

The Photoelectric Effect and a Measurement of Planck's Constant

A. Introduction

In 1887 Heinrich Hertz discovered, quite accidentally, that ultraviolet light falling on the surfaces of metal electrodes produced a spark at a voltage lower than that which would produce sparking in the absence of the light. A surprise was that different metals required light of different minimum frequencies for this to occur, while increasing the intensity of the light did not increase the electron energies. Later work by several investigators showed that the sparking was caused by the emission of charges from the metal surface under illumination, and that the charges emitted were always negative. The phenomenon is called the *photoelectric effect*. The emitted charges were initially called *photoelectrons*. We now know that photoelectrons are no different from all other electrons, but the name has been kept because it is frequently useful to know how electrons have been liberated.

A systematic study of the photoelectric phenomenon revealed the following:

1. For any given material there is a minimum light frequency (maximum wavelength) below which electrons are not emitted. This frequency is called the *photoelectric threshold frequency*. Though all metals exhibit the effect, each metal has its own characteristic threshold frequency. The alkali metals (lithium, sodium, potassium, rubidium, etc.) have the lowest threshold frequencies. For these metals the threshold frequencies are in the range of visible light. For other metals, such as those used in the early experiments (copper, nickel, zinc) the threshold frequencies are in the ultraviolet.
2. For a given surface, the number of photoelectrons emitted per unit time (i.e., the photoelectric current) is directly proportional to the intensity of the light.
3. For a given metal surface, the kinetic energy of the emitted electrons depends only on the *frequency* of the light, and is independent of the *intensity* of the light.

These findings disagree with the "classical" theory of light as an oscillating electric field. According to this theory, increasing the intensity of the light would correspond to increasing the amplitude of the electric oscillation. A stronger electric field should accelerate the electrons to higher energies, and thus higher intensity would lead to higher energy electrons. In contrast, the experiments show that increasing the intensity of the light merely increases the number of emitted electrons (i.e., the *photocurrent*), but not their energy.

In 1905 an explanation of the photoelectric effect was proposed by Albert Einstein, then a lowly young patent clerk in Bern. He postulated that a light wave has a fundamental graininess, being the superposition of a huge number of discrete wave packets, called *quanta*. Each quantum has the energy $h\nu$, where ν represents the frequency of the light, and h is the constant introduced by Planck a few years earlier to explain the spectrum of black body radiation. According to Einstein's theory, a light wave may transfer energy to an electron only in units of these quanta. If this energy transfer ejects the electron from the metal, some amount of energy (W) is used to free the electron from the surface of the metal and the remaining energy goes into the electron's kinetic energy E .

Therefore:

$$E = h\nu - W \quad (1)$$

Some important points about this equation:

1. This simple hypothesis accommodates all three of the experimental facts on the previous page. You should think this through and be able to articulate an explanation of all three issues. Note that you are addressing here some of the fundamental assumptions of quantum mechanics.
2. The “liberation energy” W can be thought of as the binding energy between a conduction electron and the surface of the cathode. This energy is called the “work function” and is characteristic of the metal. It can be modeled surprisingly well as a step function potential difference (ϕ) between the edge of the lattice and free space. The work function is then $W = e\phi$ electron-volts, where e is the charge on the electron.
3. The linear relation between E and ν is the essential prediction of the photoelectric hypothesis. This is what you want to test. Measure E for a number of different ν , plot E vs ν , demonstrate the linearity, and show that the slope has the expected value. You can use the measured slope to derive a value for Planck’s constant.

B. Experimental Technique

The experiment requires a multi-chromatic source of light, and the ability to measure the light frequency and the photo-electron energy. The frequency measurement is easy: start with light of a broad spectrum and use optical filters to create approximately monochromatic beams at a number of different frequencies.

The harder problem, the measurement of the electron energy, is accomplished through a non-standard use of a photocell. In standard photocell operation, current is read from an anode that is held at a positive potential relative to a large area *photocathode*. When illuminated by light above the cut-off frequency, the photoelectrons flow from the cathode to the anode and create a detectable photocurrent.

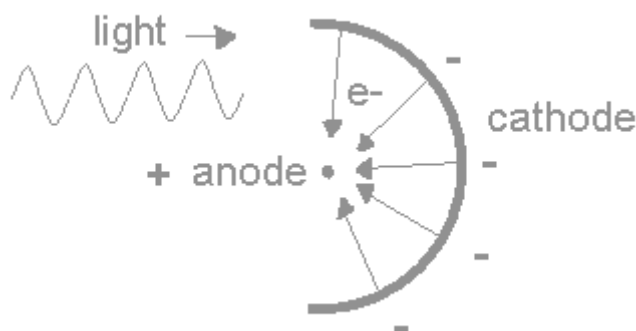


Figure 1 Normal Photocell Operation

In this experiment, we measure the electron energy by operating the photocell in *reverse*. The photocathode is connected to the positive terminal of a power supply and the anode to the negative. The photoelectrons are ejected from the cathode with energy according to Einstein’s equation, and then slowed down by the “retarding potential”.

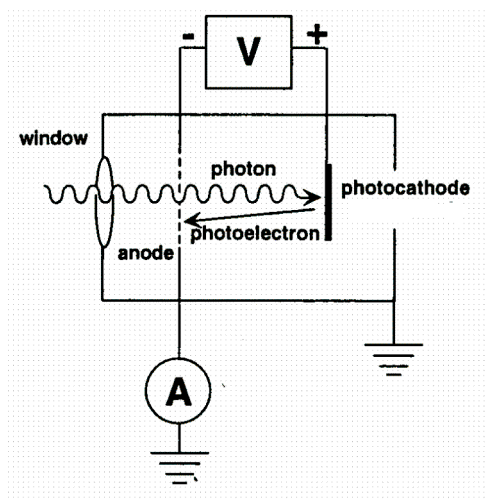


Figure 2 Reverse biased photodiode

When the retarding potential times the electron charge is just equal to the maximum energy of the photoelectrons, the current ceases. This potential is called the “stopping voltage”, V_s , and measures the maximum photoelectron energy as

$$E = eV_s \text{ when } I=0 \quad (2)$$

To verify the photoelectric effect and measure Planck’s constant h , you should measure the stopping voltage versus the wave number $1/\lambda$ for several frequencies of incident light. Equation 1 predicts that the stopping voltages and wavelengths should be related as:

$$V_s(\lambda) = \frac{hc}{e} \frac{1}{\lambda} - \phi \quad (3)$$

The slope of this line gives the quantity hc/e . You can assume e and c are known and calculate h . The intercept of the line gives the quantity ϕ , which you can compare to the expected work function for your cathode.

C. Equipment

The experiment is performed using an apparatus made by the Daedalon Corporation. To reduce spurious electromagnetic interface the equipment is housed in a metal box. The photocell is illuminated through a hole in this box. Note that the photocathode presents a large area to the light, but the anode is a thin wire. The retarding voltage is controlled by a knob, and its value appears as a voltage across the red and black jacks, which you read out with a DVM.

The anode current is extremely small to start with, of order nanoamps, and you want to measure where it goes to zero. You could use a picoammeter. Alternatively, the Daedalon device uses a current amplifier to convert the anode current to a measurable voltage, which drives a meter calibrated in nanoamps. A second knob, labeled “Zero Adjust”, allows you to balance the current amplifier so that it reads zero when the current is zero.

In order to allow a more quantitative study of anode current vs. retarding voltage, we have brought the meter inputs out on wires that can be connected to a DVM. With two DVMs, you can make a quantitative measurement of anode current *vs.* retarding voltage. Note that it is best to set the DVM that is measuring "the anode current" to measure voltage. Effectively, you are measuring the voltage appearing across the ammeter in the box. This is proportional to the anode current and you only need to know the absolute scale for the stopping voltage to measure Planck's constant. In what follows, however, we will still refer to it as the "anode current" or "photocurrent" though it is in arbitrary units.

The main light source is a mercury discharge tube that produces light at the characteristic frequencies of the mercury spectrum which you should look up. The individual mercury lines can be selected by various filters. The lines used in the experiment are:

- Red at 690.7 nm
- Yellow at 577.0 and 579.0 nm
- Green at 546.1 nm
- Blue at 435.8 nm
- Violet at 404.7 nm
- UV at 356 nm
- Helium-neon laser light at 632.8 nm

The UV from a mercury arc is a hazard and prolonged exposure to a strong source will produce sunburn or eye damage. The mercury lamp is thus inside a metal box which shields most of the light from the eyes. Avoid looking directly at the light for too long. When in use, position the small opening in the light box as close as possible to the opening in the box containing the photocell.

The filters can be clipped or taped onto the Daedalon box. The inexpensive looking filters are for 405 nm, 546 nm, and 691 nm. These are high pass filters – all wavelengths above a certain value are transmitted. (Why will this work for this experiment?) For 577 nm and 435 nm we have a small number of *interference filters* which function in band-pass mode, and isolate the given line. These are mounted on a metal plate. (When removing and inserting the interference filters, always hold them by the metal plate, never by the filter itself because the glue joint is rather weak.) The UV line may be measured by using the lamp with no filter. Note that some of the inexpensive red filters appear to pass a blue line which can significantly affect your results. If possible, check the transmission of the filters with the Ocean Optics spectrometer.

D. Procedure for Measurement of Stopping Voltages

1. Set up the apparatus on a table so that the aperture in front of the photocell faces the light source and can be slid against it. Use a block of wood or a box to bring the photocell to the same level as the light source.
2. Connect DVMs. One of these measures the retarding potential, using the jacks on the box. The other is connected to the leads from the current meter to allow measurement of the photocurrent (but set it to measure Voltage). Connect red to red and black to black to get the signs of voltages right.

3. Turn on the equipment. With the retarding voltage set to zero and no light on the photocathode set the "Zero Adjustment" knob so that the photocurrent is nearly zero <1 mV or so. Note the fluctuations in "dark current".
4. Mount a filter, the green one is good to start. Turn on the mercury lamp and place it as close as possible to the filter. The current amplifier is protected so that off-scale readings will not harm it.
5. Adjust the retarding potential and study the behavior of the photocurrent. You should be able to quickly find a voltage where the current stops changing. This is the stopping voltage. However, the current may not be exactly zero there, see below. Note that any adjustment knob, potentiometer, etc. has hysteresis. It's usually good practice to move knobs in one direction only for reproducible results. You may find it useful to make small adjustments in the "Zero Adjust" once you know the range of things. However, once it is set, be careful not to vary your zero by mistake in the middle of a measurement.
6. Record current *vs.* retarding voltage.

For the measurements with the laser, vary the aiming of the laser to maximize the photocurrent. It is best to aim the beam to the left or right of center so that you don't directly illuminate the anode center wire.

E. Photodiode Example Data and Discussion

An example of anode current vs. retarding voltage data for a number of wavelengths is shown in Fig. 3. This is from the first edition of Melissinos. Note that the polarity conventions may be different from yours. In these plots retarding voltage increases to the left.

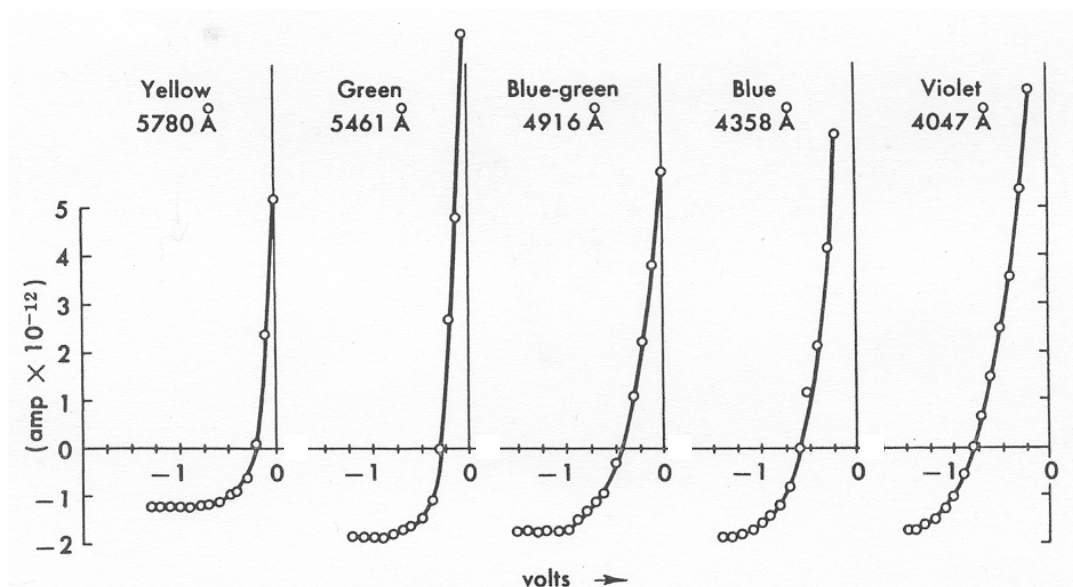


Figure 3. I-V curves for photodiode (from Melissinos, first Ed.)

These plots remind us of I-V curves for a diode. That makes sense! A difficulty in this experiment is that the equivalent of the diode threshold, the stopping voltage, is not *sharp*. As the retarding voltage approaches V_s , the anode current goes asymptotically to a constant value. This is partly because the electrons in the photocathode have a thermal energy distribution which broadens the work function.

In order to define a numerical “stopping voltage” for a given wavelength, you will have to invent a convention for deciding where the current “turns on”.

You can also notice other interesting features on this plot

1. The current is not zero when the diode is “stopped”. It becomes constant, but changes polarity before doing so. This is because there is small a reverse photocurrent flowing from the anode to the cathode! Think this through.
2. Independent of how you might define the stopping voltage, it is something like the location of “knee” in these plots, and it is clear that the knee moves to larger stopping voltage (more negative here) as the wavelength increases. This is Einstein’s prediction. Think this through.

The largest uncertainty in this experiment is that due to the technique for “defining” the stopping voltage for each filter. You should try at least two techniques, so that you can estimate how large the resulting uncertainties are. Possibilities are the point of maximum curvature (second derivative), or where it rises by a certain amount above the plateau.

F. Study of Photoelectric Effect and Measurement of Planck’s Constant

For each filter make a table and graph of photocurrent *vs.* retarding potential. Make a preliminary scan of the curve and use this to guide efficient data taking. Take fine steps near the “knee” where the current starts rising (where you need the precision). You only need coarser steps up the exponential rise, which is not so important for finding V_s .

Repeat this procedure for each of the filters with the mercury lamp and the He-Ne laser. Use the lamp with no filter to get a data point for the UV wavelengths. The photocurrent with the red filter is very small and the readings fluctuate ~ 1 mV, so do this one especially carefully. You may need to cover the gap between the two boxes to prevent photocurrents from outside light in this case.

For each value of λ , find the stopping voltage from your graph *and estimate its uncertainty*. As explained above, the definition of the stopping voltage is somewhat arbitrary, so invent your own definition and use it consistently. The “knee” of the curve, or point of maximum curvature, is one measure. Be especially careful with the He-Ne laser point. The laser intensity is so high that there is a strong temptation to overestimate the stopping voltage. In your report, include a table of wavelength, frequency, and two estimates of stopping voltages for each of your filters. Also, indicate the stopping voltages on your graphs of photocurrent *vs.* voltage.

Make a least squares fit of these data to a straight line using V_s as the y-axis and frequency or $1/\lambda$ as the x-axis. Do this for each technique for estimating the position of the “knee”. Include estimated error bars on your data points. Interpret your data in terms of the photoelectric hypothesis. Determine the slope and the uncertainty in the slope. From these results determine the quantity h (units eV-s) and its uncertainty. What are the key factors in the uncertainty? Can you improve your measurement? Determine the work function of the cathode and estimate its uncertainty. Do you get sensible results?

G. Further Questions

1. Compare your results with expectations from classical theory.
2. Photoelectrons are not just emitted from the outermost surface of the cathode, rather some photoelectrons come from below the surface. Explain how this affects the electron energies.
3. Your results depend on how you decided to define the stopping voltage. Consider the *systematic uncertainty* arising from this definition. What effect does this have on determining Planck's constant and the work function?
4. Is your result for Planck's constant consistent with expectation? If not, discuss possible reasons.
5. What is the effect of stray light on your measurements?
6. Explain why the photocurrent changes sign for large retarding voltages.
7. Look up the spectrum for mercury and verify the wavelengths of its spectral lines used in this experiment (Sect. C). Comment on any discrepancies.
8. Why isn't it necessary to use a filter for the mercury uv line?
9. Make a schematic diagram of the apparatus, including what is inside the Daedalon box.
10. Do some research to find what the photocathode material is in the Daedalon box. What is its expected work function?

References

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