

Photoelectric Effect

Equipment Sargent-Welch photoelectric apparatus, Pye Galvanometer, 2 D cells in holder, voltmeter, mercury arc source with power supply, leads

Reading Your text books

PRECAUTIONS

1. The mercury discharge tube used in this experiment emits ultraviolet (UV) radiation that can damage your eyes. Be sure to wear the protective glasses provided when the discharge is on.
2. The mercury discharge tube runs hot. Avoid touching it.

1 Introduction

Electrons are held inside metals by electric forces. For a given metal at room temperature, where thermal effects are negligible, an electron must be given a minimum amount of energy to escape from the metal. This minimum amount of energy is called the work function ϕ . Energy can be supplied to the electrons by shining light onto the metal surface. Electrons that have been liberated from the metal by this mechanism are called photoelectrons. If monochromatic light is incident on a metal surface it is found that if the frequency of the light is less than a given frequency, called the threshold frequency ν_0 , no electrons are emitted however intense the light and no matter how long you wait. If the frequency of the light is above the threshold frequency, electrons are emitted almost immediately even if the light intensity is very small. These facts cannot be explained on a classical basis in which the light is considered to be oscillating electric and magnetic fields. In 1905 Albert Einstein explained this mystery by assuming that the energy of light was not continuous but discrete. The light energy was quantized in massless particles called photons each with energy $h\nu$. Planck's constant is h and ν is the frequency of the light. An electron absorbs the entire energy of a photon or absorbs no energy at all. This simple explanation was worth a Nobel prize. Light has the usual wave-particle duality of matter. For some problems it is necessary to treat light as a wave and for other problems as a particle.

2 Theory

Photoelectrons arise from the electrons in the conduction band of a metal. A very simple model, illustrated in Fig. 1, gives the salient features. The electrons are held inside the metal by a potential energy step. The potential energy is constant on either side of the step, and we take the potential energy as zero inside the metal. Inside the metal the electrons fill up all the available energy states up to maximum energy E_{max} . There are almost no electrons with energy greater than E_{max} , assuming the temperature is low. The energy from E_{max} to the top of the potential energy step is the work function $\phi = h\nu_0$. When an electron inside the metal of a given energy approaches the surface, a force is exerted on it that reflects the electron from the surface. Consider an electron inside the metal with energy E_{max} . If this electron absorbs a photon of energy $h\nu$, The maximum kinetic energy K_{max} that this electron can have if it leaves the metal is

$$K_{max} = h\nu - \phi. \quad (1)$$

Electrons inside the metal whose energy is less than K_{max} will be ejected with less energy. There will be a distribution of energies for the ejected electrons which will extend down to zero.

K_{max} can be measured by the circuit shown in Fig. 2. The metal surface being investigated and from which electrons are emitted is called the cathode. The electrons are collected at another metal surface called the anode. The cathode and anode are in vacuum so that electrons can flow without collisions. A voltage V is applied between the cathode and anode, and the current measured by a sensitive ammeter called a galvanometer. The currents are small, and the voltage across the galvanometer is negligible. When V has the polarity shown in Fig. 2, the voltage tends to repel photoelectron emitted from the cathode. It is called a retarding voltage. When V has the reverse polarity, photoelectrons will be attracted to the cathode. For monochromatic light of fixed intensity and frequency, the cathode-anode current I will vary with the voltage as shown in Fig. 3. When the retarding voltage is negative, essentially all the electrons are collected by the anode. As the retarding voltage goes positive, electrons whose kinetic energy is less than eV cannot reach the anode, where e is the electron's charge. The stopping potential V_S is the cathode-anode voltage which is just large enough to prevent the most energetic photo-electrons, those with energy K_{max} , from reaching the anode. We then have that $eV_S = K_{max}$. If this relation is inserted into Eq. 1 there results

$$V_S = \frac{h}{e}\nu - \frac{\phi}{e}. \quad (2)$$

If V_S is measured for a number of frequencies of light ν , and then V_S is plotted versus ν , the result will be a straight line with slope h/e and intercept ϕ/e . Planck's constant and the work function of the metal are obtained.

3 Additional Considerations

The above analysis has neglected two phenomena, contact potential and anode current. We consider contact potential first. When two uncharged pieces of metal with different work functions are placed in contact, electrons will flow from the lower work metal to the higher work function metal until a potential, called the contact potential V_C , is established. There is then no net electron current between the two metals. The higher work function metal becomes negatively charged with respect to the lower work function by an amount equal to the difference in their work functions. The total retarding potential becomes $V + V_C$, and it is appropriate to rewrite Eq. 2 as

$$V_S = \frac{h}{e}\nu - \frac{\phi}{e} - V_C. \quad (3)$$

The slope of the line V_S versus ν is unchanged, but the intercept is different.

When the potential V is positive (sign convention of Fig. 2), any electrons emitted by the anode will be accelerated to the cathode. We might expect that this current would be negligible. The temperature is too low for thermionic emission, and, unless the anode surface was prepared in some special way, the work function of the anode would be too high for electrons to be ejected by the UV photons. In fact, some photoelectric emission is observed

from the anode. This is probably due to a small amount of the material used to coat the cathode contaminating the anode. Fig. 4 shows an example of the photocurrent as a function of the stopping potential. The solid curve shows the measured total photocurrent. This is the sum of the forward current (electrons going from cathode to anode) and the reverse current (electrons going from anode to cathode). The reverse current saturates and becomes a straight line that perhaps is not quite horizontal. As indicated in Fig. 4, a reasonable place to choose the stopping potential is where the solid line stops having curvature and becomes straight. You should follow this procedure in analyzing your data. Determining the exact stopping potential is difficult. You should take several sets of data and average your results.

4 The Apparatus

A vacuum diode has two electrodes, a cathode and an anode. In this experiment, the surface that emits the photoelectrons is the cathode. It is a large half cylinder whose surface has been coated with potassium to reduce its work function. The work function of potassium is 2.3 eV. The anode collects the photoelectrons and is a thin platinum wire. Platinum has a work function of 6.3 eV, although as mentioned in the previous section, there is some contamination.

This experiment uses three high frequency cut-off filters. The cut-off wavelengths are 435.8 nm, 546.0 nm, and 577.0 nm. The phototube, filters, and two potentiometers are enclosed in a box which is outlined in Fig. 5. There is a window which shows the filter in use and a thumbwheel for changing the filter. An opening or aperture in the box allows light from a mercury discharge tube to hit the cathode of the phototube. Two potentiometers permit control of the retarding voltage between the anode and cathode. Three pairs of banana plugs serve as connections for a galvanometer, a voltmeter, and a voltage source. The voltage source is two 1.5 V batteries in series. The circuit inside the box is sketched on the cover of the box as shown in Fig. 5.

The discharge tube is turned on and off by a switch on its power supply. WHEN THE DISCHARGE TUBE IS ON, WEAR THE PROTECTIVE GLASSES PROVIDED. The galvanometer is of the moving coil type. There is a switch on the front of this instrument that turns on a light pointer. You should use the X1 sensitivity scale. There is a knob on the top and back of the galvanometer that sets the zero, which can be either at the center or left end of the scale.

5 Experimental Procedures

1. Connect the galvanometer, voltmeter, and batteries to the apparatus using the polarities shown. Leave one terminal of the battery not connected so as to extend the life of the batteries, and to ensure that the applied voltage across the phototube is zero. Use the thumbwheel to put the 435.8 nm filter in front of the phototube and record the cut-off wavelength.
2. Turn out the fluorescent lights except for the bank furthest from your lab bench. Set the galvanometer sensitivity to X1, turn on the light pointer, and set the light pointer for center zero. Check to see if the fluorescent light bank you left on is producing any photocurrent by turning the lights off. If there is no effect, you can leave that bank of

lights on during your experiment. Do the fluorescent lights near your lab bench produce an effect?

3. Record the sensitivity of the galvanometer which is pasted on it.
4. PUT ON THE UV GLASSES, start the mercury discharge, and give the discharge a few minutes to stabilize. With the batteries still disconnected (zero retarding volts), adjust the distance of the discharge lamp from the aperture in the apparatus so that a galvanometer deflection of about -60 mm is obtained. Record the exact deflection and the retarding voltage (zero).
5. Being careful not to move the positions of the apparatus and discharge lamp, connect the batteries to the apparatus. Measure the galvanometer deflection as a function of retarding voltage, using 0.1 volt steps. Increase the retarding voltage until the current changes sign and saturates, as shown in Fig. 4.
6. Disconnect one battery lead, change the filter, and reposition the discharge lamp closer to the apparatus aperture, but do leave a few mm so as not to overheat the filter. As you would expect, the current will be less than before. Record the current for zero volts, connect the batteries, and take your data. Repeat these procedures for the last of the three filters.
7. You should repeat these measurements a few times so as to build up some statistics. Then turn off the discharge and galvanometer, and disconnect the batteries.

6 Analysis

Plot retarding curves of current versus retarding voltage and determine the cut-off voltages. Then plot retarding voltage versus cut-off frequency and determine the best straight line through the points. From the slope of the line obtain a value of Planck's constant and compare to the accepted value.

7 Finishing Up

Please leave the bench as you found it. Thank you.

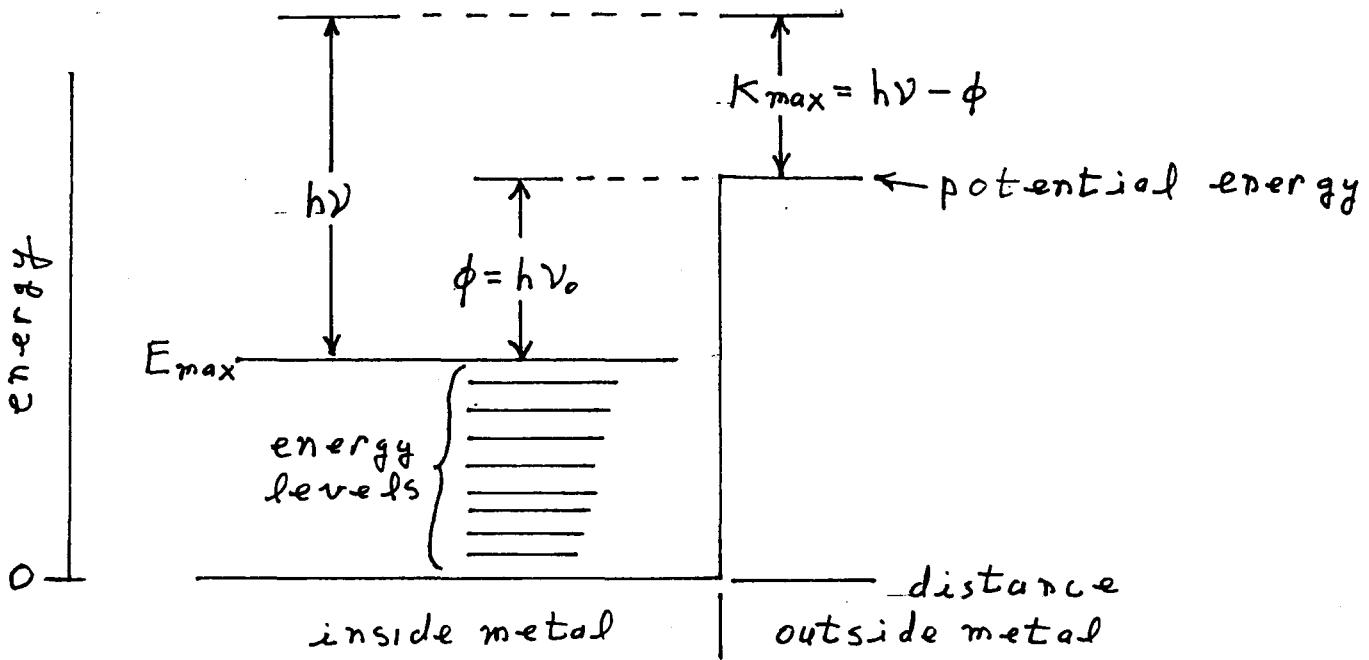


Fig. 1

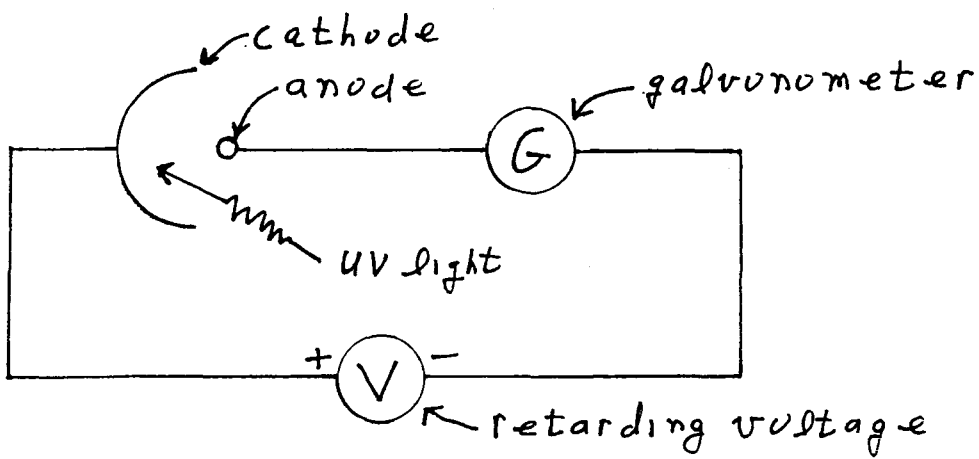


Fig. 2

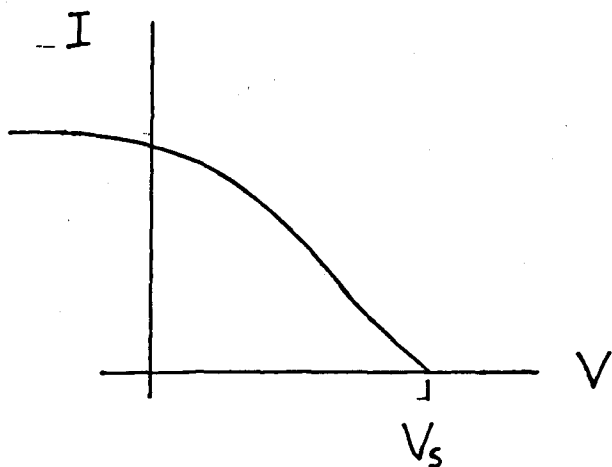


Fig. 3

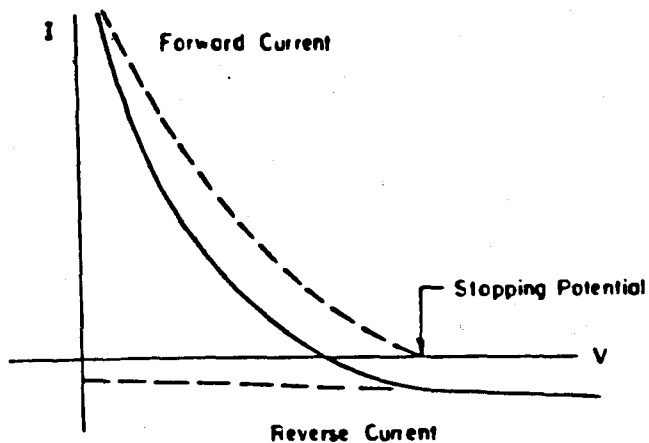
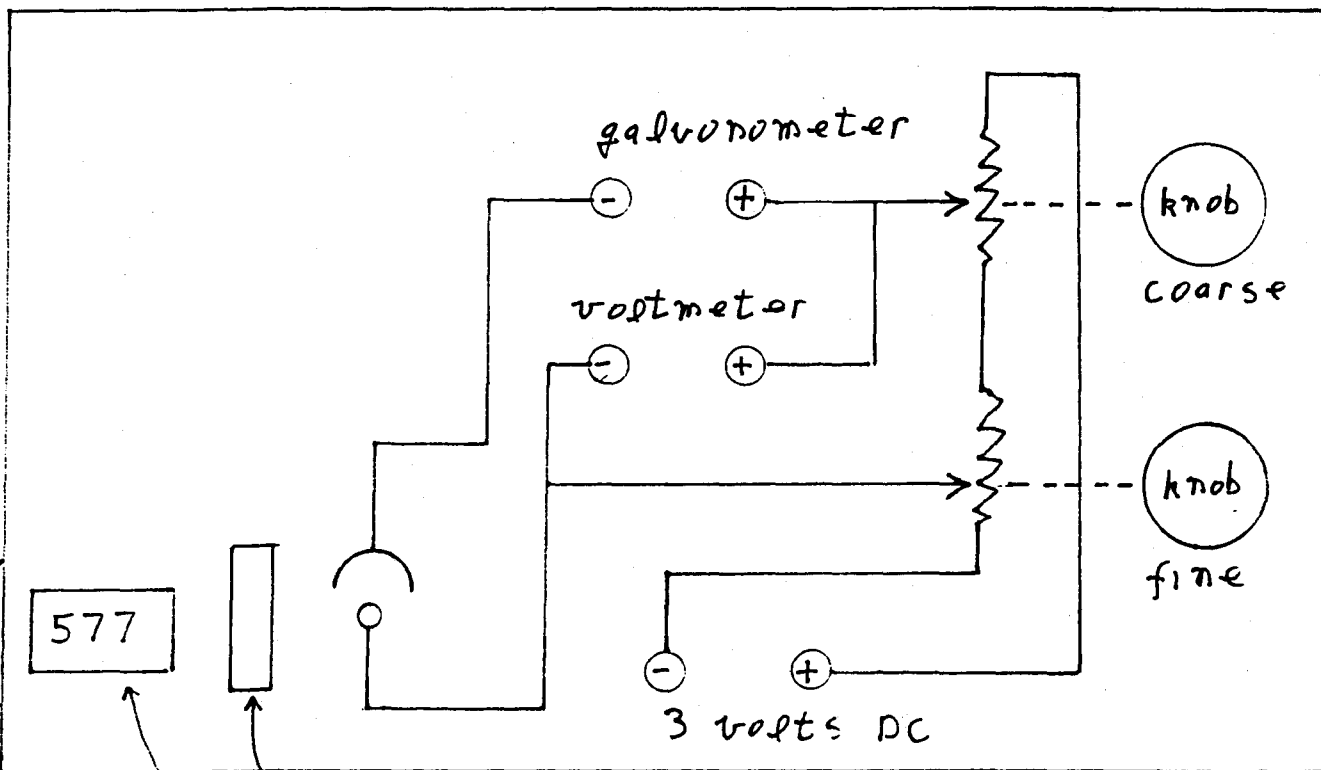


Fig. 4



wheel
light aperture
wave length

Fig. 5