T.E. Coan

PHOTOELECTRIC EFFECT

GOAL

- Verify Einstein's law for the photoelectric effect.
- Measure h/e.

OVERVIEW

Photoelectric effect

It is observed (Philipp Lenard, 1899) that electrons are emitted from a metal surface when the surface is irradiated with light of frequency ν greater than a threshold frequency ν_0 that depends on the particular metal. The maximum kinetic energy T_{max} of these ejected electrons ("photoelectrons") is described by the so-called Einstein equation:

$$T_{max} = h\nu - \Phi, \tag{1}$$

where h is Planck's constant and Φ is the "work function" of the metal, the minimum amount of energy required to eject an electron from the metal. The above equation expresses the conservation of energy for the photon-material-electron system and implies that for *each* photon with energy $h\nu > \Phi$, *one* electron is emitted. This equation was postulated by Einstein in 1905 who argued that a variety of effects associated with the photoelectric effect could be explained if you thought of light as composed of "bundles of light" or photons which each had an energy $h\nu$, where ν is the frequency of the light if you think of it as a wave. It is important to emphasize that the photoelectric effect cannot be explained by classical physics. (See your favorite physics reference.) We will not perform the full range of experiments associated with the photoelectric effect but merely confine ourselves to verifying Einstein's equation and in the process measure the important ration h/e, where e is the absolute value of the electronic charge.

A schematic diagram of the experimental setup is shown in the Figure 1. Light from a mercury-vapor arc passes through the quartz envelope containing the gas and then passes through a filter. The filter transmits only one of the emission lines from the mercury spectrum and this transmitted light is then focused onto the potassium cathode of the photocell. (A photocell is just an evacuated quartz envelope that contains some electrodes.)

The photoelectrons emitted from the cathode surface can then be collected by the platinum anode. This current passing through the photocell is proportional to a number of photoelectrons reaching the anode. Means are made for measuring the current in the photocell as a function of the "bias" voltage V applied between the cathode and the anode. Normally, the anode is at a positive potential relative to the cathode, thus attracting the photoelectrons. When the polarity of this potential is reversed, the anode will repel the electrons. If the retarding potential is adjusted such that the most energetic photoelectron is deflected back just before reaching the anode, then:

$$T_{max} = eV_s,$$

where V_s, the "stopping voltage", is just this value of the retarding potential. Combining the two equations, we have:

$$V_s = \frac{h}{e}\,\nu - \frac{\Phi}{e}. \tag{2}$$

A plot of stopping potential V_s as a function of light frequency ν should yield a straight line with slope h/e if Einstein's equation applies.

In this experiment you will plot photocell current I as a function of voltage applied to the photocell, V, for 5 different light frequencies ν produced by the mercury lamp and appropriate filters. From these plots you will determine the stopping potential V_s for each frequency. You will then plot the stopping potential as a function of ν to verify the linearity predicted by the Einstein's equation and calculate h/e from the slope.

Literature

1. A.C. Melissinos, "Experiments in Modern Physics," Academic Press, New York, 1966, pp. 18-27.
2. G.P. Harnwell and J.J. Livingood, "Experimental Atomic Physics," McGraw-Hill, New York, 1961.
3. C. Kittel, "Introduction to Solid State Physics," 5th ed., Wiley and Sons, New York, 1976.
4. Stephen T. Thornton and Andrew Rex, "Modern Physics for Scientists and Engineers," Saunders College Pub., 1993.
5. M. R. Wehr et al., "Physics of the Atom," 3rd ed., Addison-Wesley, 1978.

Lab Report Contents

1. Abstract;
2. Concise description of relevant theory and procedure;
3. Schematic of apparatus with appropriate identification;
4. Raw data;
5. Explanation of results, including answers to lab questions, and curves of I_a v. $V_{applied}$;
6. Conclusion.

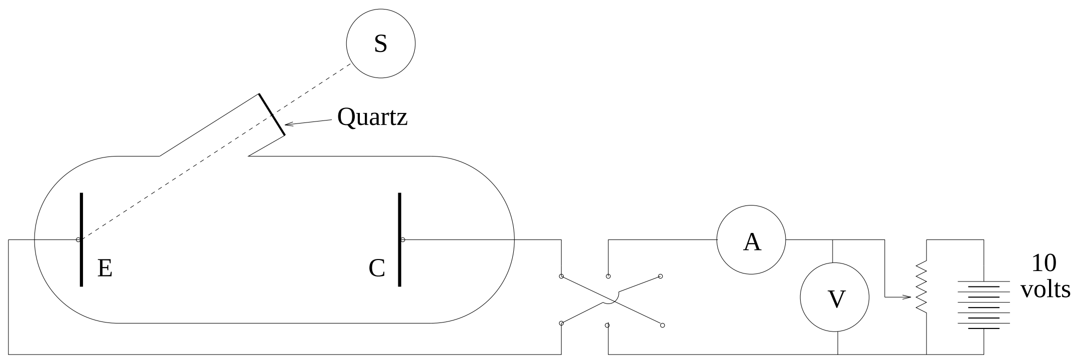

Figure 1: Photoelectric effect setup.

INSTRUCTIONS

I. Optical set-up

Refer to figure 2. Switch the mercury lamp on. Adjust the aperture of the iris on the mercury lamp so that its diameter is 4-6 mm or so. Insert the shield with a rectangular aperture in front of the lamp. Position the lens to focus light onto the cathode while avoiding direct illumination of the ring-shaped anode. Place the semi-cylindrical shield around the photocell to shield its entrance port from stray light. You may also want to drape the black felt over the photocell. Insert a filter into the holder in between the shield and the lens.

II. Electrical set-up

Connect the wires of the apparatus as shown in figure 2. Make certain that you understand in detail why the wires are connected this way. If you understand the physics, you should be able to reproduce a diagram of the wiring without reference to a book. Pay attention to the relative polarities of the electrodes, what electrodes are grounded and where in the circuit voltages and currents are measured.

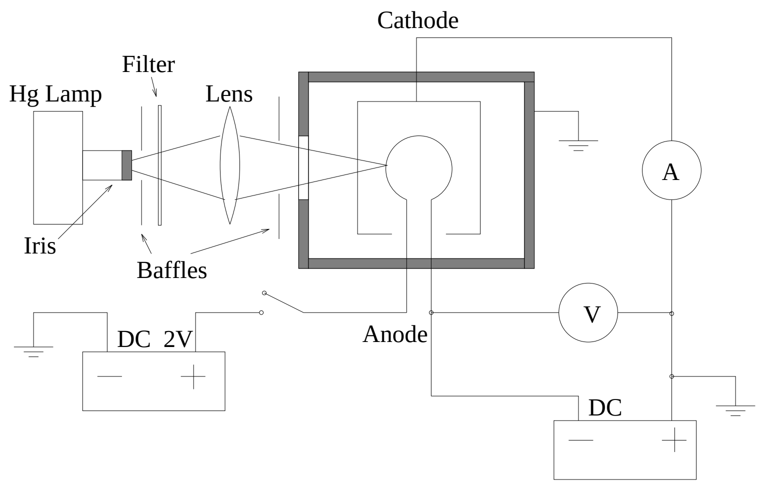

Figure 2: Photoelectric effect optical setup and wiring diagram.

The bias voltage V is set by the DC power supply. It has two control knobs: *coarse* and *fine*. Use the coarse knob to set voltage to an approximate value, and then use the fine knob for precise dialing. The meter on this power supply is too coarse for our purposes so the bias voltage is read out from the digital voltmeter. Notice that the voltmeter switches automatically between the mV and V ranges. The selected range is indicated by a red dot.

The current through the photocell I is read out by the electrometer (Keithley 617). The switches should be set to AMPS and AUTO. **Verify that no switch in the third column is set (e.g., ZERO CHECK or SUPPRESS).** The electrometer is capable of measuring very small currents. It switches automatically between the pA (pico – 10^{-12}) and nA (nano – 10^{-9}) scales.

Another DC power supply is used to provide a small voltage (set it to 2V) to heat up the anode. Set the meter on this supply to the current read-out. Press hard the push-button switch for approximately 1 second to heat-up the anode which will clean it up from any photosensitive alkali metals. The heating current should not exceed 1.2 A.

III. Measurements of I vs. V.

You should take measurements in a dark room. A flashlight may be useful to you for writing in your lab book. Start the I measurements for each filter with V set to some small positive value between 0.0 V and 0.2 V or so. For each V setting record the current through the photocell. Move in small ($\sim$ 0.2 V) steps towards increasingly *negative* potential. Use the fine setting knob to specify the bias voltage. Before recording the current I, be certain that it is "reasonably" stable.

If you reach the upper limit of the fine knob, reset it to the leftmost position and use the coarse knob to advance to a higher voltage setting. Then use the fine knob again to achieve desired voltage. Try to find exact value of V which corresponds to $I = 0$. Continue measurements beyond this point. Negative current will flow because of the photoelectric effect on the anode and because of imperfect insulation of the cell. When reverse current saturates at approximately constant value you can take larger voltage steps. Measure the current up to $V = -3$V. Include a table with your measurements in the report. The reverse current may have quite different values for different filters.

I recommend that you read the article in Melissinos' book before performing this experiment. It contains important details not included in standard textbooks. Pay attention to the concept of "contact potential difference." The book by Kittel contains information on so-called Fermi surfaces.

IV. Verification of the Einstein's law and measurement of h/e.

Because there is always some reverse current due to the photoelectric effect on the anode, there is no obvious way to determine stopping voltage, V_s. When $I = 0$, photoelectron flow from the cathode to the anode is equal to the photoelectron flow from the anode to the cathode. Thus, the true stopping voltage must be larger in magnitude. In fact, there is no precise way to determine the true V_s in our experiment although there are ways to perform a self-consistency check on a presumed value of V_s. One way is to take measurements at a fixed filter setting but to then vary the amount of light incident on the cathode. Do you see why this would work? In any event, it is possible to obtain meaningful results if the same consistent criterion is used at all light frequencies for obtaining V_s. At a constant front aperture setting, you may find this method useful. First, find a tangent line to the I vs. V curve at large negative values of V. Next, draw a line tangent to those points where the I vs. V curve first noticeably deviates from the first tangent line. Then, define V_s as the voltage where these two lines intersect. If you have the patience, you may want to perform your measurements at two significantly different aperture diameters.

Plot V_s determined for each filter in the previous step versus light frequency, ν, for the two different definitions of V_s. The table below maps a filter to its "pass" frequency.

Filter No.	color	λ in nm	ν in 10^{14} Hz
46830	yellow	578	5.19
46831	green	546	5.50
46832	blue	436	6.88
46833	violet	405	7.41
UG-1	ultraviolet	370	8.11

Does your V_s v. ν plot agree with the linear dependence predicted by Einstein? Determine h/e and compare with the accepted value of $4.14\,10^{-15}$ V·s. What is the value of the work function Φ for platinum? **Be sure to include error analysis for your results.**

V. Useful conversion realtion

It is often necessary to determine the energy E (in eV) of a photon when you know its wavelength λ (in nanometers). A useful converion is:

$$E = 1240\,\text{eV}/\lambda(\text{nm}) \tag{3}$$