Measuring Planck's Constant with the Photoelectric Effect

Abstract

We study the photocurrent generated through the photoelectric effect by shining light on a cathode and collecting the photoelectrons at an anode. A retarding voltage applied across the cathode is used to measure the energy of the photoelectrons. We qualitatively determine that the stopping potential is dependent on the frequency of impinging light, in agreement with Einstein's model. The dependence of photoelectron energy on frequency is used to measure the value of h, Planck's constant. We find $h = (4.25 \pm 0.11) \times 10^{-15}$ eV s, which is in good agreement with the accepted value (4.14×10^{-15} eV s).

Introduction

Light incident on a metal releases electrons, called a photocurrent. This well-known phenomena is called the photoelectric effect. In 1887, Heinrich Hertz accidentally discovered the photoelectric effect during his famous experiment in which he produced and detected electromagnetic waves (Tipler & Llewellyn 1999). Hertz was using a spark gap in a tuned circuit, and he noticed that the spark length was shorter when he enclosed the apparatus in a dark case. Though Hertz was annoyed by the effect at first, he later studied it and published his results. Other physicists confirmed and extended Hertz's research. In 1900, P. Lenard determined that the particles were electrons (Tipler & Llewellyn 1999). Classical electrodynamics suggests that the maximum photocurrent is proportional to the intensity of the incident light. Lenard observed this as he expected. However, Lenard also observed that there is no minimum intensity necessary to induce a photocurrent, which contradicts classical expectations. More generally, the energy of the emitted electrons does not depend on the intensity of the incident light.

In 1905, Albert Einstein explained these confusing observations by assuming the energy quantization hypothesis used by Max Planck in his solution to the blackbody problem (Tipler & Llewellyn 1999). If it is supposed that light of frequency ν is composed of discrete packets (photons) with energy $h\nu$, where h is a constant, the above results are expected: an electron is ejected only when a photon with sufficient energy hits the metal cathode. If the frequency is too low, no photons will be emitted. The intensity does not affect the energy of the emitted electrons, but instead determines the emission rate.

According to Einstein's predictions, the energy of an ejected electron is

$$E = h\nu - W, \tag{1}$$

where W is the amount of energy necessary to eject an electron from the metal.

Robert Millikan conducted careful experiments that showed the electron energy is linearly proportional to frequency. His results, published in 1914 and 1916, confirmed Einstein's prediction and gave a value of h that agreed with Planck's value. Einstein won the Nobel Prize in 1921, and Millikan won it in 1923. One of the main reasons that both Einstein and Millikan won the Prize was their work on the photoelectric effect.

Description of Apparatus

We sought to confirm Einstein's predictions and measure the value of h through the photoelectric effect. We used an apparatus made by the Daedalon Corporation that consists of a photocell (large photocathode and thin wire anode) housed inside a metal box. There is a retarding potential applied across the photocell, i.e., a power source with positive terminal attached to the photocathode and negative terminal attached to the anode. The retarding potential can be adjusted with a knob on the box. Also, there is a current amplifier that converts the pA anode current to a measurable voltage. The zero point of the current amplifier can be adjusted with a knob on the box labeled "Zero Adjust." See Amidei (2004) for schematic diagrams of the apparatus.

The apparatus has output jacks that can be connected to a digital voltmeter (DVM) to measure the retarding voltage. There is an analog ammeter on the front of the box that measures the anode current, but we ran leads out of the box so we could read the anode current off of a DVM.

We used a mercury arc lamp and a helium-neon laser as our light sources. In order to isolate single lines of the mercury spectrum, we clipped filters onto the front of the box. We used high pass filters with wavelengths of 546 nm and 405 nm and interference filters with wavelengths of 577.7 nm, 435.8 nm, and 546.1 nm. (High pass filters pass all wavelengths above the specified value. This does not matter, however, because the stopping potential is equal to the energy of the highest frequency, i. e., shortest wavelength, electrons.) We also tried to use the mercury UV line by not putting a filter on the box, but this did not work because the maximum retarding voltage is less than the stopping potential for the photoelectrons ejected by the UV light. The wavelength of the laser is 632.8 nm.

In order to minimize the effect of ambient light, we placed the lamp and laser as close to the window of the box as possible, covered the apparatus with a black cloth, and turned the room lights out.

Description of Data

For each wavelength of light, we measured the photocurrent as a function of retarding voltage. Before we took measurements, we determined a rough estimate of the stopping potential and set the zero point for the anode current. Starting with retarding voltage $V_R = 0.00$ V, we measured the photocurrent I (output as a voltage) every 0.10 V until we neared the neighborhood of the stopping potential V_S. When close to V_S, we decreased our step size. By observing the range of values of the anode current for each retarding voltage, we determined uncertainties on the current values. The uncertainty decreased as we neared the stopping voltage; in this regime, the uncertainty was on the order of ± 0.1 mV.

It was expected that the uncertainty in our final values would be dominated by the uncertainty in I and by systematic error introduced through our method for determination of V_S. The uncertainty in wavelength is minimal, because Professor Amidei showed that the FWHM of the mercury lines is on the order of angstroms. The uncertainty in V_R is also negligible because the DVMs have sensitivity of ± 0.1 mV.

Analysis of Data

Plots of photocurrent I versus retarding voltage V_R for each filter are given in Figure 1. The colors of the data points correspond to the filter used, as is explained in the key. (The filters denoted "cheap" are the high pass filters.) It is easily seen that lower wavelength (higher frequency) light required a greater stopping voltage. This is in qualitative agreement with Einstein's predictions. Error bars are not plotted to prevent the figure from being cluttered. As mentioned above, uncertainties near the stopping voltages are on the order of ± 0.1 mV.

We extracted V_S from the curves of Figure 1 through a simple procedure: we found the two smallest values of V_R that had the same value for I and defined V_S to be the retarding voltage halfway between the two points. We defined the symmetric uncertainty to be half of the difference between the points.

The above procedure is the biggest source of possible systematic error in our measurement. The stopping voltage is not well-defined for various reasons. Most importantly, the photocathode has a nontrivial depth, so the emitted electrons will have a range of energies. It is useful to think of the cathode as a diode. The natural direction of current flow for the photocell is from cathode to anode and the retarding voltage resists this. The plots of I vs. V_R resemble the same plots for a diode, as neither are sharp delta functions as they would be ideally (Melissinos & Napolitano 2003). Also, in both situations, if a large enough voltage is applied, current can be made to flow in the opposite direction.

Interpretation

The stopping potential vs frequency is shown in Figure 2. We did linear regression on the data and found that the best fit is given by

$$V_S = A + B\nu, \tag{2}$$

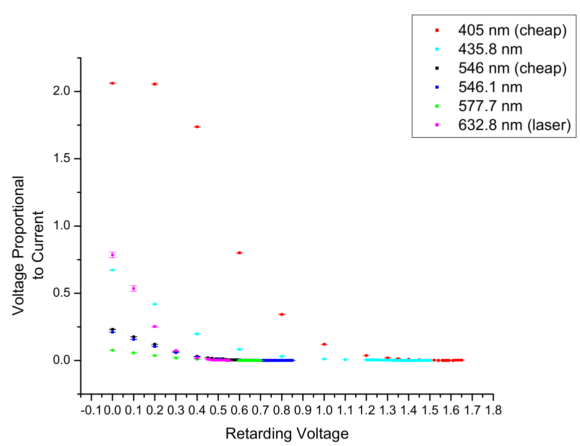

Figure 1: Photocurrent (V) vs. retarding voltage for the six wavelengths used. The plots have been normalized so that the asymptotic photocurrent is zero for all wavelengths.

with $A = -1.60 \pm 0.06$ eV and $B = (4.25 \pm 0.11) \times 10^{-15}$ eV s. Comparing Equation (2) to Equation (1) gives

$$A = -\frac{W}{e} = -\phi \tag{3}$$

and

$$B = h. \tag{4}$$

The standard deviation of the fit is 1.61, which is of order 1, so the fit is good and uncertainties are reasonable, i.e., the fit residuals essentially obey a Gaussian distribution.

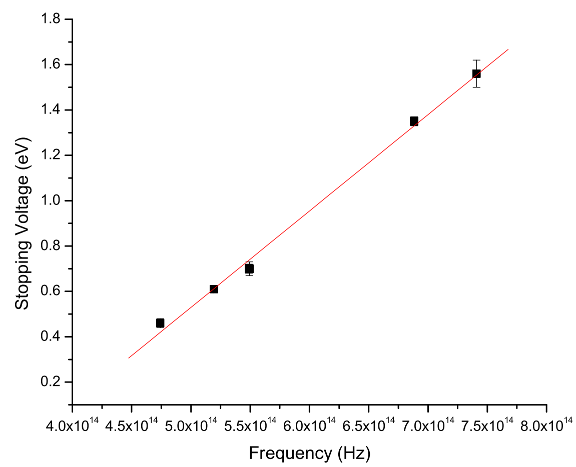

Figure 2: Stopping voltage (V) vs. frequency (Hz), with uncertainties. The six data points are fitted with a linear regression line. The slope is the measured value of Planck's constant and the y-intercept is the work function of the photocathode.

The measured value $h = (4.25 \pm 0.11) \times 10^{-15}$ eV s agrees well with the currently accepted value of Planck's constant, $h = 4.14 \times 10^{-15}$ eV s. This verifies Einstein's explanation of the photoelectric effect and suggests that systematic error was minimal.

The work function of the photocathode is $\phi = 1.60 \pm 0.06$ V. This is of the correct order of magnitude, but it is lower than that of any of the materials listed in Table 3-1 of Tipler & Llewellyn (1999), for example. It is possible that the presence of the anode has some effect on ϕ but this is unlikely because the surface area of the anode is negligible compared to that of the cathode. It seems likely that the cathode is simply just made out of an element or alloy different than those listed in Table 3-1. It is also possible that the cathode metal has been corroded, which could lower the work function.

Conclusions

We have verified Einstein's model of the photoelectric effect and measured Planck's constant. It was observed that photoelectron energy is linearly proportional to frequency with proportionality constant equal to Planck's constant. Our value $h = (4.25 \pm 0.11) \times 10^{-15}$ is only 3% different than the accepted value of Planck's constant. We also determined the work function of the cathode, but uncertainty in this measurement makes it less useful. We conclude that our results are consistent with the hypothesis that the energy of light is quantized.

References

[1] Amidei, Dan, 2001, "The Photoelectric Effect and a Measurement of Planck's Constant," Physics 441 handout.

[2] Melissinos, Adrian C., & Napolitano, Jim, 2003, *Experiments in Modern Physics: Second Edition*, Elsevier Science, p. 99-101.

[3] Tipler, Paul A., & Llewellyn, Ralph A., 1999, *Modern Physics: Third Edition*, W.H. Freeman and Company, p. 136-42.