THE PHOTOELECTRIC EFFECT (PLANCK'S CONSTANT)

OBJECTIVES

To test Einstein's theory of the photoelectric effect, to obtain evidence for the quantization of electromagnetic radiation, to use the data collected to determine Planck's constant, and to measure the effective work function of the electrode in the vacuum photodiode.

REFERENCES

The experiment is described in all modern physics textbooks.

INTRODUCTION

Einstein developed his theory of electromagnetic quanta in 1905 and used it to explain the recently discovered photoelectric effect. He was awarded the Nobel Prize in 1921 for this discovery, *not* for his theory of relativity. The experiment that you'll do was developed by Millikan in about 1910 in an effort to disprove Einstein's theory. After several years of work, Millikan conceded that Einstein was correct.

Einstein's photoelectric equation is based on two basic ideas:

- Electromagnetic radiation is quantized. Light of frequency f consists of quanta – later named *photons* – of energy $E_{\text{photon}} = hf$.
- A photon of energy hf incident on a metal (or semiconductor) transfers its entire energy to a single conduction electron.

If this energy ejects the electron from the metal, the electron is called a *photoelectron*.

Electrons in metals occupy energies up to a maximum called the Fermi energy. The Fermi energy is negative relative to a free electron, indicating that the electrons are bound inside the metal and not free to flow out into space. This energy difference, shown in Fig. 1, is the called the **work function**, W, of the metal. This is the energy you must give to an electron at the Fermi level to kick it out of the metal and turn it into a free election. (Analogous to the ionization energy of an individual atom.) Classically you *do work* on the electron to free it – pulling it through the surface of the metal – which is why the energy needed to remove an electron is called the work function. An electron below the Fermi level needs *more* than W to escape.

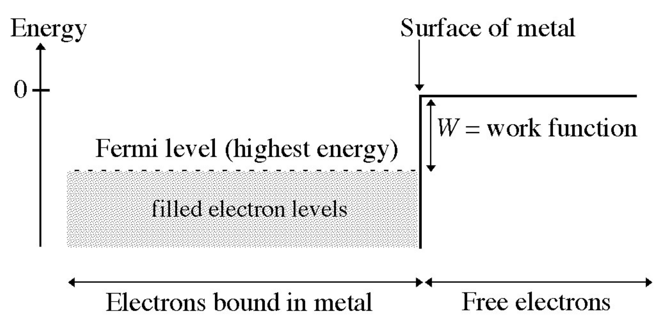

Figure 1. The work function W is the minimum energy needed to remove an electron from a metal.

Suppose an electron absorbs a photon and now has energy $E_{elec} = hf$. If the energy needed to escape the metal is E_{esc}, the photoelectron emerges with kinetic energy $K = E_{elec} - E_{esc} = hf - E_{esc}$. The escape energy varies, depending on how far the electron is below the Fermi level, so the escaping photoelectrons have a *range* of kinetic energies. But the *minimum* escape energy $(E_{esc})_{min}$ is the work function W, because that is the escape energy needed by an electron with the Fermi energy. Thus the *maximum* photoelectron kinetic energy is

$$K_{max} = hf - W. \tag{1}$$

Because K_{max} can't be zero, there is a *threshold frequency*, f_{th}, when

$$f_{th} = W/h. \tag{2}$$

The existence of a threshold frequency is a distinguishing characteristic of the photoelectric effect and was a feature that could not be explained by classical physics. Photoelectrons are observed only if $f > f_{th}$.

In this experiment, photoelectrons are produced by monochromatic light incident on a photocell. The photocell, shown schematically in Fig. 2, is a diode. Light is incident on a low-work-function cathode. Photoelectrons move through vacuum to the anode, then through a picoammeter where the current is measured.

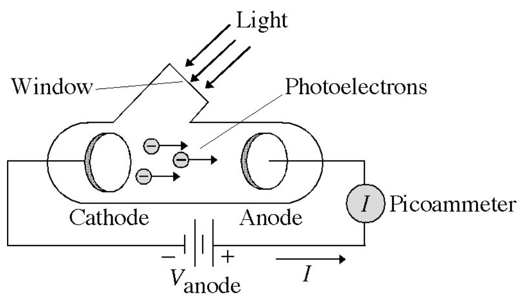

Figure 2. A schematic look at the experiment. Notice that the current I flows in a closed loop. The photoelectrons flowing through vacuum and the electrons moving through the wires are all part of the same current.

The electron's maximum kinetic energy can be measured electrically. If the anode is biased negatively with respect to the cathode, the electrons will be slowed as they approach the anode. Photoelectrons that had too little kinetic energy leaving the cathode will be turned back. The current will decrease as the bias voltage V_{anode} becomes more negative until there comes a voltage $-V_S$ at which the current reaches zero. This is the voltage that stops the most energetic photoelectrons, those with kinetic energy K_{max}. When this point is reached, we can equate K_{max} to eV_S. V_S is called the **stopping voltage** and is positive.

Note: We've defined V_S as a positive number. The anode voltage, relative to the cathode, is $V_{anode} = -V_S$.

Equation (1) can now be written

$$V_S = K_{max}/e = hf/e - W/e.$$

Write $f = c/\lambda$ and let $W = e\phi$. The work function W is an energy (joules), so ϕ is a potential (volts). Numerically, W in eV is the same as ϕ in volts. That is, if $\phi = 2$ V then $W = 2$ eV.

Thus
$$V_S = \left(\frac{hc}{e}\right)\frac{1}{\lambda} - \phi \qquad (3)$$

Equation (3) is the basis of an experiment to measure both Planck's constant h and the work function W of the photocathode. In practice, you need to correct for the contact potential difference between the cathode and anode (see the Franck-Hertz experiment for a discussion of contact potential difference) to find the true work function. The uncorrected "raw" value that you can determine from your data is called the *effective* work function.

EQUIPMENT AND PROCEDURE

Monochromatic light of different wavelengths is obtained using a strong Hg light source and passing the light through a monochromator. Specific wavelengths in the mercury spectrum are then focused on the cathode of the photocell.

The mercury wavelengths available for use in this experiment are:

578 nm (an unresolved blend of two lines at 577 and 579 nm)
546.1 nm
435.8 nm
404.7 nm
365.0 nm

CAUTION: Do not ever allow the full intensity of the mercury lamp to shine on the photocell.

The photocurrent will be measured with a picoammeter. The picoammeter is a very high input impedance voltmeter that measures the voltage drop across the high resistance. The high impedance gives it a long time constant, so be patient as the reading settles to a steady value. The currents are very small, and a critical part of the experiment is the reduction of unwanted currents due to leakage, electron emission from the anode, etc. The photocell is housed in a closed box and shield which provides both electrostatic shielding and protection from the room light.

CAUTION: Do not disconnect the cable between the photocell and the picoammeter. Because shielding is so important, there's considerable risk involved and nothing to be gained by messing with this cable.

CAUTION: Set the picoammeter on the highest current scale (least sensitive scale) before turning it on or before making any electrical changes anywhere in the experiment. Allow it to stabilize before taking serious measurements. Check the zero of the picoammeter when **no** light is falling on the photocell. Also, measure the background current due to ambient light.

Figure 3 shows the experimental set up. The voltage source has both a "coarse" adjust and a "fine" adjust knob. **You can bias the anode either positive or negative relative to the cathode simply by switching the leads from the voltage source.** Note that the photocell shield and the cable shield are grounded.

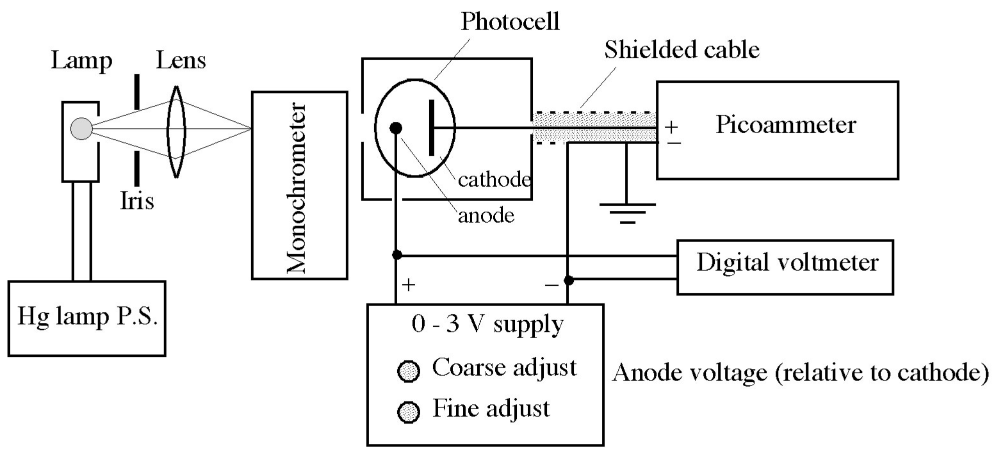

Figure 3. Experimental set up. Make sure you understand how this is the same circuit as Figure 2. Current flows *around* a complete circuit, going *through* current meters.

1. Position the lens to focus a *sharp* image of the lamp on the entrance slit of the monochromator. The lens is used to “gather light” from the lamp.

2. Start with the 546.1 nm wavelength. Turn on the monochromator controller. Press “GoTo,” enter 5461 (*Note*: wavelengths are entered in **angstroms**), and press “Enter.” If you place your eye at the exit slit, you should be able to see green light coming through. Verify that the light goes away if you change the wavelength to 556 nm or 536 nm. Then place the photocell directly behind the exit slit , as close as possible, with the green light centered on the cell.

With the bias voltage at zero, adjust the iris to give a current of a few nA. The wavelength calibration on the monochromator may not be perfect, so vary the wavelength in 1 nm (10 angstrom) steps to maximize the current. After optimizing the monochromator, adjust the iris again to get a current of about 5 nA.

Measure the current-voltage curve between V_{anode} = –3 V and V_{anode} = +3 V. (Note: Positive voltages make the current increase, negative voltages make it decrease.) **Your report should explain why the curve has this shape.**

3. Measure, as accurately as you can, the stopping voltage V_S for 546.1 nm light. As you get to the most sensitive scales, you’ll need to check the picoammeter **zero** when you change scales. Do so by *completely blocking* any light from hitting the photocell.

Enable ZCHK (“ZC” or “ZZ” will be displayed).
Select the 2 nA range and press ZCOR (“ZZ” should be displayed).
Select the range you want to use (or press AUTO for autoranging).
Now allow the light to hit the photocell.
Disable the ZCHK (“CZ” will be displayed) and take a reading.

4. Make measurements to determine the effect of the light intensity on the stopping voltage. You can use the photocurrent when $V_{\text{anode}} = 0$ V as a measure of the relative light intensity.

5. Design and carry out an experiment to measure Planck’s constant and the effective work function of the cathode. Make sure you normalize the light intensity for each wavelength: set $V_{\text{anode}} = +3$ V and adjust the iris to get the same current as with the 546.1 nm wavelength. Also, your experiment should be based on very low current measurements and is thus susceptible to background photons, the photocell’s dark current, and more. Do not record data below 10 pA.

6. Return the equipment to the way it was when you arrived.

REPORT

Among other things, your report should:

- Explain the shape of the current-voltage curve.
- Explain your observations about the effect of the light intensity on the stopping voltage.
- Describe and justify your method for measuring Planck’s constant.
- Determine Planck's constant h, including an experimental uncertainty δh, and compare to the accepted value.
- Determine the effective work function W (in eV) of the cathode.
- Determine the threshold frequency and corresponding wavelength of the cathode.