Experiment 5
Light, Electrons, Particles, and Waves

This laboratory consists of a number of different experiments, all of which adress the wave vs. particle nature of photons and electrons - some to play with for a couple of minutes, some to take data. You will work in groups, rotating through the lab.

A. Diffraction of Light
B. Photoelectric Effect (Takes the most time, so read this thoroughly before coming to lab.)
C. Diffraction of Electrons
D. Standing Waves

A. Diffraction of Light

The question of whether light is composed of waves or particles has had a profound effect on modern science. During the 18th century, Isaac Newton was a prominent supporter of the particle theory and most people believed that light consisted of particles. In 1801, however, Thomas Young observed the interference of two light beams, a phenomenon that can be explained much more easily with waves.

Apparatus:

Use care in working with the He-Ne laser; the power of this laser is low enough that you cannot burn your skin, but you can damage the retina of your eye. NEVER look directly into the laser beam - you must also be cautious of reflections from mirrored surfaces (such as watches or jewelry) and take care not to point the laser inadvertently at anyone. If you need to track the beam for purposes of alignment, use a piece of paper. Do not sit in a low chair that would put your eyes at the same height as the laser beam, even if your are out of the path of the laser.

Using a double slit and the relationship **$\lambda/d \approx \sin\theta \approx Y/L$ (see diagram below)**, you will calculate the wavelength of the laser. (see Figures 1 and 2.)

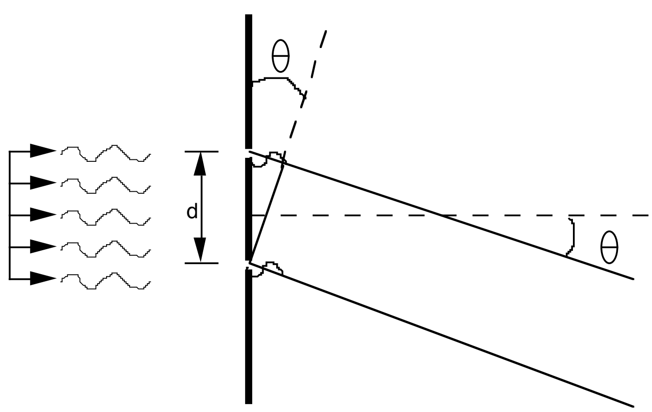


Figure 1 . Diagram showing conditions close to the slits. d is the distance between slit centers. Here, for the first maximum in intensity: $\lambda/d = \sin\theta$. Successive maxima occur at angles given by $\theta = m\lambda / d$ where m is an integer.

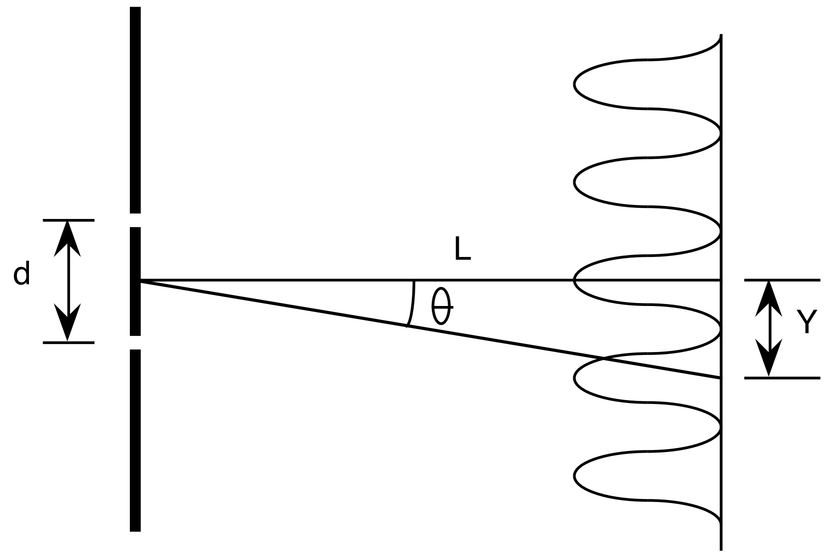


Figure 2 . Diagram showing light intensity at the screen, again assuming the screen is far from the slits.

The angle θ shown in Figure 2 is the direction to the first maximum of the pattern, where

$$\tan\theta = \frac{Y}{L} \sim \sin\theta\,, \text{ for small } \theta.$$

Procedure

1. Measure L and Y_m for several maxima on either side of the central maximum for one of the four double slits on the right side of the glass lantern slide. Put a piece of paper or your notebooks up to the wall and sketch the pattern.

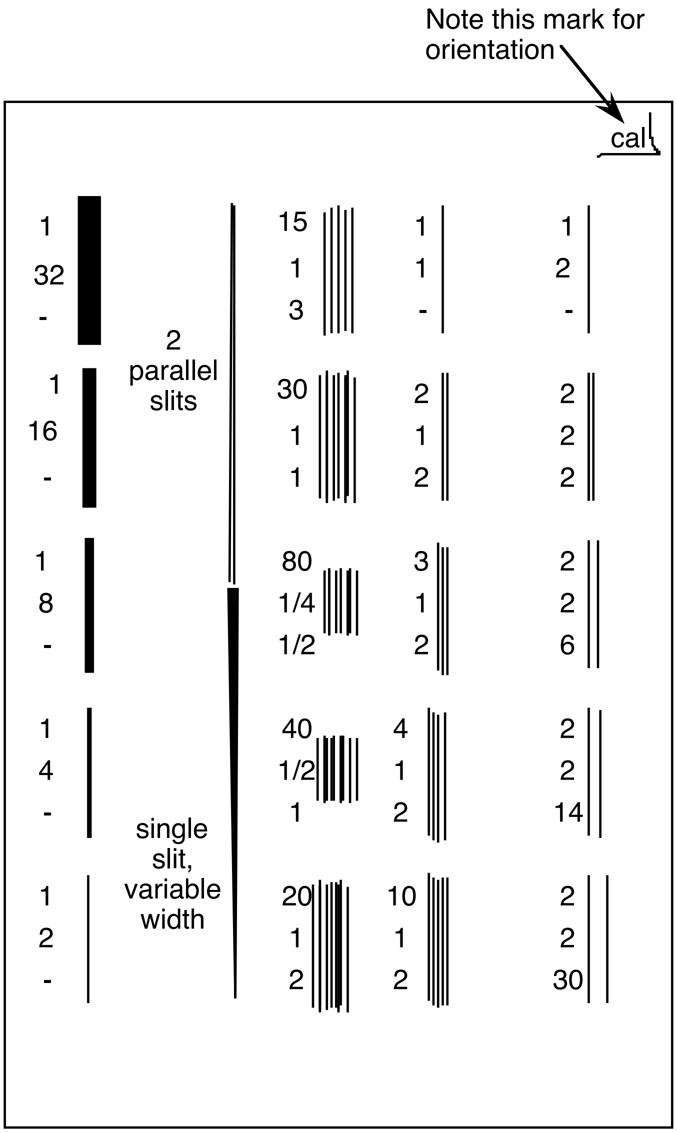
2. Use the following table of slit separations for the right-most row on the slit-plate.
The chart for the entire plate is on the following page. Use a different slit for each person in the group (up to 4).

Second position from top	$d = 4 \times 4.4 \times 10^{-3}$ cm
Third position from top	$d = 8 \times 4.4 \times 10^{-3}$ cm
Fourth position from top	$d = 16 \times 4.4 \times 10^{-3}$ cm

3. Use the formula

$$\frac{m\ \lambda}{d} = \sin\theta_m \sim \frac{Y_m}{L}$$

(where m is an integer) to find λ for the laser. Everyone should calculate λ themselves. Does the value you calculate make sense for the color of the HeNe laser?



The numbers by each set of slits give the following information:

TOP = Number of slits

MIDDLE = Width of slit in eighths of points

BOTTOM = Distance between slits in eighths of points (This distance is between the inside edges of neighboring slits.)

1 point = 0.013837 inch
0.035146 cm

Figure 3. Cornell Aeronautical Laboratory (CAL) Slide (from Physics Department)

The slit separation we want, d, is the distance between the centers of the slits, so d is the sum of the middle number and the bottom number.

***Use the right-most row of slits, skipping the top slit since it is only a single slit.

B. The Photoelectric Effect

During the 1860's, James Clerk Maxwell showed theoretically that disturbances in an electromagnetic field will propagate as waves moving at the speed of light. Maxwell's theoretical work provided convincing evidence that light is an electromagnetic wave.

In 1888, Heinrich Hertz published the results of experiments in which he transmitted and received long-wavelength electromagnetic waves. These experiments helped confirm Maxwell's theory. Also, quite accidentally, Hertz discovered the photoelectric effect. He noticed that when he shined light on a spark gap, a spark could jump a longer distance than in the dark. Hertz did not understand the significance of this discovery, so he did not follow up on it. Fortunately others did. Although Hertz had intended his experiments to support the wave theory, his discovery of the photoelectric effect eventually led others to develop a particle theory for light.

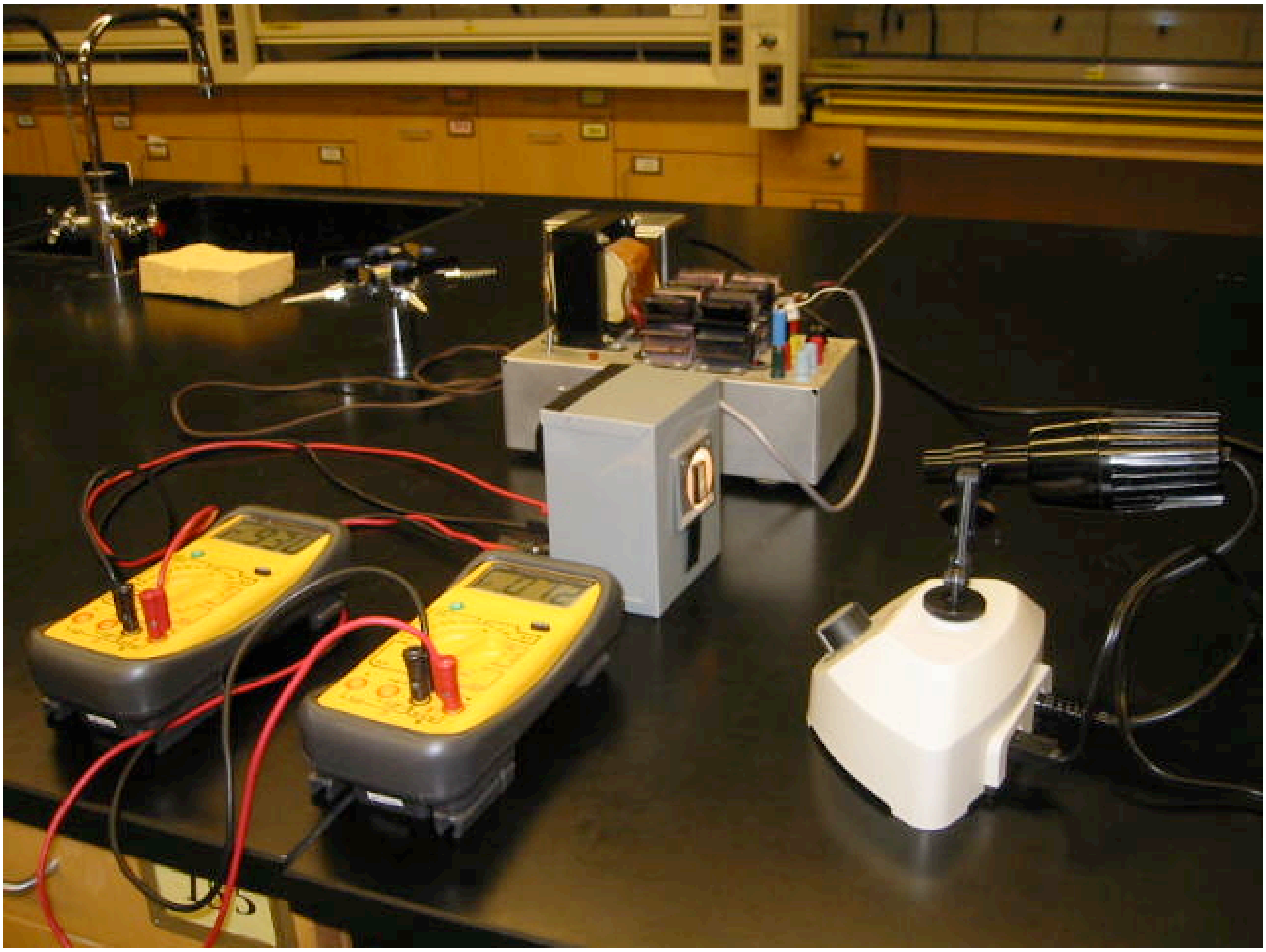
In 1905, Albert Einstein proposed an explanation for the photoelectric effect. He claimed that light comes in discrete bundles of energy which we now call photons. The energy of each photon is simply a constant times the frequency of the light.

$$\text{Photon energy} = h\nu$$

where h is Planck's constant and ν is frequency. A single photon absorbed on a metal surface can kick an electron out of the surface. This theory was able to explain all of the observed features of the photoelectric effect. Robert Millikan decided to test Einstein's theory for the photoelectric effect experimentally. He wrote:

> I spent ten years of my life testing that 1905 equation of Einstein's and, contrary to all my expectations, I was compelled in 1915 to assert its unambiguous verification, in spite of its unreasonableness since it seemed to violate everything we know about the interference of light.

The photoelectric effect, along with other curious observations made in the late 1800's and early 1900's, ultimately led to the development of modern quantum mechanics.



Apparatus:

The main part of the apparatus consists of a phototube mounted inside a gray metal box. A light filter covers the opening in the box through which light shines. (**NOTE: the light filters are fragile and expensive - please handle gently! Do not touch the surface of the filters!**) There is a spare phototube for you to examine. The large curved plate is called the cathode and the wire at the center is called the anode. When light shines on the cathode, electrons are ejected and they travel across the vacuum to the anode. We can observe current flowing around the circuit due to the incident light by placing a current meter in the circuit between the anode and the cathode. (See Figure 4.)

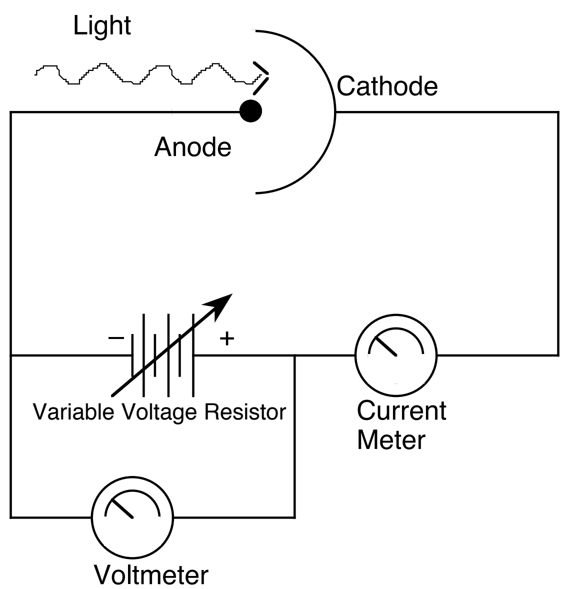


Figure 4. Circuit diagram showing the photodetector, power supply, and meters.

Figure 5. Retarding voltage, V_R, can block the "photoejected" electrons

To study the photoelectric effect, we need to measure the kinetic energy of electrons when they leave the cathode. A clever way to make this measurement is to apply a reverse voltage, V_R, across the phototube. That is, we attach the positive terminal of a voltage source to the cathode and the negative terminal to the anode, as shown in Figure 4 above. We also connect a voltmeter across the voltage source to measure V_R. This reverse voltage opposes the motion of electrons that may be emitted from the cathode, Figure 5. (Since we are measuring a voltage, it is most convenient to use electron volts (eV) as the unit of energy. An electron volt is the change in energy of one electron as it moves across a one volt potential difference. 1 eV = 1.6×10^{-19} Joules.) Now the kinetic energy of an electron ejected from the cathode must be greater than eV_R in order to pass from the cathode to the anode (e is the charge of the electron). If we increase V_R to the point where no current flows through the circuit, we know that the potential energy (eV_R) to be gained equals the initial kinetic energy of the electrons. This voltage is called the stopping voltage, V_S. Therefore, by adjusting V_R until the current meter indicates that no current is flowing, we can simply read V_S directly off the voltmeter.

<u>**Caution:**</u> **•Never shine light directly on the phototube without a filter in place**

Procedure:
First, "zero" the current meter. To do so, block the light beam and set the "zero" on the current meter.

Start with any one of the filters available and place it in the holder (See Figure 6). Each filter lets through light with only a narrow distribution of wavelengths as marked. Turn on the white light source. Always turn off the lamp before changing light filters, since unfiltered light will damage the phototube. Position the light source to direct the light on the filter. Turn on the power supply and the digital voltmeters.

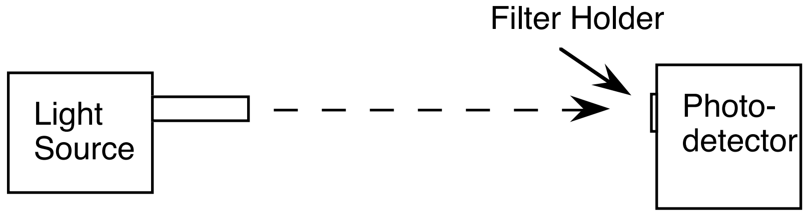


Figure 6. Simple arrangement of light source and detector.

Set the reverse voltage to zero. With the lamp on, check the meter connected to the current amplifier to see if a current is flowing. Use an opaque object to block the lamp to be sure that the current is due to the light.

Vary the light intensity by varying the lamp voltage. **Note what happens to the current.** (The lamp's intensity is not linear with its voltage, so you cannot obtain an exact formula describing the current as a function of light intensity.) **How do your observations fit with the wave vs. particle description of light?**

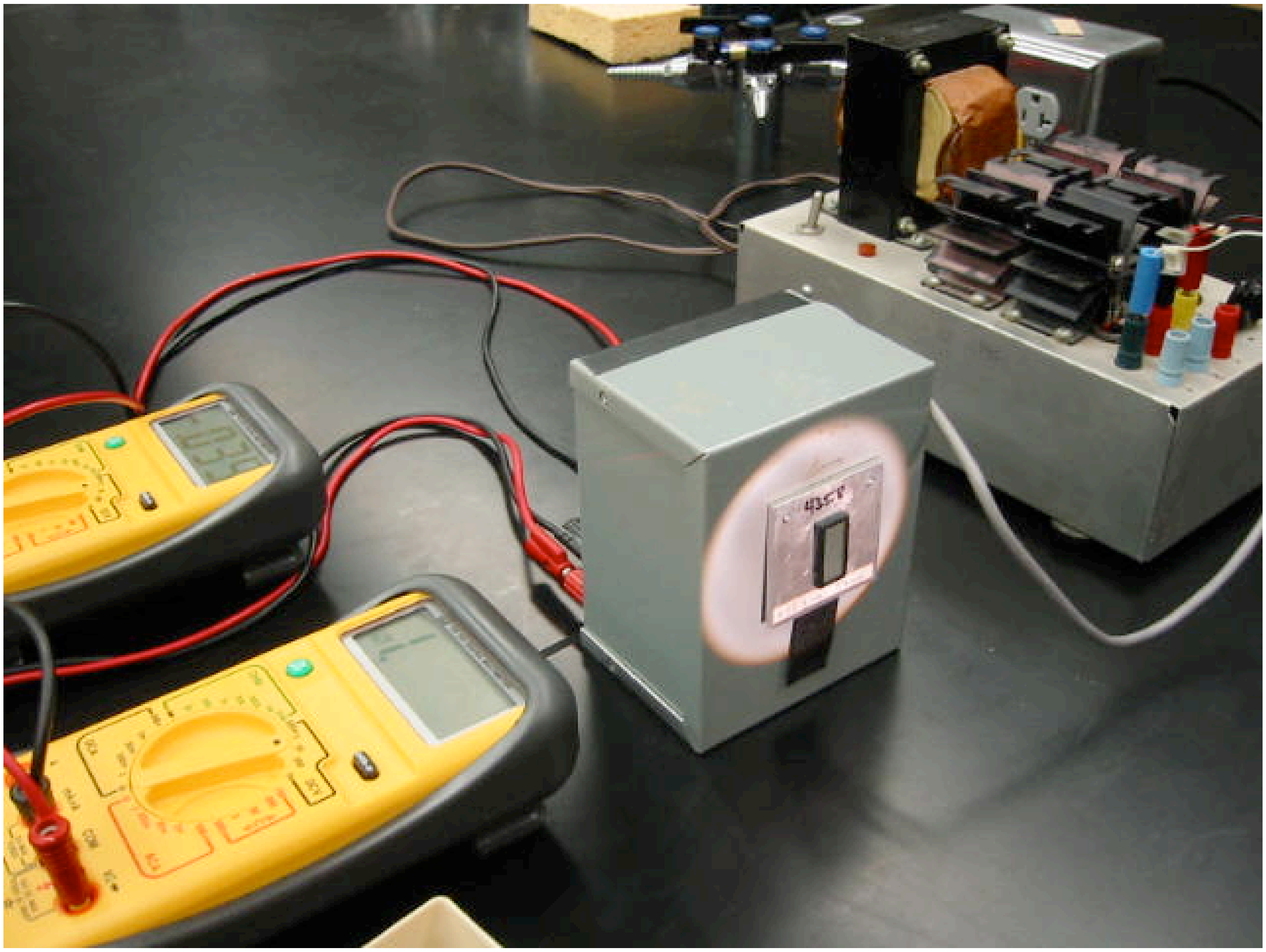
2. Operate the lamp at medium intensity. Increase the reverse voltage until the current stops. (The most sensitive zeroing method is to alternately block and unblock the lamp.) Turn up V_R until blocking the light has no effect on the analog meter. If you increase V_R too much, you may notice that blocking the lamp seems to increase the current slightly. When V_R is too high, the anode behaves like a cathode and emits electrons, so current flows in the reverse direction.

Once you have canceled the current exactly, record the stopping voltage from the digital voltmeter. Repeat the whole procedure several times for each wavelength until you get results reproducible to 0.01 V or better. Average the results of three or more trials if the reproducibility is poor. Make note of the wavelength of the filter.

3. Use the filters provided to measure V_S for 6 different wavelengths of light. Note: 850 nm light will not eject photoelectrons from the cathode. In between each reading, be sure to return the reverse voltage to zero. Calculate the frequency of each wavelength.

Plot the initial kinetic energy, KE, in electron volts (from the stopping voltage) vs. the frequency of the light. Note, plot *KE* versus *frequency* (in sec^{-1} or Hz). Be sure to choose appropriate axes. Draw the straight line that best fits your data and determine the slope and y intercept. Calculate Planck’s constant h and the workfunction of the cathode metal from these results.

To determine the error of the slope graphically, draw two lines which just barely fit through your data points, one line with a smaller slope than the best fit, one with a larger slope. Determine both slopes, and use half the difference as an estimate for the error of the best-fit slope. Alternatively, spreadsheet programs and scientific plotting programs calculate estimates for the error of the linear regression parameters automatically.



C. Electron Diffraction

In the first two experiments, you explored the quantum mechanical behavior of light. Now, let's look at electrons.

Background:

If light, which we generally think of as a wave, can behave like a particle, then can an electron, which we generally think of as a particle, behave like a wave? It turns out, the answer is yes. Louis de Broglie presented the concept of wave-particle duality in 1923. The wavelength of an electron is related to its momentum in the following relationship:

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

where h is Planck's constant, p is the momentum, m is the mass, and v the velocity. So, if electrons behave like waves, they can exhibit some of the effects we have observed for waves such as diffraction.

From McQuarrie, Quantum Chemistry, University Science Books, 1983, pp. 33-34:

> When a beam of X rays is directed at a crystalline substance, the beam is scattered in a definite manner characteristic of the atomic structure of the crystalline substance. This phenomenon is called *X ray diffraction* and is due to the fact that the interatomic spacings in the crystal are about the same as the wavelength of the X rays. ...[A similar pattern] results when a beam of electrons is directed at a similar aluminum foil. The similarity of the two patterns shows that both X rays and electrons do indeed behave similarly in these experiments.
>
> The wavelike property of electrons is used in electron microscopes. The wavelengths of the electrons can be controlled through an applied voltage, and the small de Broglie wavelengths attainable offer a more precise probe than an ordinary light microscope. In addition, in contrast to electromagnetic radiation of similar wavelengths (X rays and UV), the electron beam can be readily focused by using electric and magnetic fields. Electron microscopes are now used routinely in chemistry and biology to investigate atomic and molecular structures.

Apparatus and Procedure

In this set-up, we will shine a beam of electrons through a graphite or aluminum target and observe the pattern of the electrons on a phosphorescent screen. The "target" consists of a thin film of graphite in 3 quadrants and a thin aluminum foil in the fourth quadrant as shown here:

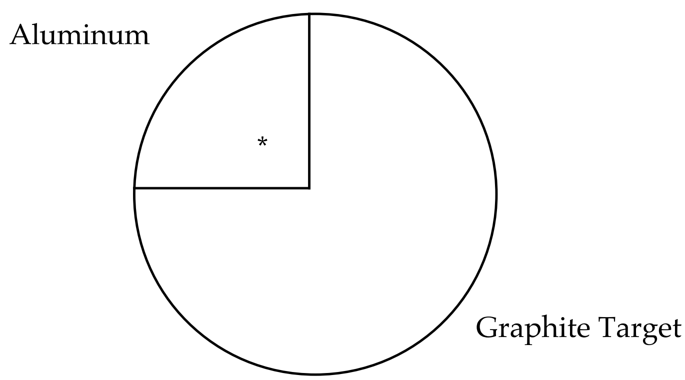


Figure 7. Screen on electron diffractometer

Your instructor will have set up or may help you turn on the instrument.

Things to adjust:
- •The vertical and the horizontal position of the electron beam .
- •Adjust voltage, within range 2-8 kV.
- •Adjust intensity slightly.

•Try moving the electron beam to different spots on the target. Near the asterisks (on the diagram above) is the "sweet spot," the best spot to view cool diffraction pattern of aluminum.

•Note and explain qualitatively the dependence of the diffraction pattern on the applied voltage (i.e. the kinetic energy of the electrons).

D. Standing Waves
This is a quick and fun experiment. Just try not to blow out the fuse on the driver, *please*. Follow specific instructions posted near the apparatus.

Caution: Do not look directly at the UV light source.

Adjust the frequency (course and fine knobs on left side of left box).
Don't adjust any other knobs--we don't have any spare fuses.

Try to get the fundamental ($\lambda/2$) and higher harmonics (multiple waves). Record the corresponding frequencies.

How are the frequencies related for single, double, etc. stable standing waves?

Experiment 5 Worksheet – Waves and Particles

Name ______________________ Lab Partners: ______________________________

Date of Experiment: ___/___/___

Date of Report: ___/___/___

A. Diffraction of Light

What slit spacing did you use? ________________

How far away was the diffraction grating from your paper/notebook?________________

Draw the diffraction pattern and indicate the spacing you measured for your calculation of λ. (This drawing should also be in your lab book.)

What is the wavelength of the laser? ________________nm

Suppose that you could use a beam of very intense white light instead of the laser – what would you observe?

How do the interference patterns you observe vary with the different gratings? (i.e., Note the relationship of the width between the slits versus the width between the fringes.) Can you explain this?

B. Photoelectric Effect

What value did you get for Planck's Constant? How does your value compare to the literature value. Please attach your plot and your calculations.

h = (________________________ ± __________________) Js

How could you use this experiment to identify the metal used as the cathode?

C. Diffraction of Electrons

What is the significance of the rings around the central dot?

How does the diameter of the rings change as you change the voltage? Why?

D. Standing Waves

What is the relationship between the frequencies for the single, double, and triple standing waves? How could you test your hypothesis?