Physics 25L lab manual

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This is a modified version of the original manual
written by Professor David Stuart

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Contents

4 The Photoelectric Effect, Photons and Planck's constant

Abstract: Two critical experimental observations led to the development of Quantum Mechanics: the blackbody spectrum and the photoelectric effect. In this lab you will explore the photoelectric effect and use it to measure Planck's constant.

4.1 Pre-lab preparation

Quantum Mechanics was developed in the early 1900's, but the evidence for it began to appear even in the late 1800's. For example, Heinrich Hertz noticed that sparks started more rapidly when electrodes were illuminated with ultraviolet (UV) light. Other investigators later determined that free charges (*i.e.*, electrons) were emitted from metal electrodes illuminated by UV light. These were called "photoelectrons". Some metals, mostly the alkali metals in the first column of the periodic table, produced a steady supply of photoelectrons (called a "photocurrent") when illuminated by either UV light or visible light, but other metals only did so for UV light. Detailed measurements of this "photoelectric effect" established the following characteristics:

- For a given metal, there exists a definite cut-off frequency, ν_0. Incident light with frequency below ν_0 produces no photocurrent regardless of its intensity.
- For light with frequency $\nu > \nu_0$, the magnitude of the photocurrent produced is directly proportional to the intensity of the incident light.
- The maximum kinetic energy of the photoelectrons does not depend on the intensity of the light, but it is proportional to the frequency of the incident light.

These characteristics could not be explained by the classical description of light as a wave that continuously transmits energy in proportion to the intensity of the light. Explaining these observations required a different description for light, which was proposed in papers by Max Planck (1901) and Albert Einstein (1905).[8] They proposed to describe light as consisting of discrete bundles of energy, rather than as a continuous stream of energy. The bundles, or "quanta", of energy were named "photons". Each photon carries an energy of $E = h\nu$, where h is Planck's constant with units of energy times time. The name of this constant honors Planck because he was the first to use the idea of quanta to explain the blackbody radiation spectrum. Einstein then used it to explain the photoelectric effect as follows.

A photon of incident light transfers all of its energy to an electron in the metal. If that energy is sufficient, it can dislodge the electron from the metal, *i.e.*, it does some amount of work, W, to overcome the potential energy binding the electron in the metal. Any excess energy goes into the kinetic energy of the ejected electron,

$$E = W + \frac{1}{2}mv^2.$$

Using the photon energy, $E = h\nu$, we get

$$\frac{1}{2}mv^2 = h\nu - W.$$

Not every electron is in the same potential, so the work required to eject them varies and their resulting kinetic energy varies. However, there is a minimum amount of work required for the most loosely bound

[8] The quantum explanation for the photoelectric effect is described concisely in a three page section of Einstein's paper, Ann. Physik 17, 132 (1905), and was the reason for his subsequently being awarded the Nobel Prize.

electrons, which corresponds to a maximum kinetic energy for the ejected electrons. We can measure that maximum kinetic energy by applying a "stopping voltage" that photoelectrons must overcome to be detected. If we call V_s the voltage required to stop the most energetic electrons (and all the other electrons as well, of course), then $eV_s = \frac{1}{2}mv_{\max}^2$. Putting this all together we get the expression

$$V_s = h\nu/e - \phi \tag{13}$$

where ϕ is called the "work function" of the metal and corresponds to the minumum work required to eject an electron from that particular type of metal. Since we divided through by e, the work function ϕ has units of volts.

Equation (13) is a straight line on a graph of $V_s(\nu)$, with a slope of h/e and a y-intercept of $-\phi$. By measuring V_s for different frequencies of light and fitting such a line we can determine both Planck's constant and the metal's work function.

4.1.1 Apparatus

The apparatus that we will use is shown in Fig. 13. It consists of a mercury discharge lamp that is the light source; a set of filters that transmit only a narrow range of wavelengths from that light and a special kind of vacuum tube called a phototube. The phototube has a cathode, from which a photocurrent will be produced, and an anode that will collect and measure the photocurrent, as well as provide an adjustable stopping voltage to impede the current. Using different filters allows you to change the ν of the light. For each filter you can then adjust the anode-cathode voltage and find the value, V_s, that stops all photoelectrons from reaching the anode. Finding that value requires measuring the photocurrent that flows between the cathode and the anode in the vacuum tube; you can do that with the "electrometer", which is a sensitive ammeter that can measure down to the picoampere range (1 pA = 10^{-12} A). A voltmeter is also provided to measure the impeding voltage applied between the anode and cathode. A diagram of the circuit you'll use for that is shown in Fig. 14, along with a more detailed view of the phototube.

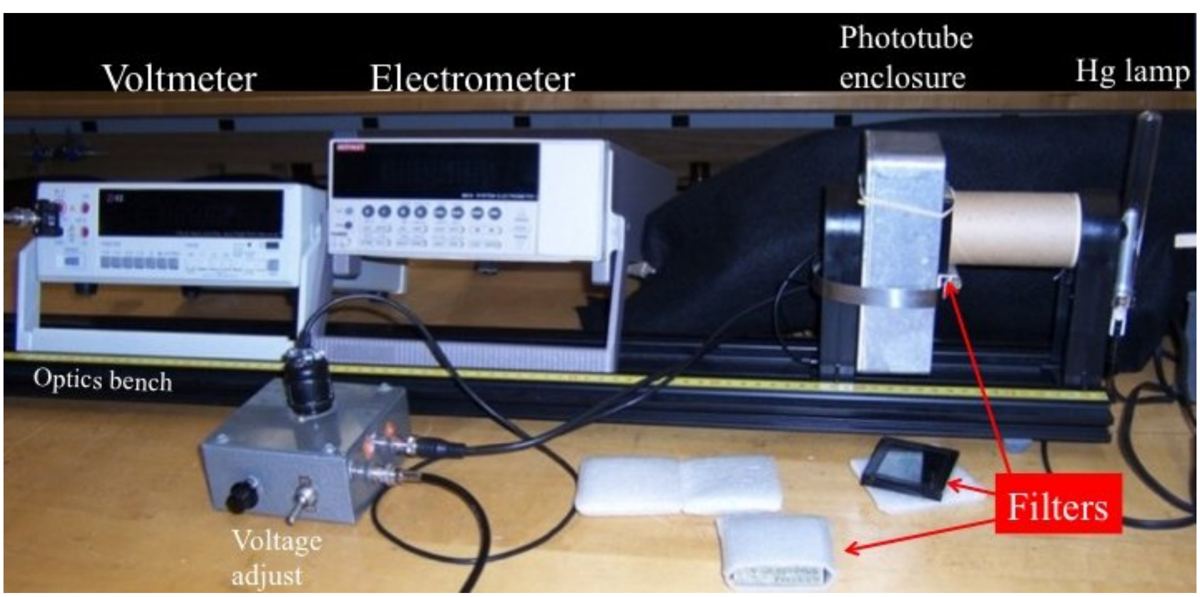


Figure 13: Photo of the apparatus mounted on an optics bench.

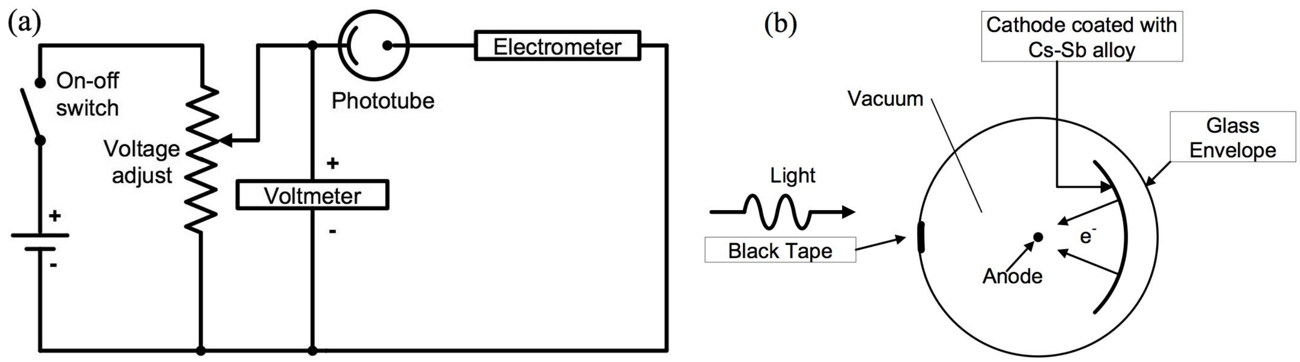


Figure 14: (a) Diagram of the circuit used in the experiment. An adjustable voltage divider controls the impeding voltage. Notice how the voltmeter and electrometer are connected in parallel and in series with the phototube, respectively. (b) Schematic of the phototube

Light enters the phototube and strikes the cathode, which is a metal plate coated with a Cesium-Antimony alloy. That alloy is chosen so that photoelectrons can be ejected from it by a range of visible light wavelengths without having to rely on UV light, which involves hazards worth avoiding. A small fraction of the photoelectrons ejected from the cathode will be directed toward and hit the anode. They'll generate a photocurrent that runs through the electrometer back to the cathode. (The phototube thus converts photons into an electric current, just like a solar cell does, but it is very inefficient.) The battery and an adjustable voltage divider in Fig. 14(a) apply a voltage between the anode and cathode that impedes the natural flow of the photocurrent. The applied voltage pushes the electrons back from the anode to the cathode, so only electrons with sufficient kinetic energy to overcome the eV potential from the battery can reach the anode and flow through the electrometer back to the cathode.

Note that Fig. 14(b) shows a piece of black tape situated in the light path so as to keep the anode in its shadow. Think about why that is necessary, and write a brief explanation in your logbook.

The phototube is evacuated. Think about why it is important to have a vacuum between the cathode and anode, and write a brief explanation in your logbook.

4.1.2 Safety

The Hg lamp presents two hazards.

- It generates a spectrum of light that extends beyond the visible range into the ultraviolet. Prolonged exposure to ultraviolet emissions is hazardous to your eyes and skin. A glass test tube placed over the lamp is a simple way to shield yourself from the ultraviolet component of the lamp's emissions because most glass is opaque at ultraviolet wavelengths. *Before turning on the Hg lamp, make sure that the test tube shield is in place.* Note also that the test tube has a white marking on it. This is normally used for labeling the contents. In our application is it not useful and could even be problematic if it blocks the light path. Keep the test tube rotated so that this white mark is out of the way of the light path.
- It gets hot. *Don't touch the lamp or test tube after it has been turned on, and keep any other materials away from contact with it.*

You'll want to make sure that the lamp is properly situated and turn it on at the beginning of the lab.

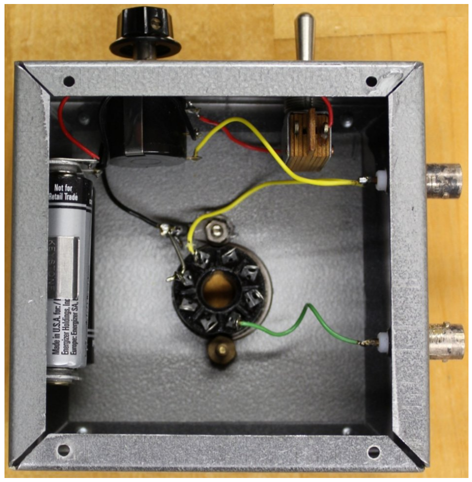
(a)  (b) 

Figure 15: Photographs of the contents of the aluminum boxes containing (a) the voltage adjustment circuit and (b) the phototube.

Then leave it on and untouched. That way it will warm up and its output will remain more stable.

The phototube is enclosed in an aluminum box that has a small window to admit the incident light. This prevents ambient light, which has not been carefully wavelength selected by the filter, from affecting the measured photocurrent. Similarly, a short cardboard tube is used to block ambient light from entering the optical path between the filter and the light source. It also serves to keep your hands away from the hot lamp while swapping the filters. The battery and adjustable voltage divider are placed in another aluminum box with connectors for the voltmeter, electrometer and phototube. You won't need to open either of these boxes, and you shouldn't. To satisfy your curiosity, however, photos of their contents are shown in Figure 15.

4.2 Getting started and gaining familiarity

The first thing you should do in lab is turn on the meters so that they have time to warm up. Most equipment has a "warm up" period, which is simply the time it takes for all the heat production and dissipation mechanisms to come to equilibrium so that the device's components remain at a constant temperature. Variations in temperature can alter operational details of electronics, such as amplifier gains and leakage currents. The electrometer has calibration circuitry that measures and corrects for most of these temperature dependent effects, but operating at a stable temperature still improves its precision. After re-reading the safety section... turn on the mercury lamp. Use a black cloth to make a tent over the lamp and metal enclosure, but make sure that the cloth does not touch the hot lamp.

Before taking data, spend some time to be sure you understand how the equipment works and take some more time to document its configuration. Take a photo of your setup and add it your logbook. Don't use the photo in Fig. 13 because it is not *your* setup. Taking photos is one way to record views of *your equipment* from which you can later extract any details (*e.g.*, make, model, size, position) that might be needed. You should also make a diagram of your circuit setup and put it in your logbook. It should look like the diagram in Fig. 14, but you should trace the connections in your setup just to be sure.

(a) 

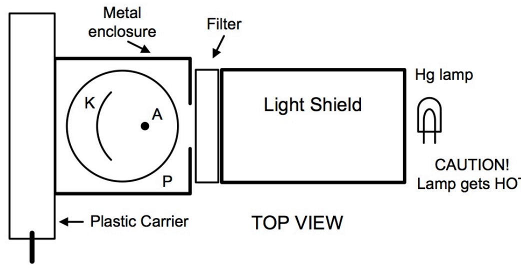
(b) 

Figure 16: (a) Front panel of the Keithley 6514 Electrometer. (b) Diagram showing where to position the filter between the lamp and the phototube assembly.

4.2.1 Operation of the electrometer

The electrometer (Fig. 16) is central to your measurement, so you should understand its operation. You can find full details by googling for the equipment manual; what follows is excerpted from it.

The Keithley 6514 electrometer can be used to measure voltage, current, resistance or charge. We will only use the current measurement capability. When powered on, it defaults to voltage measurement mode. You can switch to current mode using the front panel button, but you should put the device into Zero Check mode (see below) when switching modes. It has ten ranges for current measurement, with the full scale values varying 20 pA to 20 mA. You'll need to select an appropriate range for each of your measurements, or use the autoscale feature. For our measurements, the nA scale is probably optimal.

The electrometer is capable of precision measurements of very small currents, but that precision requires some careful procedures. In particular, you need to calibrate and correct for any offset currents. This can be done with the Zero Check and Zero Correct functions. When Zero Check is enabled, the input signal is shorted so that the input amplifier sees only offset currents and voltages that are not from the input signal and thus should be subtracted. That subtraction can, and should, be done internally using the Zero Correct function, following the procedure listed in Fig. 17. It is reasonable to perform the zero correction procedure between each set of measurements (*e.g.*, for each new filter) to compensate for any drifts that may occur over time.

You should also set the RATE setting to SLOW and the DIGIT setting to display 2 or 3 digits after the decimal point. Displaying more digits provides greater precision, but the temporal variation of the measurements is likely to be what will determine the uncertainty on your current measurements.

Zero Correction procedure to remove offsets

- Enable Zero Check mode. Press ZCHK; you should see a "ZC" message appear at the right side of the display.
- Select the current measuring mode by pressing I (if not already in that mode).
- Select the appropriate measurement range.
- Perform a zero correction by pressing ZCOR; you should see a "ZZ" message appear in the display.
- Press ZCHK to disable the Zero Check mode; you should now see a "CZ" message appear in the display to indicate that the subsequent readings are corrected for any zero point offsets.

Figure 17: Zero correction procedure.

4.3 Measure $V_s(\nu)$ and extract h

There are four optical filters which only pass light in a narrow range of frequency. By placing these different filters between the Hg lamp and the phototube, you can make measurements of the phototube's response as a function of the frequency, ν. A filter can be mounted on the small shelf that is attached to the phototube's mounting box and held in place by a rubber band, as shown in Fig. 13. The filters vary in thickness, so you will have to adjust the space between the cardboard light shield and metal enclosure so that the light shield is touching the filter. Make this adjustment by sliding *only* the plastic carrier holding the metal enclosure; do not move the carrier holding the lamp. After mounting each filter, cover the lamp and phototube box with a tent made from the black cloth to minimize the effects of ambient light.

With a filter in place, you can measure V_s by adjusting the impeding voltage until the photocurrent reaches zero; the impeding voltage that stops all the current is the stopping voltage V_s. To make a reliable measurement of V_s, you should measure the photocurrent, I, as a function of the impeding voltage, V, and fit the data to obtain V_s. Taking a quick, coarse scan will give you an idea of the overall shape of $I(V)$. You can then decide on a set of voltages that seem appropriate and record a table of measurements in your logbook. Plot each of the $I(V)$ curves you measure and fit them for V_s. Make sure to put these plots in your logbook (and make sure they have proper labels on the axes, error bars on the points, the fitted function and its parameters).

After you obtain the V_s for each value of ν, fit that data to Equation (13) to obtain h/e and ϕ. This plot is the key result. While Planck's constant is the main result, the fit will also determine the metal's work function, which is also an interesting, though less fundamental, parameter.

Although the lab period does not have sufficient time for a thorough exploration of systematic uncertainties in the measurement, you should spend a few minutes thinking about what possible effects might have systematically biased your measurement and what auxiliary measurement you might make to measure these effects.

You can compare your measured value to the most precise measurement currently available, from NIST, of $h = (6.62606957 \pm 0.00000029) \times 10^{-34}$ J s. However, don't let your thought process be biased by how close or far your measurement is from that value. *You should approach your measurements as if you were the first to have ever measured this value!*

Finally, write your conclusion. It should include a statement of what you did, how you did it, what you measured, the uncertainty in your measurement and what the main contributions to your uncertainty were.

4.4 Going Beyond

There are several ways that exceptional students could improve the precision and robustness of this measurement. A few ideas are listed below, but I encourage you to use your own creativity.

- Repeat the V_s measurements with at least some of the filters. If the results differ significantly from your first set of measurements, you have evidence for a systematic uncertainty, and you have a measurement of that uncertainty, which should be included in your final determination of h.
- It would be best to electronically record the currents and voltages to obtain a fine grained $I(V)$ curve. The electrometer has a computer interface that would allow this, but using it requires a lot of setup. Can you think of another, simpler way to record both I and V as fine grained raw data

that you could subsequently extract for an $I(V)$ plot with many data points?

- Talk to your classmates and collect their measured values. With all of that data, you could do a global analysis of $V_s(\nu)$ that would let you both understand any systematic uncertainties and obtain a more precise determination of h.
- We relied on the advertised wavelength range for the filters. Can you think of a way to measure the filters' wavelength range yourself? Even if you don't have time to do so, it is interesting to think through and write out a plan for how you might carry it out in lab.