Planck's constant from the Photoelectric Effect

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By measuring the current on the photocathode of the vacuum phototube and varying the voltage, the stopping potential was determined for a set of wavelength ranges. After applying a linear fit to these stopping potentials versus the frequency of radiation, the work function Φ of the photocathode of our vacuum phototube, and Planck's constant h were calculated. We found a value within 22.6% of the accepted value for h of $5.13 \pm 1.01 \cdot 10^{-34}\ J \cdot s$.

I. INTRODUCTION

When electromagnetic radiation comes into contact with a material, electrons are emitted which are referred to as photoelectrons. This is known as the photoelectric effect, and when investigated in depth in the early 20th century helped to propagate the emerging idea of wave-particle duality. The effect observed could not be characterized by the classical wave description of light, which predicted that electrons would build up energy over time and then be emitted, since the measured energy of the emitted electrons was not dependent upon the intensity of the radiation.

We sought to observe the photoelectric effect using a mercury lamp as our light source, a set of wavelength filters to monochromatize the radiation, a vacuum tube, and photocathode.

II. THEORETICAL BACKGROUND

Heinrich Hertz observed the photoelectric effect in 1887 by studying a coil with a spark gap that produced a spark when electromagnetic waves were detected. When he placed his apparatus in a dark box to better view the sparks produced, he noted that this reduced the maximum length of the spark. After inserting a glass panel between the electromagnetic wave source and the receiver this also decreased the spark length. [1] His discoveries were then studied more in depth by others, including Aleksandr Stoletov, who discovered Stoletov's Law which described the direct proportionality between induced photoelectric current and the intensity of light. [2]

In 1902, Phillip Lenard qualitatively observed that the energy of individual electrons increased with the frequency of the light. The measured maximum stopping potential of the phototube allowed Lenard to determine the electron energy, and he saw that the maximum kinetic energy of the electron was related to the frequency of the radiation. [3]

In 1900, Max Planck proposed that the energy of electromagnetic waves was released only in packets, and in 1905 Albert Einstein advanced this hypothesis to explain the experimental data of the photoelectric effect, theorizing that these light quanta had energy equivalent to the the frequency of the light ν multiplied by a constant h which was later called Planck's constant. [4] [5]

$$E = h\nu \tag{1}$$

The light quanta, photons, have the required energy to dislodge one electron only when above a threshold frequency. Before being ejected from their atomic binding, the electrons have a maximum kinetic energy given by

$$KE_{max} = h\nu - \Phi, \tag{2}$$

where Φ is the work function or minimum energy required to remove an electron from the material's surface

Although this description was in agreement with experimental results, it was met with resistance due to the contradiction of James Maxwell's equations of electromagnetism.

In 1914, Robert Millikan experimentally determined the precise mathematical relationship between ejected electrons and the frequency of light, showing that Einstein's description was correct, and yielding a key advancement in the development of quantum mechanics. [6]

A. Photoemission

Bounded electrons in atoms occupy distinct states of binding energies. When an individual electron receives energy more than this defined amount from light quanta, the electron can be freed and emitted with excess kinetic energy that is greater than its binding energy by an amount $h\nu$.

As an electron escapes through a surface barrier into the vacuum, the electron loses energy equivalent to the work function and loses momentum in the direction perpendicular to the surface. The kinetic energy of emitted electrons can be expressed by

$$KE_{max} = h\nu - \Phi - KE_b, \tag{3}$$

where KE_b is the binding energy of the electron.

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B. Experimental Observation of Photoelectric Emission

Typically, a clean metal surface in an evacuated tube is employed for the observation of the photoelectric effect, although photoemission can occur from any material. Unless neutralized by a current, the process creates a charge imbalance with produces a potential barrier that increases until emission is stopped. In addition, a vacuum prevents gases from interfering with the electron flow between electrodes. [7]

A voltage is supplied to direct photoemitted electrons onto a collector with externally controlled voltage. With the intensity and frequency of radiation fixed, the photoelectric current increases with increasing positive voltage as more electrons reach the electrode until a maximum number of photoelectrons are collected and the photoelectric current achieves a maximum value. This current can only be increased with a greater radiation intensity. [2]

When no current is observed, the negative voltage, which allows only the highest energy electrons to reach the collector, is at the value that stops most photoelectrons of KE_{max} and is called the stopping potential V_0. This relationship is given by

$$KE_{max} = eV_0, \tag{4}$$

where $e = 1.602 \cdot 10^{-19}$ C is the charge of the electron.

Increasing the intensity of the monochromatic light, within a certain threshold, increases the photoelectric current but does not effect the stopping voltage of kinetic energy of the photoelectrons.

The stopping potential can be expressed

$$|V_0| = \frac{hc}{e}\frac{1}{\lambda} + \frac{\Phi}{e}, \tag{5}$$

where $c = 2.998 \cdot 10^8$ m/s is the speed of light in a vacuum and λ is the wavelength. There are various approaches for experimentally determining this stopping potential, but one method is by estimating where the current curve begins to increase. [7] Once these stopping potentials have been determined by the graphs of retarding current versus voltage for multiple wavelengths, they can be plotted as a function of frequency and fit linearly to determine the slope which represents h/e and the V_0-intercept which corresponds to Φ/e.

III. EXPERIMENTAL PROCEDURE

Our apparatus was configured inside of a large wooden box with a lid and consisted of a mercury lamp with positive and negative terminals accessible on the outside of the box. Directly in front of the lamp was an optics caddy consisting of slots where we placed the wavelength and neutral density filters. A lens was positioned midway between the optics caddy and RCA 935 vacuum phototube in order to focus the light beam from the lamp onto the center of the photodiode. The phototube's anode and cathode terminals were also on the outside of the box.

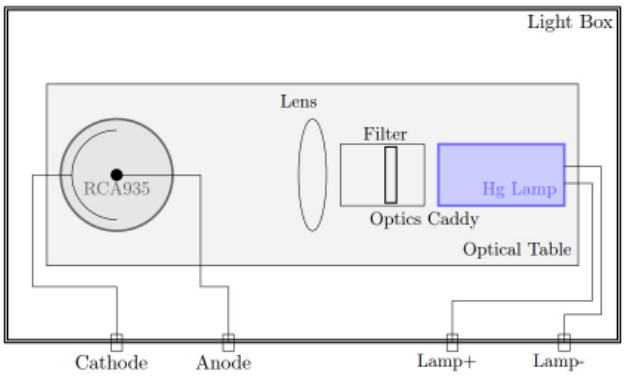

FIG. 1. Top View of Photoelectric Effect Apparatus Box [8]

After plugging in the LG DC GP-4303A power supply and ensuring both the voltage and current knobs were turned all the way down, we connected the positive and negative outputs using a banana plug and switched it on. Then we turned the current knob so that the current was set to 250 milliamps, and adjusted the voltage to 22 Volts, since this is approximately the voltage required for the mercury lamp to light. Once on, however, the lamp ran at a slightly lower voltage of 18 Volts.

We then switched off our power source and connected it to our mercury lamp using banana plugs. The mercury lamp itself also had a switch which we turned on.

Next, we used a BNC cable to connect the cathode of our phototube to the AO1 output port of our NI-USB 6341 DAQ, and the anode to the A02 output. We next connected the analog out terminal of our Keithley 6485 picoammeter to the AI0 input of our DAQ also using a BNC, and connected our DAQ via USB to our computer. This was configured so that our LabView VI code was set to program the retarding potential between the anode and cathode of the photodiode, and read the current from our picoammeter.

After turning on the power supply, DAQ, and picoammeter, we adjusted the LabView settings to correspond to the picoammeter's scale of microamps. We set our program's starting potential to -9 Volts, ending potential to 9 Volts, timescale to 0.1 seconds, and voltage increments to 0.1 Volts.

After taking a test recording to ensure our configurations were correct and connected properly, we turned off our power supply and inserted a 249-259 nanometer wavelength filter between the mercury lamp and lens. We then turned our power supply back on and ran our program with the same settings to determine the KE_{max} transition region and thus how we should adjust our voltage range, timescale, and voltage increments. We de-

termined this range from the graph of retarding current versus voltage the LabView software recorded and displayed, and observing the sharp increase that indicated the photocathode's stopping potential. We then ran the program again with these adjusted ranges, and saved the data file. We repeated this process for filters with wavelength ranges of 249-259 nanometers, 360-370 nanometers, 410-418 nanometers, 431-440 nanometers, 545-555 nanometers, and 575-584 nanometers in order to determine Planck's constant and the work function of the photocathode.

In order to determine the dependence of photoelectron energy on light intensity, we repeated the same procedure by instead using neutral density filters, which attenuate the intensity of the light I_0 times 10^{-OD}, with varying optical densities (OD) of 0.1 OD, 0.3 OD, and 0.7 OD along with a constant 431-440 nanometer wavelength filter.

IV. DATA

Figure 2 displays our raw voltage versus retarding current data for each wavelength filter used, and figure 3 shows our voltage versus retarding current data for each neutral density filter paired with a 431-440 nanometer wavelength filter.

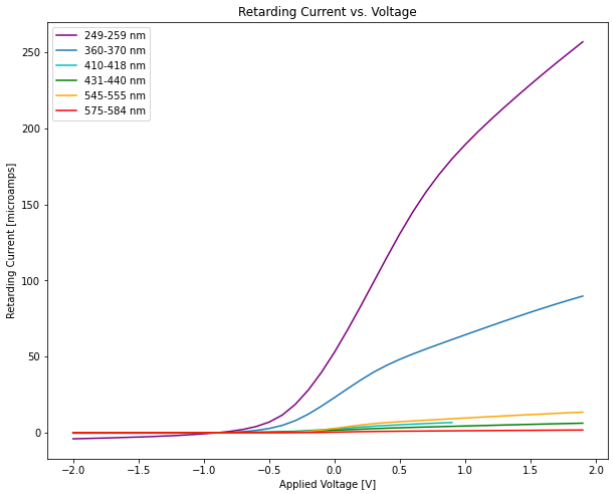

FIG. 2. Current vs. Voltage for Wavelength Ranges

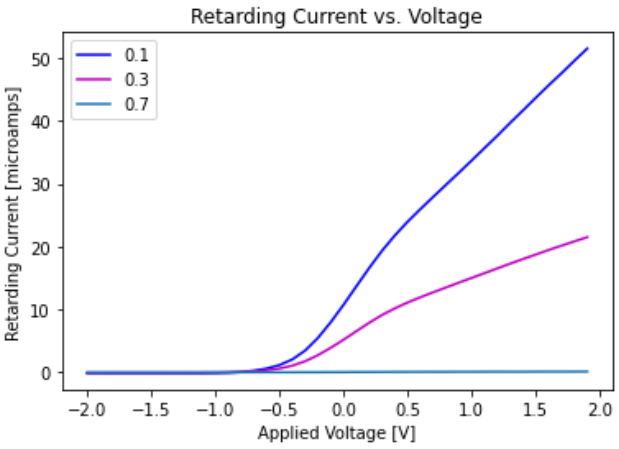

FIG. 3. Current vs. Voltage for Optical Densities

V. ANALYSIS

Table I lists the stopping potentials determined for each wavelength range.

TABLE I. Stopping Potential

Wavelength λ [nm]	Stopping Potential V_0 [V]
249-259	-2.00 ± 0.10
360-370	-1.90 ± 0.10
410-418	-1.20 ± 0.10
431-440	-0.40 ± 0.10
545-555	-0.10 ± 0.10
575-584	-0.05 ± 0.10

Table II lists the stopping potentials found for each neutral density filter. Each filter was paired with a 431-440 nanometer wavelength filter.

TABLE II. Stopping Potential

Optical Density	Stopping Potential V_0 [V]
0.1	-0.80 ± 0.10
0.3	-0.80 ± 0.10
0.7	-0.80 ± 0.10

After plotting $|V_s|$ as a function of $\lambda/1$, shown in figure 4 and applying a linear fit to this data, we determined h/e from the slope and Φ/e from the y-intercept. Our linear fit was found to be

$$|V_0| = (3.2 \cdot 10^{-15} V \cdot s)\nu - 1.45V \tag{6}$$

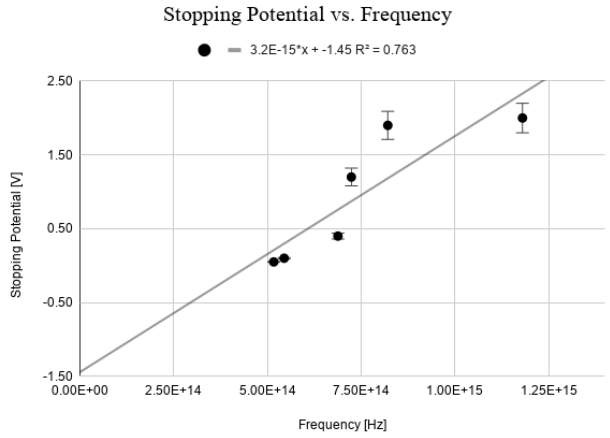

FIG. 4. Stopping Potential vs. Frequency

VI. CONCLUSION

The value of h/e we found was 3.2±0.63 $\cdot 10^{-15}$ V·s which, when multiplied by the elementary charge, yielded a value of 5.13±1.01 $\cdot$ 10^{-34} $J \cdot s$ for h, which is within 22.6% of the accepted value of 6.63·10^{-34} J·s.

Our value for Φ was 1.45±0.10 V. Our goodness of fit for these values was 0.763.

Figure 3 depicts the relationship between intensity and current of the electrons which agrees with the theoretical description of the relationship. We found that the voltage does not depend on the intensity, therefore illustrating that the classical description of this phenomena is inadequate.

Issues and error in our experiment may have been a result of an excess of leakage of the current between the phototube's electrode terminals. [7] Another important factor contributing to the quality of our data is the purity of the photoemissive surface and vacuum environment. In addition, dark currents or reverse currents due to the photoelectric emission from the electrode of the phototube that were in excess of the correction in our software would cause deviations in the data. Electrons in the space between the electrodes could potentially produce space-charge effects which would interfere with our data. The spectral purity of the light illuminating our phototube, as well as the consistency of the intensity during runs had impacts on our recorded current versus voltage. [9] Finally, the sensitivity and accuracy of our equipment measuring the photocurrent would effect our recorded values. [10]

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