

# Modern Physics Lab

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Photoelectric Effect

10/04

## Purpose of the experiment

- Investigate the photoelectric effect.
- Determine the ratio of Planck's constant to the charge on an electron.

## Background Information

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In 1887, while investigating sparks in a gap between two metals, Heinrich Hertz noted that light falling on the gap made it easier to create sparks. This observation suggested that metals emit electrons when exposed to electromagnetic radiation. This phenomenon is now known as the photoelectric effect. Further experimentation has resulted in several interesting observations:

- 1.) The energy of the emitted electrons increases linearly with the energy of the light above a threshold energy and is independent of the intensity of the light.
- 2.) The emission of electrons occurs almost immediately ( $<10^{-12}$  s) after the light is turned on.

The photoelectric effect was one of the first indications that light is quantized as photons. In 1905, Albert Einstein presented an explanation of the photoelectric effect. He assumed that light of frequency  $\nu$  could be considered to consist of particles (photons) of energy  $E = h\nu$  where  $h$  is Planck's constant. He further assumed that electrons required some minimum amount of energy to escape from the metal. This escape energy is called the work function ( $W$ ) of a metal.

This experiment makes use of a photodiode that is under vacuum. It contains a cathode on which we will shine light of various frequencies. The lamp should be a broad wavelength source such as a mercury lamp or a tungsten-halogen lamp. A monochromator and/or filters are used to break up the light from the lamp into well-defined frequencies (energies) that will be used to study the photoelectric effect. There is a grating inside the monochromator that spreads the light into a spectrum. Additionally, the output of the monochromator passes through a slit to provide some spatial limiting of the output frequencies.

Electrons emitted from the cathode are collected at an anode, giving rise to a small measurable current. A potential is applied between the cathode and the anode. The number of electrons reaching the anode can be changed by changing this potential. If the anode is negative with respect to the cathode with a potential  $V'$ , only electrons with energies  $E$  greater than  $eV'$  will reach the anode. At some potential,  $V_0$ , no electrons will reach the anode. The potential at which this occurs is called the stopping potential.

Thus far, we have only discussed the work function of the metal that the electrons will escape from. This is the cathode's work function  $W_C$ . But, the electrons will also be captured by the anode. Therefore, the anode work function  $W_A$  will also influence our measurements. The easiest way to see this is to look at an energy diagram that represents the energies of electrons in solids. Consider the following diagram:

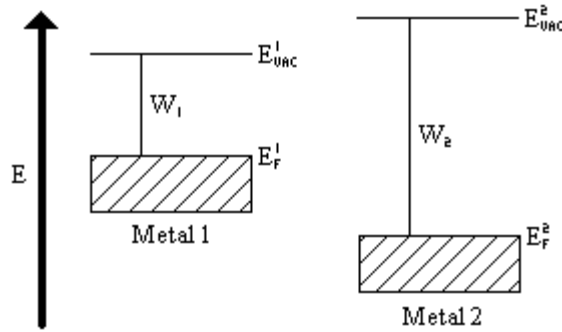


Figure 3: Energy level diagram for two different isolated metals.

In Figure 3, the Fermi energies  $E_F^1$  and  $E_F^2$  represent the energies of the highest filled electron state for each metal. For an electron to escape the metal, it must gain energy. The minimum energy levels needed for an electron to be free of each metal are called the vacuum levels  $E_{vac}^1$  and  $E_{vac}^2$ . Notice that the vacuum levels and Fermi levels are different for each metal. The difference between the vacuum level and the Fermi level is exactly the work function of the metal.

Now, consider what happens if we connect the two metals with a wire. Recall from electrostatics that the potential inside a conductor is constant.

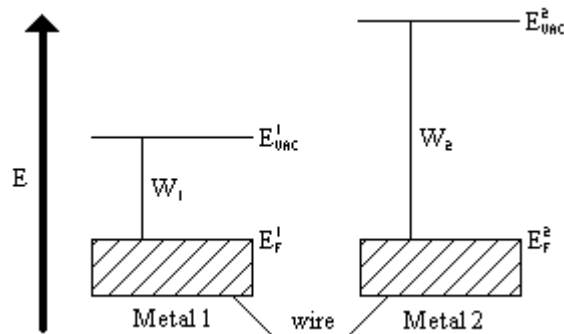
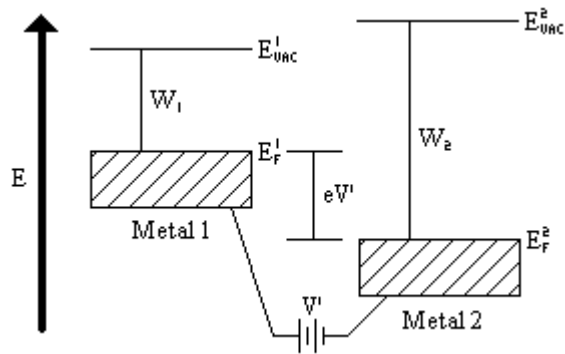


Figure 4: Energy level diagram for two metals connected by a wire.

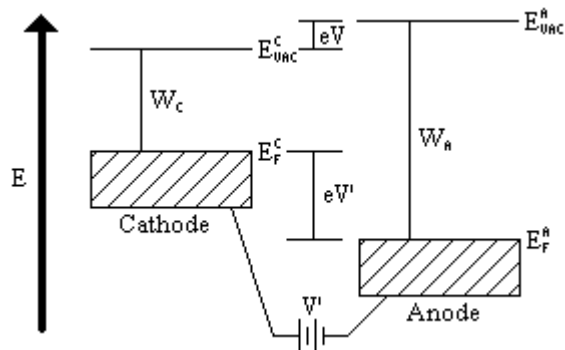
Figure 4 shows that when our two metals are combined into a single conductor by a wire, the Fermi levels are forced to be the same. This is because the electrons will flow from one conductor to the other to fill the lowest available energy levels.

There is one last case to examine. This time, we will connect the two metals together by a battery. As a result, the metals now have a constant potential difference  $V'$  and the Fermi levels have an energy difference of  $eV'$ . This situation is shown below in Figure 5:



**Figure 5:** Energy level diagram of two metals with a potential difference  $V'$  between them.

Finally, Figure 6 presents the relevant energies for a system where we apply a potential  $V'$  between anode and cathode:



**Figure 6:** Energy level diagram of the cathode and anode in the photoelectric effect.

Applying this potential difference between the anode and cathode raises the Fermi level of the cathode. The work function  $W_c$  is the amount of energy needed for an electron to escape from the Fermi level of the cathode to the vacuum level. The amount of kinetic energy which an electron escaping from the cathode will gain (or lose) in travelling to the anode is determined by the potential difference  $V$  between the cathode and anode levels. Conservation of energy allows us to relate the applied potential  $V'$  to the actual potential  $V$  experienced by the free electron (see Prelab).

## Prelab

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- Although quantum mechanics is needed to correctly describe the photoelectric effect, some understanding can be obtained using the classical free electron gas model. In this model, the metal's conduction electrons can be treated as a gas of free electrons surrounding an array of immobile positive charges. Consider a photon of energy  $h\nu$  is incident on the surface of the cathode, which is a metal of work function  $W_C$ . The photon collides with an electron in the cathode, transferring energy to the electron. What is the maximum kinetic energy  $K$  that an electron can have after escaping from the cathode?
- In this experiment, a retarding potential  $V$  (see Figure 4) is used to determine the kinetic energy of the escaping electrons. After receiving energy from an incident photon, an electron is launched from the surface of the cathode and into the retarding potential  $V$ . Using your result from the previous question and the conservation of energy, show that the electron will reach a potential:

$$V = \frac{h}{e}\nu - \frac{W_C}{e} \quad (\text{Equation 1})$$

before coming to a stop and turning back toward the metal. (Hint: This is similar to a projectile motion problem.)

- Using Figure 6 and the conservation of energy, show that the relationship between the work function of the anode, the work function of the cathode, the potential applied by the battery  $V'$ , and the retarding potential  $V$  is given by:

$$W_C + eV' + eV = W_A \quad (\text{Equation 2})$$

- At a particular potential  $V'_O$  applied by the battery (called the stopping potential), we expect the flow of electrons to stop. When the applied potential is the stopping potential  $V'_O$ , we will call the retarding potential  $V_O$ .
  - a.) Explain why the electrons stop flowing.
  - b.) Combining Equations 1 and 2, show that the stopping potential depends on the frequency of light used to free the electrons:

$$V'_O = -\frac{h}{e}\nu + \frac{W_A}{e} \quad (\text{Equation 3})$$

- c.) Equation 3 is the equation of a straight line. What is this line's slope and intercept?

- By continuing to increase our applied potential  $V'$  beyond the stopping potential  $V'_o$ , the vacuum levels will eventually be aligned. For this potential  $V'_s$  and any higher potential, all electrons that escape from the cathode should be collected by the anode. This potential  $V'_s$  is called the saturation potential and is shown below in Figure 7:

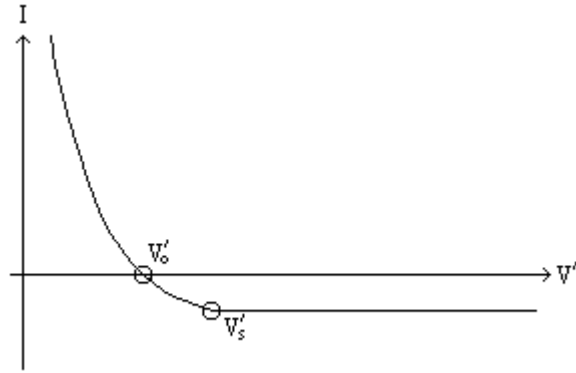


Figure 7: General form of anode current (corrected for dark current) vs. anode potential.

From Equation 2, show that the work function of the cathode is given by:

$$W_C = W_A - eV'_s \quad (\text{Equation 4})$$

## Set Up

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**Warning!** The light source used in this experiment is a high intensity broad-spectrum lamp that emits some ultraviolet light. Avoid direct exposure to the light on your eyes and skin.

Set up the equipment on an optical rail as shown in the figure.

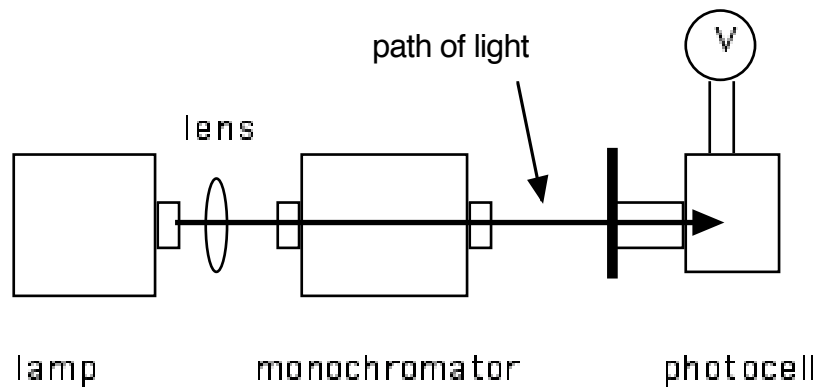


Figure A. Experimental set-up for photoelectric effect.

NOTE: The lens is not necessary when using the Hg vapor lamp.

The Oriel monochromators that we typically use in this experiment have a different grating in them than they normally would have. As a result, the wavelength readout may be half of what you are actually seeing. To test this, turn the wavelength readout to around 250 - 300 nm and see if you see colors. If you do, you are actually seeing the wavelengths 500 - 600 and you should work with the monochromator in the range of 175 - 325 on the dial to see wavelengths of 350 - 650 nm. As you go out beyond 650 nm, you will start to get interference from the 2nd order spectrum and your results may be off since they will be a mixture of two different wavelengths. For more details on how monochromators work, see the PDF tutorials available from Oriel at their web site <http://www.oriel.com/tech/tutori.htm>. See the grating physics tutorial and the ones that describe monochromators.

The Hg lamp requires about 20 minutes to warm up and stabilize so turn it on as soon as you begin preparing the equipment.

Make sure the light from the lamp is centered onto the entrance slit of the monochromator by adjusting the height of the monochromator and the position of the lamp.

The Hg lamp emits a line spectrum with the following characteristic wavelengths and intensities:

Color	Wavelength (nm)	Intensity (mW/5nm)
Ultraviolet	365.483	480
Violet	404.656	220
Blue	435.835	310
Green	546.074	400
Yellow	578	320

In addition we often note a red line around 630 nm. This is not a standard part of the Hg spectrum. Unfortunately, this line overlaps with the UV radiation from the next higher order diffraction and it can not be used in this experiment.

Starting at a monochromator dial setting around 100 nm, sweep through the wavelengths and confirm that you can detect these lines in both the first order and in the second order diffractions. Try to determine, by eye, which wavelength setting on the monochromator corresponds to the brightest output for each line. These values should be close, but not necessarily exact, to the values in the table above.

Make sure the light from the monochromator fills the entrance slit on the photocell. Move the photocell back and forth as needed. If you need to adjust the lateral position of the light, try moving the lamp to one side or the other. Since the Hg source has distinct spectral lines associated with it, you may need to change the wavelength setting on the monochromator to see light coming through it. Usually around 550 nm will give you a bright green light.

Roll the cylindrical light shield on the photocell out of the way so that you can see the white photodiode mask inside the apparatus. Move the photocell apparatus and/or the lamp until the light is centered on the window in the photodiode mask. Then roll the cylindrical light shield back into place.

Turn the power switch on the photo-cell apparatus ON. Turn on the digital volt meter and set it to measure DC volts on a 2 or 20 volt scale.

You are now ready to begin to take measurements.

# The Lab

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**The goal:** To measure the ratio of Planck's constant to the charge on the electron using the photoelectric effect.

**Remember to include the uncertainty  
in your measurement and the units**

This photoelectric apparatus measures the stopping potential automatically for you. The photodiode tube and its associated electronics have a small capacitance which becomes charged by the photoelectric current from the photoelectrons leaving the cathode and being collected on the anode. When the potential on this capacitance reaches the stopping potential of the photoelectrons, the current decreases to zero, and the anode-to-cathode voltage stabilizes. This final voltage between the anode and cathode is, therefore, the stopping potential of the photoelectrons.

To let you measure the stopping potential, the anode is connected to a built-in amplifier with an ultrahigh input impedance ( $>10^{13}$  Ohms), and the output from this amplifier is connected to output jacks on the front panel of the apparatus to allow direct measurement of the stopping potential with a digital voltmeter.

Due to the ultrahigh input impedance, once the capacitor has been charged from the photodiode current, it takes a LONG time for this potential to discharge. To speed things up, a shorting switch labeled "PUSH TO ZERO" allows you to quickly bleed off the charge and be ready for another measurement.

To make a measurement of the stopping potential, press the "PUSH TO ZERO" button and release it. The reading on the digital volt meter should drop to zero when the button is pushed and then jump up to a high value. It will rise toward the stopping potential value. Sometimes it will go back down or oscillate. The critical issue is that you wait until the value seems pretty stable before recording it. Depending on the intensity of the light, this can take about 30 – 120 seconds. If you want to get a better indication of the trend, instead of a digital volt meter you can connect the computer to the output using the Vernier Logger Pro interface.

Once the interface is connected open the Logger Pro software on the computer. You may need to adjust the maximum time for the data collection by clicking on the small clock icon in the top row. Then click on COLLECT in the upper right of the screen to start collecting data. When done, click on STOP. If you want to autoscale, click on the small button with the A on it. Data can be exported to a text file which can be read by Excel or other spreadsheet/graphing programs.

## **Part 1: Light: Waves or Particles ?**

The quantum and wave models of light have very different predictions for the maximum kinetic energy of the photoelectrons. Quantum theory of photons predicts that this energy is independent of the intensity of the light but does depend on the frequency of the light. The higher the frequency, the higher the energy. The classical wave model, however, predicts that intensity of the light will change the kinetic energy. The brighter the light, the greater the energy of the light.

In addition to measuring the stopping potential which is an indication of the maximum kinetic energy of the photoelectrons, we can measure the time it takes for the capacitor to charge. This will give us an indication of the number of photoelectrons produced. Capacitors, however, do not care about the kinetic energy of the electrons, only the number.

Select a wavelength on the monochromator in the range of 350 - 600 nm corresponding to one of the bright Hg lines in a first order diffraction (dial setting might be 175-300). Use the magnetic variable transmission filter slide to adjust the intensity of the light by placing different parts of the filter over the entrance slit to the photocell apparatus.

Record the stopping potential and the time it takes after releasing the "PUSH TO ZERO" button to reach the stopping potential. Do this with each of the filter sections over the slit, giving you data at 100%, 80%, 60%, 40% and 20% transmission.

Choose one additional wavelength corresponding to a different bright Hg line and repeat the experiment.

Does the change in intensity have a strong effect on the maximum kinetic energy of the photoelectrons ? Does it change the number of electrons emitted in the photocell?

Note: The electronics in the circuit does allow some bleeding off of charge from the capacitance at the same time that it is being charged up by the photoelectrons. At lower intensities (where the rate of charge build up is less) this may change your results and cause an apparent change in the stopping potential).

## **Part 2: Measuring $h/e$**

From the theory, we see that a graph of stopping potential vs. frequency of light should allow us to easily calculate both the ratio  $h/e$  and the work function of the anode

Measure the stopping potential at each wavelength of the Hg spectrum in BOTH the first order and the second order diffractions. When looking at the second order yellow and green lines, you will need to use the filters which are provided to remove other unwanted

light. You might measure each one more than once (since more data is always better). Make sure that you wait long enough to get a good value for the stopping potential. This may take at least a minute.

It seems to me that there is a possible problem in this experiment. The electronics causes an apparent (although slight) variation in the stopping potential with intensity. The Hg lamp produces bright lines of different intensity. I wonder if the data could be distorted somewhat by the intensity variation of the lamp? You could try to compensate for this by measuring intensity using the time to reach final value and adjusting the intensity at each wavelength to get about the same time at each wavelength. I am not sure if it is worth the effort, but it might give more accurate results.

Calculate the ratio  $h/e$  and compare it to the accepted value. Compare your cathode work function value with values for typical materials and comment on whether it is reasonable. This experiment works best with a low work function material so you should find a value that is a little lower than most metals. The process used to make the photocell combines antimony with cesium vapor to try to create Cs<sub>3</sub>Sb as the active layer on the cathode.

**Remember to include uncertainty in your measurements and calculations !!!!**

## Shut Down

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- Turn off the power supply on the  $h/e$  photocell box.
- Turn off the lamp.
- Take apart your circuit.
- FYI

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<sup>FYI</sup> The Sanskrit word for “war” translates to “the desire for more cows”.