Lab 5. Photoelectric Effect

(Light is a particle!)

Summary of Einstein's theory

Einstein's theory of photons (contained in section 8 of his 1905 paper) offers the following explanation for the photoelectric effect.

The energy in a beam of light is carried in indivisible packets called *photons*, each of which carries an amount of energy hν, where h is a constant (*Planck's constant*) to be determined from our experiment, and ν (the Greek letter *nu*) ($n = \frac{c}{l}$) is the frequency of the light. (In sections 3-6 of the paper he "present[s] the line of thought ... which led [him] to this view.")

When one of these "energy quanta" strikes a metal surface, it may (if it has enough energy) knock an electron loose from the metal; if there is energy left over the electron will go flying off at high speed. If there is an electrode to collect these flying electrons, a current will flow between the metal surface (the photocathode) and the collecting electrode.

If we think of this speed in terms of "kinetic energy," KE, we must have

$$KE = h\nu - W \tag{1}$$

(equation 1 of Einstein's paper). W is the amount of energy required to knock an electron free from the metal surface; it is a property of the surface. Only if $h\nu > W$ is an electron actually liberated.

If you use a battery to apply a positive charge to the metal plate (or a negative charge to the collecting electrode) you will interfere with this process, by making it harder for an electron to be ejected from the plate (or collected by the collecting electrode). A large enough charge should in fact *completely* inhibit the photoelectric effect from occurring.

In courses on electricity, students learn that a voltage multiplied by a charge corresponds to an energy; if the voltage is allowed to accelerate the charge, then

$$V \times \text{charge}$$

is equal to the kinetic energy gain of the accelerated charge. In our case, we use a field which *de*celerates the charge, and V x charge therefore measures the *loss* of kinetic energy.

In light of the above, Einstein concludes that equation (1) can be written

$$V_S \cdot e = h\nu - W. \tag{2}$$

V_S is the "stopping voltage": in a real experiment, the reading of a voltmeter attached between the two electrodes when the photoelectric effect just barely stops; and $V_S \cdot e$ is the corresponding energy of one of the electrons. This relationship is illustrated in Figure 5-1.

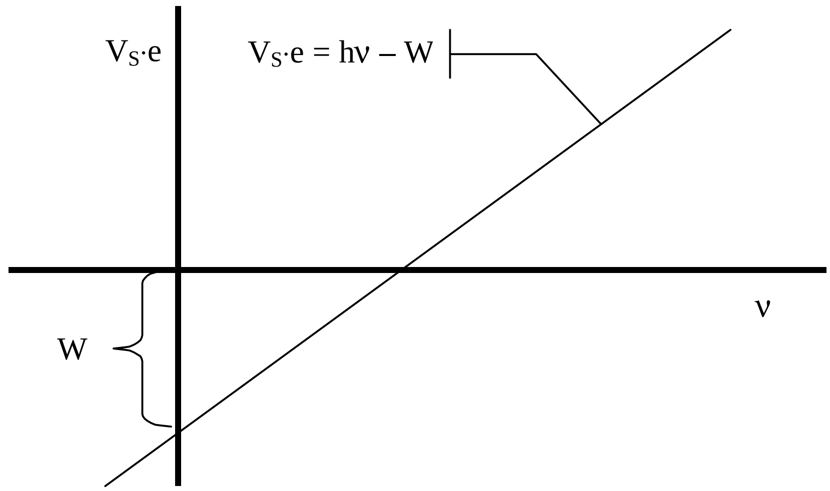

Figure 5-1. A graphical representation of the relationship between stopping voltage and frequency ($V_S{}^{x}e = hn - W$).

Physicists *define* a unit of energy, called the "electron Volt", symbol eV, to be the kinetic energy of an electron accelerated by one volt; thus, the reading of our volt meter is directly the electron energy, in units of electron volts.

Our Goals in this Laboratory

Einstein's model thus predicts two things: that the voltage required to stop the photoelectric effect from occurring should be independent of the intensity of the light, and that we should obtain a linear relation between the stopping voltage, V_S, and the frequency, *n*, of the light with which we illuminate the photocathode.

Our lab has four goals:

1. We wish to demonstrate the photoelectric effect.

2. We wish to test whether the light intensity affects the stopping voltage.

3. We wish to test whether the relationship between the stopping voltage V_S and the frequency, *n*, is indeed linear – i.e., whether it is possible to draw a straight line through a graph of our data points, with due allowance for experimental error and the peculiarities of our commercial (not ideal) photocell.

4. We wish to determine the two constants h and W from the graph of our data.

If Einstein's model is correct, then h is a fundamental constant of nature, and W is a property of the particular metal contained in our photocathode. Figure 5-2 shows the general appearance of the device we'll be using; Figure 5-3 is a schematic representation of a photocell, copied from *Selected Readings*; Figure 5-4 is a circuit diagram of its electronic inner workings.

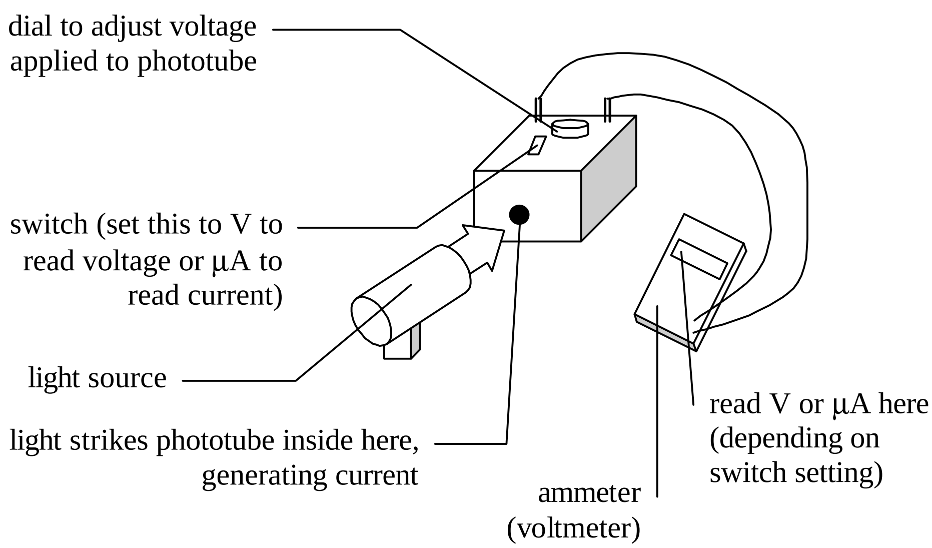

Figure 5-2. Photoelectric apparatus. The light shines through the aperture and onto the phototube. If the switch is set to mA, the current shows on the ammeter. The dial allows you to apply a voltage to the photocell, stopping the current. When the switch is set to V, the voltage shows on the ammeter.

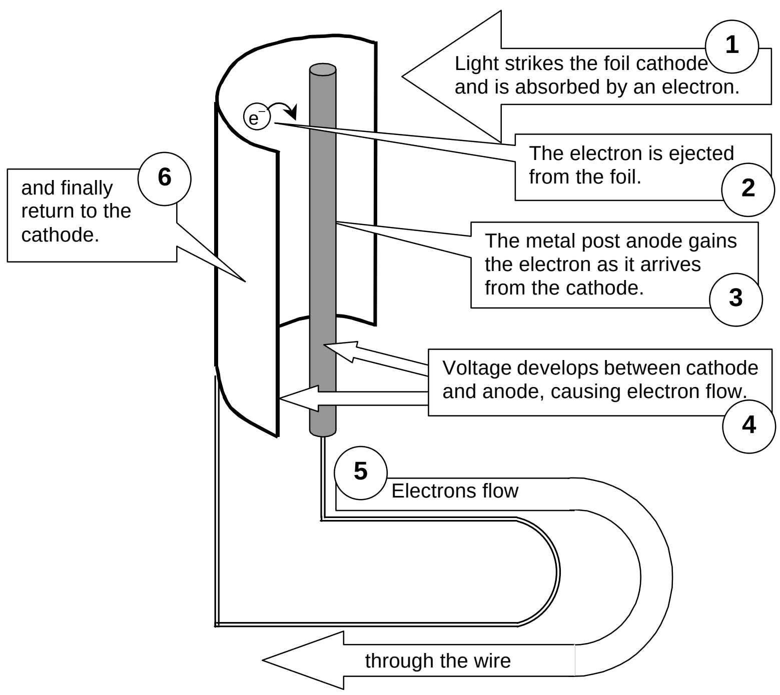

Figure 5-3. A photocell.

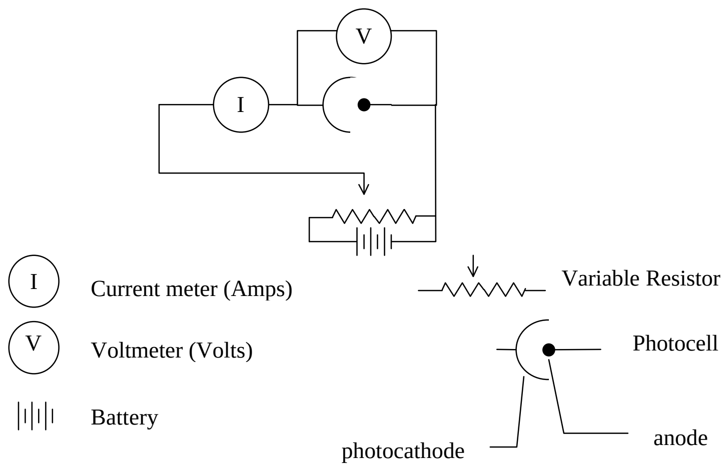

Figure 5-4. Circuit diagram of photoelectric effect apparatus. When the switch is set to V, the ammeter shows the voltage between the photocathode and the anode. When the dial is turned, the variable resistor changes the voltage applied to the photocell by the battery. When the switch is set to mA, the ammeter shows the current caused by the light striking the photocathode. A high enough voltage will prevent the electrons from crossing the vacuum between cathode and anode, and thus stop the current.

Doing the work

1. **First, confirm that the photoelectric effect occurs with our apparatus**. Set the switch to V, and use the dial to set the applied voltage to zero. Cover the aperture, change the switch to μA and read the current. (There should be none.) Now shine the light into the opening. What happens?

2. **Observe the effect of changing the intensity of the light.** Use the screen provided to reduce the light entering the photocell. What happens to the current?

   Stop the current by applying a voltage to the photocathode. Increase the voltage until the current just barely stops, being careful not to overshoot. Read the voltage. Repeat this with and without the screen in place.

	I	**V_s**
Full intensity		
Partly screened		

3. **Observe the effect on the stopping voltage of varying the wavelength** (or the frequency) of light.

   Our small interference filters each have a very narrow bandpass; they admit light only within 5 nm of the specified wavelength. The wavelengths of our filters are: 405, 430, 480, 520, 549, 589, 656, and 694 nm. Use several wavelengths across the visible spectrum, getting as wide a spread as the filters will allow. (Warning: the longest wavelengths may work poorly.)

   Insert one of the filters into the aperture, and shine the light in. Apply voltage until the current just stops, and record how much voltage was required. Repeat this process for the other filters. You should obtain a set of measurements of stopping voltage through each of the filters, some of them repeated several times (to give you an idea of your own repeatability), and *some* of them made personally by you. Each such experiment is a measurement of the stopping voltage V_S at a particular ν.

λ (nm)	(color)*	ν (Hz)†	V_s

* Look at a very bright light through the very center of the filter. Make sure you are seeing light transmitted through the filter, rather than light reflected off its surface.

† Calculate these after you have collected your data (see **First, fix your units** on page 6).

4. Analyze your data (to find *h* and *W*).

First, fix your units. Our filters transmit at varying wavelengths between 405 and 694 nm (1nm = 10^{-9} meter, i.e., 1 meter = 10^{9} nm). But Einstein's theory is formulated in terms of the *frequency*, ν. Therefore, *before* you plot any data, convert the wavelengths to frequencies. Recall the relationship between frequency and wavelength from *Making Waves:*

$$\text{frequency} \quad \times \quad \text{wavelength} \quad = \quad \text{speed}$$

or

$$\frac{\text{cycles}}{\text{sec}} \times \frac{\text{m}}{\text{cycle}} = \frac{\text{m}}{\text{sec}}$$

In terms of light, this can be represented by the equation:

$$c = \lambda\nu,$$

where c is the speed of light ($c = 3 \times 10^{8}$ m/sec), λ is the wavelength, and ν is the frequency.

This equation can be rewritten for our purposes (dividing both sides by λ):

$$n = \frac{c}{l}, \text{ or}$$

$$\frac{\text{cycles}}{\text{sec}} = \frac{\text{dist}}{\text{sec}} \times \frac{\text{cycle}}{\text{dist}}$$

Note, however, that we must make all the units match. One technique is to convert c from units of m/sec to units of nm/sec. 1m = 10^{9} nm, so

$$\frac{\text{nm}}{\text{sec}} = 10^{9} \times \frac{\text{m}}{\text{sec}}$$

Plot your data for V_S (vertically) as a function of ν (horizontally). [Think about why they are plotted this way.] Your graph should go all the way to 0 on the frequency axis, even though your data are all positive frequencies; a sensible choice would be to let the horizontal axis range from 0×10^{14} Hz to 8×10^{14} Hz. (Figure 5-1 suggests the way to set up the axes.)

Determine h and W from your graph. To do this, first draw a single straight line which "best represents" all the data points (as you did in the electricity lab). Except by a miracle (or fudging of the data) this line will *not* pass through *all* the points; but estimate by eye the line which does as good a job as possible "on the average".

Extend (extrapolate) this line all the way to zero frequency even though you do not have data there. Even though this extension of the line has no meaning in terms of your experiment, it *does* have mathematical significance; for it is the line which we hypothesize to be a graph of equation (2).

Read off your graph the ordinate (V_S) at $\nu = 0$; this is –W.

To determine *h*, find the slope of your line. You may use the technique from the previous lab: find convenient places where your line (not your points!) neatly runs through an intersection of grid lines, and measure the rise and run (take care with the units on your axes!).

Another technique is to pick a point on the line (not a data point) near the upper right end; read off $V_S \cdot e$ and ν. Substitute these two numbers into equation (2) (including now the numerical value of W) to find h.

According to current reference works, $h = 4.1356692 \times 10^{-15}$ eV·s (electron Volt-seconds), with an estimated uncertainty of 12 units in the last decimal place. How well did we do? (A percentage-error calculation suggests itself!) [Note: in an *ideal* photocathode, the slope of the line is an accurate measure of h. Commercial photocells, however, are made to emphasize sensitivity at the expense of ideal response. Therefore, although the qualitative effect can be clearly seen, and a reasonable estimate of h obtained, the line may not be completely straight, and its slope not necessarily a precise measure of h.]

5. Think about what it means.

How does changing the intensity of the light affect the current? Why? (Think blizzard, not tidal wave.)

Why doesn't changing the intensity affect the stopping voltage?

Which photons have more energy, those in blue light or those in red light? Which requires a higher stopping voltage?

Generally speaking, what is the relationship between the frequency of light causing the current and the voltage necessary to stop that current?

What is the relationship between *wavelength* and stopping voltage?

Why is the stopping voltage so similar for white and far blue light, even though the white light has about 100 times as much light as the light through any of the filters?

How does the photoelectric effect in general, and your data in particular, demonstrate the quantized nature of light?

What property (or properties) of *waves* did we use in today's experiment demonstrating the quantized nature of light (i.e., the existence of *photons*)?