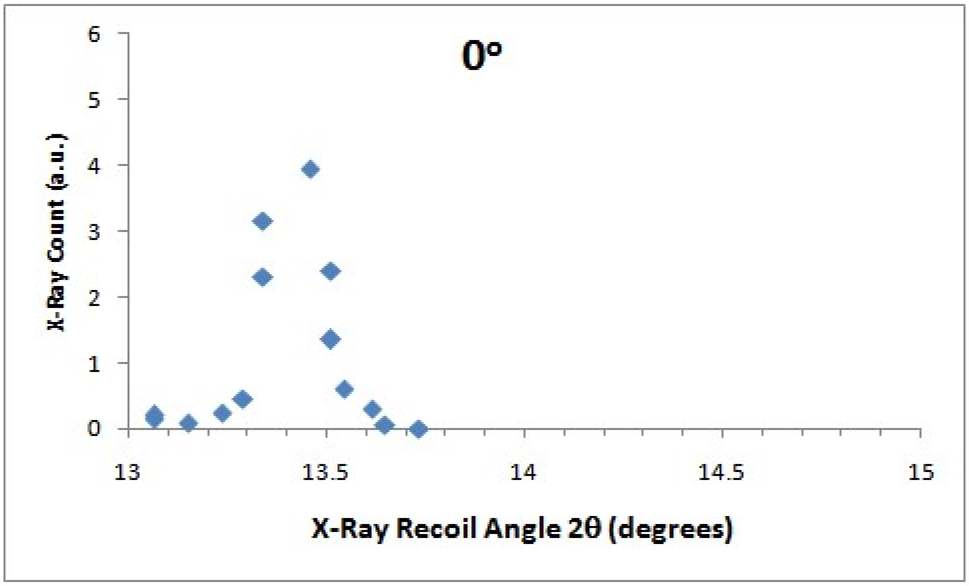
3) Plot your data is such a way as to obtain a straight line. Comment on how well these data support Compton's theoretical prediction. What is the slope of your line, and how well does it compare to the theoretical value? Compute a percent difference.

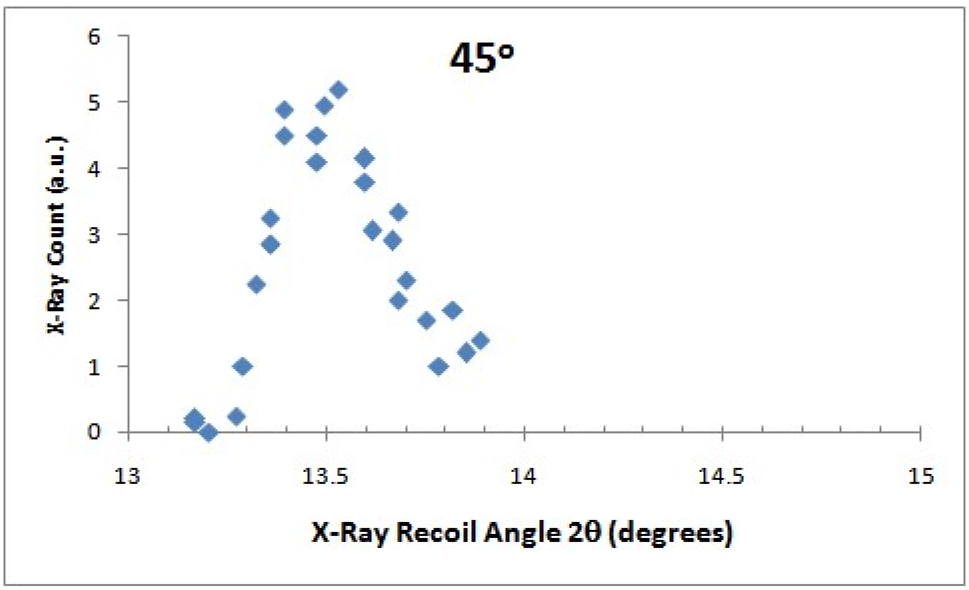
---

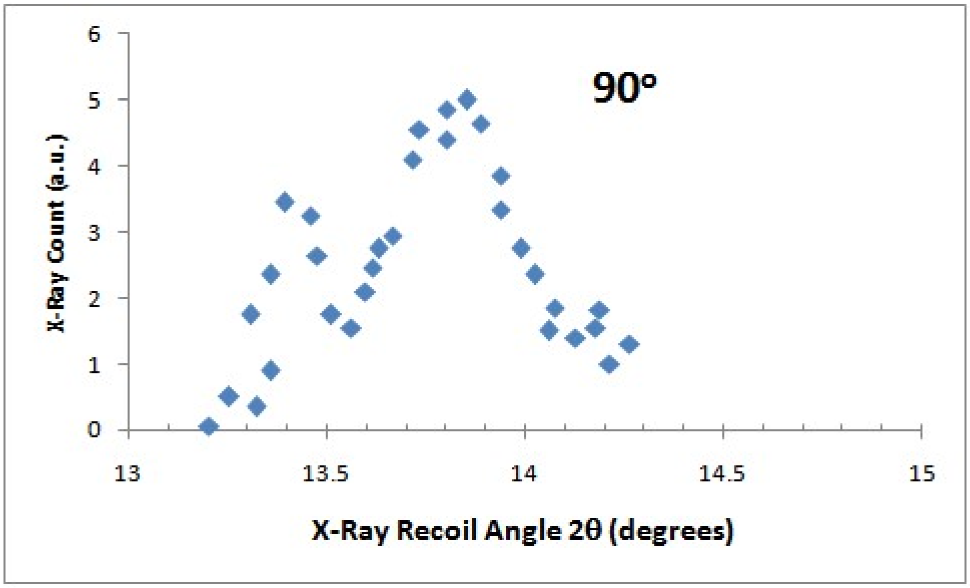
[1] These data were taken from Compton's original paper and transcribed by Mr Russell Scott. Compton, Arthur H., 'The Spectrum of Scattered X-Rays,' *Phys. Rev.* **22** 5 p409 (1923).

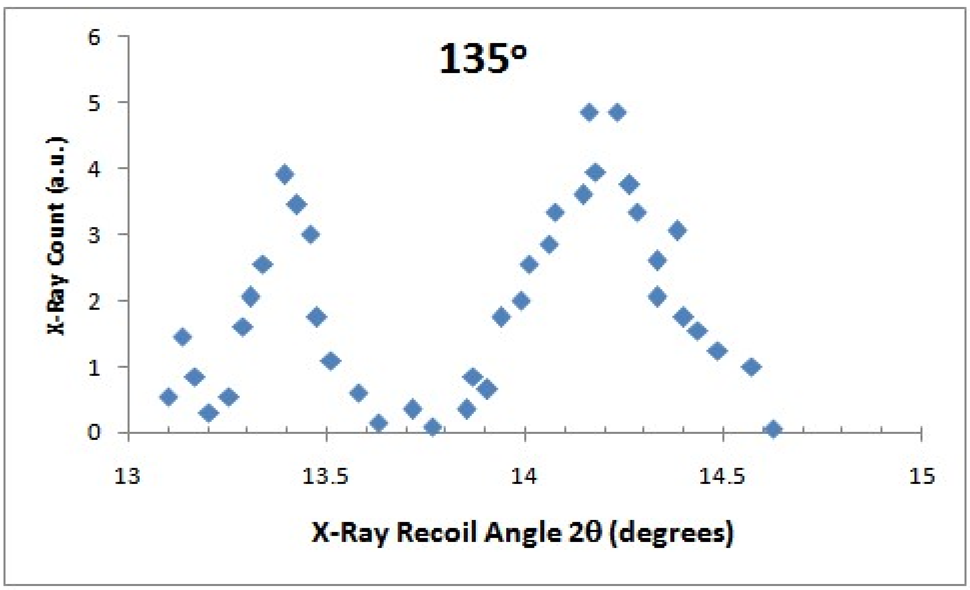
[2] Your instructor will indicate the method to use for this; see the Appendix to this exercise for a description of each.

WORKSHEETS FOR COMPTON EFFECT ANALYSIS





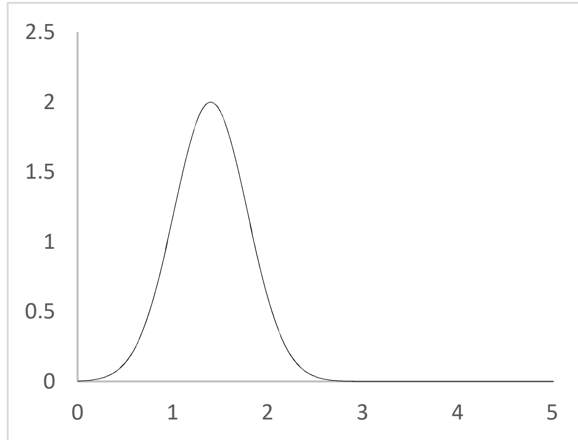




Data for these worksheets were adapted by Russell Scott from:

Compton, *Phys. Rev*. **22**, 411 (1923).

APPENDIX

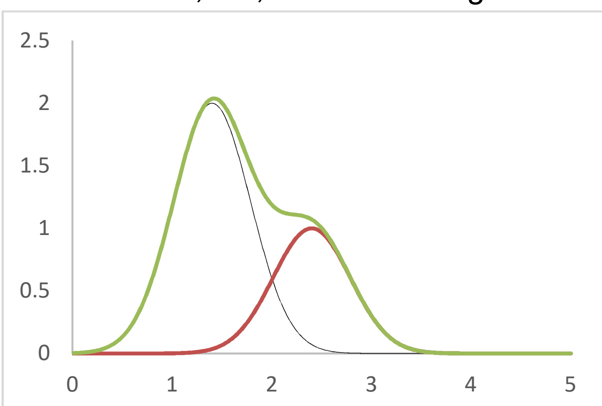


The Gaussian curve is just one of many we could use to fit the data points, but it is fairly easy to analyze.

The mathematical formula for such a curve is

$$y(x) = A\, e^{\frac{-(x-x_o)^2}{w^2}},$$

where A is the maximum value of the curve, x_o is the location of the maximum, and w is related to the width of the curve. Often, two Gaussian curves overlap, but we can only see the sum of the two, as in the figure below. We would like to be able to deconvolute the two curves, so that they can be analyzed independently. For this exercise, we are interested only in the peaks of the two curves, *i.e.*, the double angle of the diffraction maximum.



Your instructor will ask you to find these maximums in one of two ways. The first method is to make use of the worksheets included with this exercise and draw by hand the gaussian curves. The location of the peak can then be estimated by eye. The second method makes use of a feature in Excel called *Solver*. Open the Excel workbook *Compton Data.xlxs*. The same data as in the worksheets appear in each of four spreadsheets.

Start with the 0° worksheet. Theoretically, there is only one curve to fit here. A gaussian curve is already programmed into the sheet, but you can change the shape by adjusting the height, center double angle, and width parameters. The R^2 factor is the same one you're familiar with from fitting a line to data. Try to guess vaules of the parameters so as to maximize the value of R^2. Record the center double angle value.

Move on to the 135° worksheet. Here, there are two gaussian curves already calculated. You must adjust six parameters to maximize the fit to the data, and then record the center double angles for each. Try your best; we'll come back to these data later.

Go to the 90° worksheet. Once again, the calculations have been done for you. The parameters to fit two gaussian curves to the data and the resulting R^2 value are near the top of the sheet. Excel's Solver is able to adjust a number of parameters in order to optimize a particular condition. Enter what you think are reasonable guesses for the six parameters. Click the DATA tab, then Solver. In the Solver box, enter the location of the cell containing the R^2 value, and click the MAX button. While holding down the CTRL key, click the cells containing the guessed parameters, then hit the SOLVE button. Solver's optimal values will appear in the cells, and the

R^2 value will update. If the fit line does not match the data well (this does ocassionally happen), try guessing other initial values and repeat.

Return to the 0° and 135° worksheets and unlock them. Repeat the procedure above and optain best estimates of the center double angles.

Move on to the 45° worksheet. Here, you are expected to program the sheet yourself. The formula for R^2 is

$$R^2 = 1 - \frac{\sum_i (y_i - y_{AVE})^2}{\sum_i (y_i - Y_i)^2},$$

where y_i is the X-ray count for the i-th double angle, y_{AVE} is the average of all count values, and Y_i is the fitting function's value for the i-th double angle.

1) Calculate the average of all count values given in the worksheet.
2) Using the values in the six parameter cells near the top of the sheet, program in a fit curve using this formula:

$$Y_i = H_1 e^{\frac{-(2\theta - 2\theta_1)^2}{w_1^2}} + H_2 e^{\frac{-(2\theta - 2\theta_2)^2}{w_2^2}}$$

where the Hs are the respective heights, the ws the respective widths, and the $2\theta_i$s the respective center double angles.

3) Program in the R^2 function as given above.

4) Run Solver again to get a best fit and record the center double angle.

Lab 506 - The Photo-electric Effect

OBJECTIVE

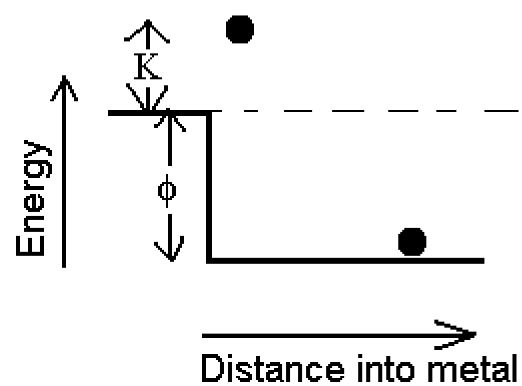
To measure the work function of the metal in the Pasco tube; to determine a value for Planck's constant, h.

BACKGROUND

In Einstein's model of light, energy is carried by particles called *photons*, each with an energy dependent on the frequency of the light:

$$E_{PHOTON} = hf = hc/\lambda$$

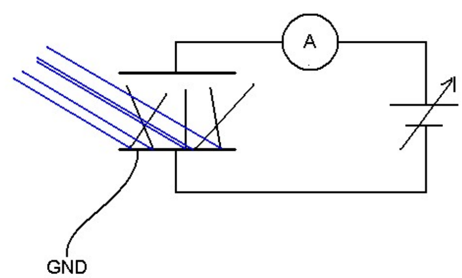
When one of these particles is incident on a metal surface, it is absorbed by an electron in the metal, which acquires the photon's energy. If enough energy is transferred, the electron will leave the metal with kinetic energy, K. However, in order to penetrate the surface barrier of the metal, a minimum amount of energy is necessary, now called the *work function*, φ.



Since there may be losses of energy during the process, we usually write that

$$K_{MAX} = hc/\lambda_{MIN} - \varphi_{MIN} \quad \text{(Eq. 1)}$$

The kinetic energy of the electrons emitted into vacuum can be measured by placing a collector electrode near to the metal (now called a *photocathode*). Connect a source of potential difference, as shown. If the collector plate is held at the same potential as the photocathode, electrons of sufficient energy will be emitted in random directions, as shown. If the collector is made positive, the electrons will be attracted to the plate; if it is positive enough, virtually all of the ejected electrons will be collected. In this situation, the current can be monitored as a function of light intensity.[1] If instead the collector plate is made negative, it will repel the ejected electrons; only electrons whose kinetic energy is greater than $q\Delta V$ will cross the gap. By measuring the *stopping potential*, the potential difference at which the



[1] The Pasco and Cenco apparatus are not capable of making this measurement.

current goes to zero, we can find the maximum kinetic energy, and from that the work function. By making these measurements at a number of light wavelengths, we can fit the data to Eq 1 and determine a value for h.

PROCEDURE

For the CENCO apparatus, you can control only the reverse bias of the tube. Attach a zeroed galvanometer to the current output on the PEE box. Adjust the height of the mercury source so as to be opposite the window to the phototube. Rotate a filter into place and turn on the lamp. Turn the room lights off and if possible, cover the apparatus with a black cloth. Adjust the reverse voltage until the current goes to zero; the voltage at this point is the stopping potential for that wavelength. The built-in filters are long-pass filters each with a cutoff just to the short side of a bright mercury line. Determine which mercury line each filter corresponds to.

The PASCO apparatus is designed a bit differently than the apparatus described above. The photo-tube acts like a capacitor that gets charged by the transfer of electrons from one plate to the other. Like for any other capacitor, the potential difference between the plates increases as more change is transferred. This potential difference is monitored using a high impedance *operational amplifier* as a source follower. When the potential difference across the tube reaches the stopping potential, charging stops (no more charge can cross the gap between plates); the stopping potential is then read directly from the op amp's output with a voltmeter. The filters are labelled with the

Determine the bright emission lines of the mercury vapor lamp. Match each of them if possible to one of the transmission filters. Plot your data is such a way as to obtain a straight line. Determine the values of the work function and Planck's constant. Compare your values to the accepted values: $\varphi = 1.41$ eV and $h = 4.14 \times 10^{-15}$ eV-s.

Lab 14 - The Franck – Hertz Experiment

OBJECTIVE:

To observe evidence that atoms (such as neon and mercury) have discrete energy levels.

BACKGROUND

One year after Bohr's model of the atom explained the optical spectrum of hydrogen as energy released by electrons as they dropped from one discrete energy level to another within the atom, the Franck-Hertz experiment demonstrated by independent means the existence of these discrete levels in mercury gas and the correspondence with observed emission lines.

Figure 1 shows the basic apparatus. The grid on the left is present only in the neon tube, not in the mercury tube. The heater on the left boils electrons off of the attached wire, which fly into the tube. They are accelerated by the potential difference V_G; some pass through the grid on the right and are decelerated by a reverse bias V_T. If the electrons make it to the plate on the right, they are measured as a current by the ammeter.

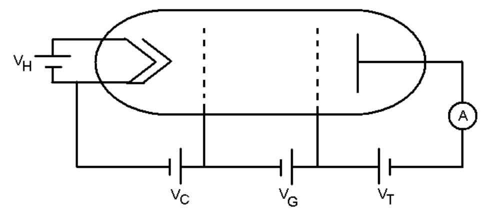


Figure 1 - Schematic of Franck-Hertz tube.

The basic concept is that electrons that have a kinetic energy less than 4.9 eV (this corresponds to the transition from ground state to first excited level) do not interact with the mercury atoms, since there is not enough energy to raise an electron. However, if V_G is large enough, the electrons near the plate do have more than 4.9 eV of energy, and a collision with a mercury atom results in a transfer of energy to the atom. Two things happen: as the atom returns to the ground state, it emits a characteristic wavelength of light with energy 4.9 eV (= 2530 A), and the electron starts to accelerate again. If V_T is set to prevent slow moving electrons from hitting the end plate, the current will drop. Raising V_G will accelerate the electrons more quickly, so that after one collision, they still have enough energy to make it to the plate. If V_G is high enough, the electrons may even gain enough energy to have a second collision with a different atom, thus lowering the current again. So, what should be observed is a I-V curve with minimums separated by about 4.9 Volts.

The theory for the neon tube is the same, except that the critical voltage difference is about 19 Volts and the transition corresponds to a rise from the 2s to the 3p level. The visible emission corresponds however to a drop from 3p to 3s.

PROCEDURE

1) Turn the control box off. Turn all knobs on the control box to the left. Connect the tube to the control box as directed. Connect up the oscilloscope in XY mode.

2) Set to Ramp and set filament voltage V_H (*Heizung*) to about 8 volts. Wait about 2 minutes for the cathode to warm up.

3) Turn the accelerating voltage (V_G) to about 70 volts for neon. Observe the I-V curve on the scope. You may need to increase the heater voltage and adjust the reverse bias (*Gegenspannung*) to optimize the curve.

4) Measure the spacings between the minimums of the I-V curve. Average and compare to the accepted value (4.9V for Hg, 19V for Ne). Remember that the voltage displayed on the oscilloscope is one-tenth of the actual V_G.

Lab 508 – Diffraction of Electrons

OBJECTIVE

To verify the wave-like nature of small particles.

BACKGROUND

In 1924, De Broglie postulated that, if light can be thought of as a particle, perhaps particles can be thought of as waves. For photons, the momentum is given by

$$p = \frac{h}{\lambda},$$

so then we might expect the wavelength of a particle to be given by

$$\lambda_{de\ Broglie} = \frac{h}{p}.$$

Several years later, Davisson and Germer performed an experiment analogous to X-ray diffraction, in which electrons were incident on a crystalline target. The resulting angular dependence of the scattering matched the pattern seen for X-Rays, thereby confirming the wave nature of electrons.

In a vacuum tube, non-relativistic electrons are accelerated across a potential difference ΔV, thereby acquiring kinetic energy

$$\mathrm{K} = \mathrm{e}\,\Delta\mathrm{V} = \frac{\mathrm{p}^2}{2\mathrm{m_e}},$$

resulting in a theoretical De Broglie wavelength of

$$\lambda_{\mathrm{dB}} = \frac{\mathrm{h}}{\sqrt{2\mathrm{m_e e}\,\Delta\mathrm{V}}}. \quad (\mathrm{Eq.}\,1)$$

Making use of the Bragg diffraction criterion for X-Rays, we see that waves scattered at angle theta from a set of parallel planes of spacing d will have a wavelength of

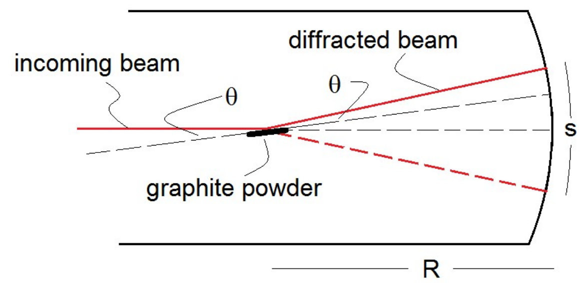
$$\lambda = \frac{2\mathrm{d}\,\sin\theta}{\mathrm{m}}, \quad (\mathrm{Eq.}\,2)$$

where m is the order of the diffraction maximum and d is the plane spacing. The material used in this experiment is graphite, with plane spacings d_{10} = 2.13Å (inner ring) and d_{11} = 1.23 Å (outer ring).

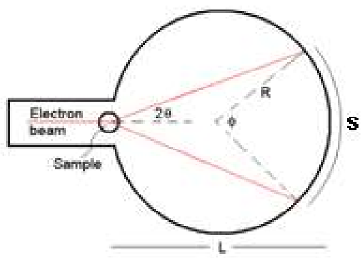
Since the crystal target is poly-crystalline, the scattered electrons strike the phosphorescent screen in a ring pattern and the scattering angles can be measured.

There are two types of tubes available for this lab experiment. The first one has a flat-ish screen for which the angle θ can be determined fairly easily by

$$\theta = \frac{s}{4R}$$



where s is the arc-length corresponding to the diameter of the diffraction ring measured along the screen on the screen and R is the distance from the sample to the screen.



For the round tubes, the situation is more complicated. Let s be the diameter of the ring as measured along the curved surface of the tube. Do not measure the diameter directly and try to use the relationship above; different diameter rings will be different distances L from the sample. The angle phi is given by

$$\phi = \frac{s}{R},$$

where R is the radius of the tube. Let L be the distance from the sample to the screen. Then, a short derivation indicates that

$$\theta = \frac{1}{2}\, arcsin\left(\frac{\sin(\frac{\phi}{2})}{\sqrt{\left(\cos\left(\frac{\phi}{2}\right) + \frac{L-R}{R}\right)^2 + sin^2(\frac{\phi}{2})}}\right).$$

PROCEDURE

1) Make certain that the High Voltage supply is turned off and that the HV control is set all the way CCW. Connect the high voltage and cathode heater power supplies to the tube as directed.

2) Turn the heater supply on and let it run for at least a minute so that electrons will be thermally ejected from the cathode.

3) Turn the HV supply on and slowly increase the accelerating voltage until diffraction rings are clearly visible.

4) Measure the diameters of the rings in a manner appropriate for your tube shape and record the corresponding accelerating potential. You should measure the diameters on the inside edges of the rings; this is where the most energetic electrons should impact the screen.

5) Adjust the potential to several other values (over as large a range as possible) and measure the corresponding ring diameters.

6) Calculate the theoretical De Broglie wavelengths of the incident electrons from Eq. 1. Calculate the measured De Broglie wavelengths of the diffracted electrons from Eq. 2. Plot these data in such a way as to generate a straight line. Comment on the agreement between theory and your experimental results.

Lab 509 – Particle in a Box: Quantum Dots

OBJECTIVE

To verify the relations derived for a particle in a box with impenetrable walls.

BACKGROUND

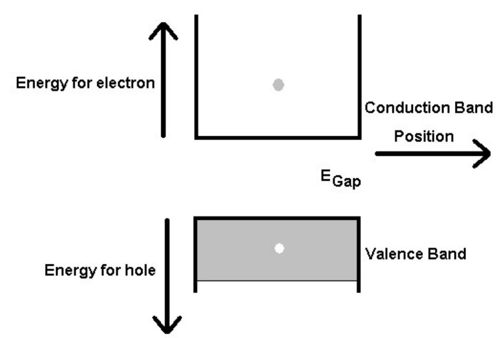
A *quantum dot* is a small particle or inclusion within a larger piece of material (approximately 10-50 times the diameter of an atom) in which small particles such as electrons may be confined. In class, we determined that the bound energy levels of an electron in a one dimensional square potential well with impenetrable walls is

$$E_n = \frac{n^2\pi^2\hbar^2}{2mL^2}$$

A similar, though much more difficult, derivation for a particle in a spherical container of radius R results in a similar relationship:

$$E_n = \frac{n^2\pi^2\hbar^2}{2m_e^*R^2}$$

In the present situation, however, additional terms and corrections must be introduced.



First, consider that almost all of the electrons in a semi-conductor are bound to atoms; these electrons are said to be in the material's *valence band*. It requires a certain amount of energy to lift an electron out of the atom so that it may move around freely within the material (in the *conduction band*). The minimum amount of energy necessary is referred to as the band gap of the material, E_{Gap}. For this particular material, E_{Gap} is 1.344 eV at room temperature. Often, a diagram similar to the one at right is drawn, with energy on the vertical axis and position (in 1d only) on the horizontal axis. Now, when an electron is removed from its usual position, it leaves behind an empty space. Many electrons can move around in the valence band, but it is much easier to follow the motion of the empty space than to follow the positions of the many electrons around that space. As an analogy, consider a bubble in a beer glass. The bubble is actually a region in which there is no beer; rather than describe the complicated motion of the beer moving downward in the glass, it is much easier to describe the motion of the bubble upward. In the same way, we define a new particle, the *hole*, as a location at which we expect to see an electron, but don't. Note that the energy for a hole increases toward the bottom of the figure, since a hole moving downward actually corresponds to real electrons moving upward to higher energies.

Once enough energy is transferred to the electron, it will jump to the conduction band, then fall into the lowest stationary state allowed in the 'box' according to the equation above. The hole, also, will 'fall' into its lowest stationary state:

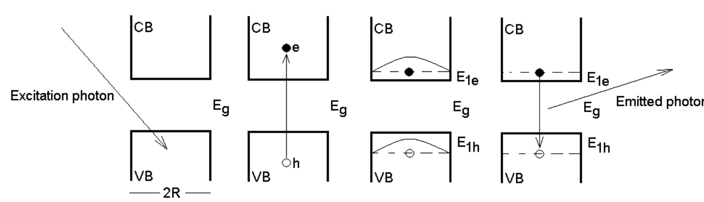
$$E_n = \frac{n^2\pi^2\hbar^2}{2m_h^* R^2}.$$

Other corrections are necessary. For example, the electron in the box is not moving through vacuum but rather through a semi-conductor material. As a result, the *effective mass* (in this particular material, m_e^* = 7.29x10^{-32} kg) must be used. Similarly, the hole also has an effective mass: in this material, m_h^* = 5.47x10^{-31} kg. Note that the effective masses and the bandgap energy are determined from measurements in a larger bulk sample, where the quantum effect being investigated is not seen.

The last step is that the electron falls out of the conduction band and recombines with the hole, emitting a characteristic energy photon:

$$E_{1,1} = \frac{\pi^2\hbar^2}{2m_e^* R^2} + \frac{\pi^2\hbar^2}{2m_h^* R^2} + E_g \qquad (Eq.1)$$

You will verify this relationship by exciting the production of an electron-hole pair with ultraviolet light (E_{Photon} = 3.07 eV using the keychain source or 3.40 eV using the lamp). This energy lifts the electron out of the hole into the conduction band. Then both particles fall into their ground states. After some time, the electron falls back into the hole in the valence band, emitting its characteristic energy photon (note that there is some spread in the energy released).



The four samples of quantum dot solutions are identical except for the size of the dots. Radiuses given by the manufacturer are

Green	2.367 nm
Yellow	2.534 nm
Orange	2.718 nm
Red	2.925 nm

PROCEDURE

1) Mount the rack of solution cells so that only one can be observed by the spectrometer.
2) Excite the material in the cell with a UV light source.
3) Record the emission spectrum and determine the peak output wavelength.
4) Calculate the theoretical emission energy using Eq 1.
5) Calculate the observed emission energy using $E_{ph} = hc/\lambda$.
6) Repeat for the rest of the cells.
7) Plot your points on a graph in such a way as to obtain a straight line.
8) Comment on the validity of the theory.

Lab 510 – The Emission Spectrum of Hydrogen

OBJECTIVE

To verify the predictions of Bohr's planetary model with regards to the differences in energy levels by measuring the energy radiated during Balmer line transitions.

BACKGROUND

Bohr's planetary model assumes that electrons can orbit the hydrogen nucleus only with certain well defined energies, given by

$$E_n = -\frac{me^4}{8\varepsilon_o^2 n^2 h^2} \qquad n = 1, 2, 3, \ldots.$$

Photons emitted by electrons changing orbits must have energies given by

$$E_{n_f \to n_i} = \frac{me^4}{8\varepsilon_o^2 h^2}\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) = 13.6\ eV\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \quad n_i > n_f$$

Only four such lines are visible to the naked eye. They are all in the *Balmer series* ($n_f = 2$) and correspond to $n_i = 3$ through 6. Spectrometers with sensitivity into the UV and near-IR can record several others. The $n_f = 1$ and the rest of the Balmer series are in the UV, while all other lines ($n_f > 2$) are in the infrared.

Atoms other than hydrogen follow the same behavior, with the nuclear change replaced with Ze, so long as there is only one electron:

$$E_{n_f \to n_i} = 13.6\ eV\ Z^2\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \quad n_i > n_f$$

The introduction of even a second electron distorts the energy function of the first enough to render this result invalid. However, atoms with one outer electron follow this relationship approximately due to *shielding*.

PROCEDURE

1) Calculate the wavelengths of the first seven or eight Balmer emission lines of hydrogen.
2) Use the spectrometer to record the emission spectrum of hydrogen gas. Identify the wavelengths of all lines.

3) Try to match each line to one of the predicted emission lines of hydrogen. Plot your data in such a way as to obtain a straight line. Comment on the validity of the Bohr model.
4) Try to identify any other lines that may have been recorded. If you are successful, add these to your graph.
5) *Repeat this experiment with helium. Predict the emission lines from an ionized atom and try to match the observed lines to the theoretical lines. How valid is the Bohr model for helium?

Lab 511 – Simulated Radio-active Decay

OBJECTIVE

To study the rates of radio-active nuclear decay through simulation.

BACKGROUND

Spontaneous emission of radiation is fairly common and is the result of the decay or disintegration of unstable nuclei. Three types of radiation can be emitted by such a radio-active material: alpha (α) particles (helium nuclei comprising two protons and 2 neutrons); beta (β) rays (either electrons or positrons); and gamma (γ) rays (high energy photons). One important characteristic of this process is that the probability of decay P of any one nucleus in a given time interval *d*t is proportional to the length of that interval, or

$$\mathrm{P} = \lambda\, d\mathrm{t}.$$

If there are some number N of nuclei at the beginning of some time interval, then the number of nuclei that are expected to decay by the end of the interval, -dN, is

$$-d\mathrm{N} = \mathrm{P\,N} = \lambda\,\mathrm{N}\,d\mathrm{t}.$$

Re-arranging this relationship leads to the familiar differential equation you encountered in PHYS 2:

$$\frac{d\mathrm{N}}{d\mathrm{t}} = -\lambda\,\mathrm{N}.$$

Often, it is stated in textbooks that the rate of nuclear decay in a sample is proportional to the number of atoms that are present. Although this statement is true, it sounds a bit like magic and obfuscates the true reason for this behavior, developed from the equations above. The solution of this equation is well-known:

$$\mathrm{N(t)} = \mathrm{N_o e^{-\lambda t}}\,.$$

The decay parameter λ is often described in terms of a quantity called the half-life, $t_{1/2}$. The half-life is the amount of time after which only half of the original nuclei are expected to remain.

$$\mathrm{N}\left(\mathrm{t}_{1/2}\right) = \tfrac{1}{2}\mathrm{N_o} = \mathrm{N_o e^{-\lambda t_{1/2}}}$$

$$\frac{1}{2} = e^{-\lambda t_{1/2}}$$

$$t_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

After an additional half-life, only half of the half, or one quarter, of the original number will remain un-decayed. After each subsequent half-life has passed, half of the remaining nuclei will have decayed.

The *activity* A of a sample is the rate at which nuclei decay:

$$A = -\frac{dN}{dt} = \lambda N_o e^{-\lambda t}.$$

Generally, this is the quantity that is actually measured.

PROCEDURE

1) You will use special dice as the substitute nuclei in this exercise. The dice have twelve sides, each with an equal probability of appearing face-up when a die is thrown. If the time interval *d*t is made to correspond to one throw, calculate λ.

2) Starting with 200 dice, roll them, then pick out and count the dice that land with '1' facing up. The number picked out *per* roll is the activity, A. Continue to roll, remove, and count dice, recording the activity for each roll.

3) Plot the activity *v*. time. Determine lambda from the best-fit curve using Excel. Compare this value to that which was calculated from theory. Alternately, give your data to your instructor, who will combine it with that of previous classes.

4) Discuss why the plot of your data does not follow exactly the theoretical behavior expected.