Princeton University
Physics Department

Advanced Laboratory, Physics 312

The Photoelectric Effect
A Measurement of Plancks Constant

References:

1. R. A. Millikan, Physics Review, 7, (1916) 355. This is the original paper; it is an excellent account and highly recommended.

2. G. P. Harnwell & J. J. Livingood, Experimental Atomic Physics (New York: McGraw Hill, 1961), 214-223.

3. A. C. Melissinos, Experiments in Modern Physics (New York: Academic Press, 1969), 18-27. Note: Our apparatus is similar to the one described here.

Background:

A photon of frequency ν carries energy hν, where h is Planck's constant. If such a photon strikes an electron inside a metallic conductor it can knock the electron out of the metal. Once liberated, the free electron has an energy h$\nu - \phi$, where ϕ is the binding energy which formerly kept it inside the metal. The binding energy is called the work function of the metal. This explanation of the photoelectric effect was given by Einstein (Ann. Physik, 17, 132, 1905; 20, 199, 1906) and was (after Plancks description of black body radiation) the second big step away from classic physics.

As you will appreciate after reading the references, this experiment has some subtleties, which make it more difficult to perform than you might expect from its straightforward theoretical explanation. The electrical measurements must be very sensitive, which already suggests many possible difficulties; in addition, be forewarned that the apparatus does not behave exactly like the idealized one. Mastery of the subtleties will assure a good experimental result, and will serve as a welcome reward for your patience and skill as an experimenter.

One significant deviation from ideal behavior is the presence of contact potentials in the circuit. For many purposes we can consider metals as lattices of positively charged ions producing a potential well that is partly filled by a sea of freely moving electrons. Overall, of course, the metal is neutral in charge. The electrons have an energy distribution, which extends from the bottom of the well through a conduction band of well-defined width, as shown in the sketches to follow. The energy required to lift an electron from the top of the band just out of the well is the work function ϕ. Thermal effects make the top of the band somewhat fuzzy.

Now what happens when we join two pieces of different metal together? Let metal A have the lower work function, i.e., $\phi_A < \phi_B$. At the instant of contact the electrons are at a higher potential in A than in B, and hence some rush into B (remember, a conductor can have no electric field inside it). This behavior, however, leaves A with an excess of positive charge, thereby lowering its potential until the electron seas in A and B (that is, the tops of the conduction bands) are at the same level. The net result of connecting two wires of different metal is that there exists an electrostatic potential difference between the two free
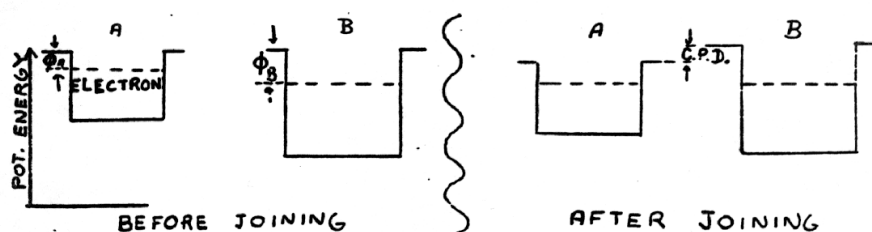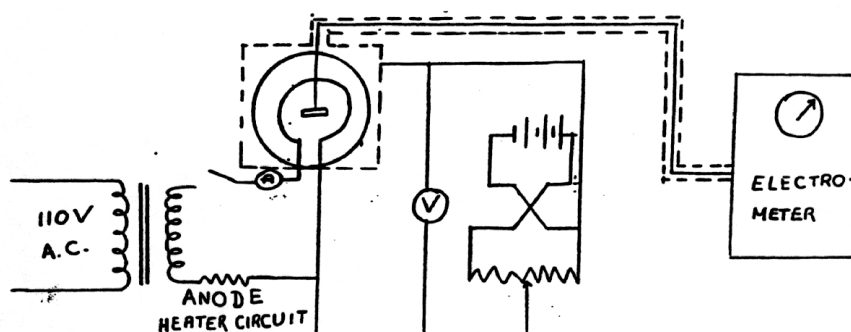
Figure 1:

Figure 2:

ends of the wire. This potential difference is equal to $(\phi_A < \phi_B)/e$, where e is the electron charge. The metal with the smaller work function will be positive. The potential difference can amount to as much as several volts and acts much like a battery hidden in the point of contact.

Experimental Set-up:

An evacuated commercial phototube (Leybold Model 55877) is used in the experiment. It contains a potassium photo-cathode and a loop of platinum wire as anode. Potassium is used because of its low work function, and platinum because of its work function and high melting point. (What does this tell you about the contact potential generated between the anode and cathode when your connect the wires? Work this out in your pre-lab preparations).

A suitable circuit for the electronics is given in the diagram below. Show in your pre-lab preparation that for theoretical purposes the circuit on Fig 2 can be reduced to the circuit shown in Fig. 3.

The electrons are ejected from the potassium cathode and collected on the platinum anode after being accelerated through a potential difference made up of the contact potential and an externally applied voltage that can be measured with a digital voltmeter. You will measure the current due to the ejected electrons reaching the anode with an ammeter capable of measuring 10^{-12} amps, a Keithley Model 485 Pico-ammeter. The two digital meters are the only black boxes in the experiment; everything else you should understand from first principles.

By varying the accelerating voltage V you can vary the current of ejected electrons and even stop it if the anode is sufficiently negative with respect to the emitting cathode to prevent the electrons from reaching it. The value V_o for which the photocurrent becomes zero is such that the kinetic energy of an electron is zero when it reaches the anode. Therefore:

$$h\nu - \phi = eV_o \tag{1}$$

Prove in your pre-lab preparation that if V_o in this equation is what your voltmeter reads, then ϕ is the
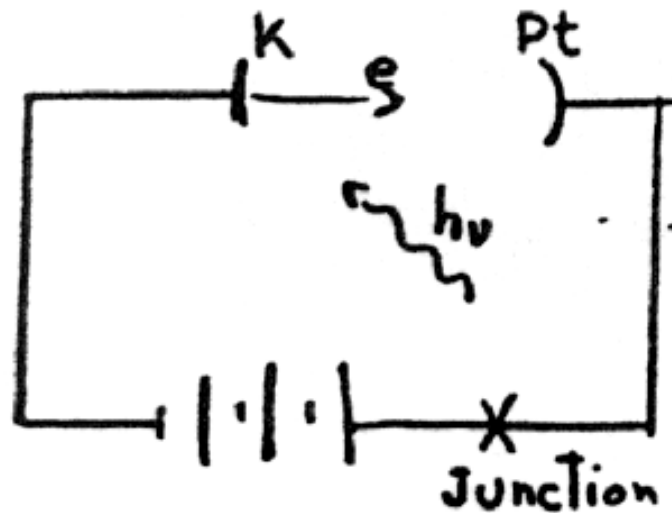
Figure 3:

work function of the anode. To answer this question correctly you must think about what happens to an electron as it just reaches the platinum anode.

Objects of the Experiment:

In general, of course, your object is to verify Einsteins theory of the photoelectric effect. In doing so, you should:
Verify that for each frequency ν there is a stopping voltage $V_o(\nu)$, beyond which no electrons ejected from the cathode reach the anode. Plot appropriate curves of photocell current vs bias voltage, using the LabView program.
Understand experimentally the current saturation for large accelerating voltages. What will you vary to prove your explanation?
Understand the presence of a small reverse photocurrent going from anode to cathode when the accelerating voltage V is reversed.
Verify that V_o for a given ν is independent of light intensity. **This is the main quantum aspect of the experiment**.
Show that there is a linear relationship between stopping voltage V_o and ν, and hence:
Determine h/e from the slope of the graph of V_o vs ν.

Pre-Laboratory Preparation:

In addition to doing the reading and answering the questions given so far, calculate the following: assuming that the work function of the anode (platinum contaminated with some outgassed potassium) is 3.0 volts, compute the stopping voltages Vo for the various spectral lines emitted by the mercury lamp. Assuming that the work function of the potassium cathode is 2.0 volts, compute the stopping voltages for the reverse photocurrent caused by light hitting the anode. (Be sure that you have a method for defining the signs of the voltages unambiguously!) Sketch the photocurrent curves to be expected for the yellow and blue lines, assuming that the magnitude of the saturated reverse photocurrent is 10% of the saturated forward photocurrent.

Experimental Details:

It is a good idea to mask the tube so as to prevent light from striking the anode directly, because traces of

potassium tend to settle on it due to the vapor pressure of potassium. It may help to evaporate such traces by passing a current of 1 ampere through the anode wire for a few seconds. (Do not exceed 1 ampere; to avoid overheating, do not heat for more than 5 seconds. In no case carry out the evaporation procedure while light is shining on or voltage is applied across the tube.) It is well to try the experiment before attempting to clean the anode wire, as stability of the anode work function may not be reached for some hours after the evaporation.

The quartz mercury arc lamp emits strong ultra-violet radiation. Avoid viewing it directly! A large selection of filters is provided to enable you to single out particular lines (or closely spaced groups of lines). Check the specifications of the filters in the Kodak data books. The following table lists colors and wavelengths of the most important spectral lines, and gives suggested filter types (others are possible).

Mercury Lines		
Color	Wavelength (nm)	Color
Yellow	578	23A
Green	546	74
Blue-Green (weak)	492	58
Blue	436	50
Violet	405	2C
Ultra-violet	366	18A (or none)

It is probably sensible to work out the details of the method using the line that gives the highest photocurrent. There is a LabView program on the PC which will automatically scan the bias voltage and record the photocurrent. To run the program on the computer: Double-click the program's icon on the computer's desktop. Your files are saved by default in the folder whose shortcut is located next to the program's icon. Take data over a range of ± 3 volts (or more if you decide so later).

Physics 312 March 2002 Robert H. Austin