Determining h/e and Cs_3Sb Work Function by Measurements of the Photoelectric Effect

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(Dated: February 24, 2024)

We investigated the photoelectric effect by observing the electron emission of a Cs_3Sb photo-cathode irradiated by a Mercury lamp. By varying an applied voltage to the photo-cathode, we can determine a relationship between photon energy and electron ejection. Quantifying the relationship between the stopping potential — a voltage at which the photo-current begins to linearly increase — and the light wavelength, we calculated Planck's constant as $(1.43 \pm 0.17) \times 10^{-34}$ Js and the work function of the photo-cathode as $(-3.2 \pm 1.2) \times 10^{-20}$ J. Additionally, we tested the dependence of the stopping potential on light intensity and found no correlation, illustrating that light behaves as a particle, and agreeing with Einstein's quantum theory of light.

I. INTRODUCTION

In 1845, Michael Faraday showed that magnetism and light were coupled through his polarisation experiments. Shortly after, various scientists had proposed theories to explain the links between electricity and magnetism. In 1865, James Maxwell explained light as a continuous electromagnetic wave of a uniform velocity through his four equations. He found that the color of light depended on the wavelength of these electromagnetic fields [1]. However, several experiments toward the late 19th-century produced results that differed with this explanation. Notably, in 1887, Heinrich Hertz observed sparks — the discharge of electrons — emitting from a metal plate irradiated with ultraviolet light. When he repeated his experiment, he noticed that sparks were emitted only below a characteristic wavelength of light which differed between different types of metals. Above this wavelength, no sparks were emitted. This contradicted Maxwell's theory of light which predicts electronic discharge proportional to the wavelength of the electromagnetic wave. In 1905, Albert Einstein explained Hertz's observations through the description of light as existing in distinct quanta, called photons [2].

Einstein's paper, *Über einen die Erzeugung und Verwandlung des Lichtes betreffenden heuristischen Gesichtspunkt*, or "On a Heuristic Viewpoint Concerning the Production and Transformation of Light," explained two of Hertz's findings as illustrating the particle interpretation of light [3].

When irradiating a metal with light:

1. there exists a photon energy below which no electrons are ejected from the metal, and above which electrons are ejected.
2. there is no relationship between the intensity of the light and the kinetic energy of the ejected electrons.

We derive the first property from conservation of energy. Electrons are bound by a potential. Should the energy of a photon, $h\nu$, not exceed that of the binding potential, the electron will remain in the metal. Any excess photon energy contributes toward the kinetic energy of the ejected electron. The second property states that electrons absorb photons either in their entirety or not at all, illustrating that photons are indivisible particles [3].

In this experiment, we use a lamp to excite electrons from the photo-cathode of a vacuum photo-tube. By applying a negative voltage across the photo-tube, then slowly decreasing its magnitude, we can determine the point at which the photo-current transitions from no signal to linearly increasing; this voltage is called the stopping potential which we denote V_S. Melissinos derives a method for relating the magnitude of the stopping potential to both the wavelength of the photon, λ, and the work function of the metal, Φ [4]:

$$\begin{aligned} \Delta E &= 0 \\ E_{\text{photon}} &= E_{\text{electron}} \\ h\nu &= \text{KE}_{\text{max}} + \Phi \\ h\nu &= e|V_S| + \Phi \end{aligned}$$

which reduces to:

$$|V_S| = \frac{hc}{e}\frac{1}{\lambda} + \frac{\Phi}{e} \tag{1}$$

Since energy must be conserved, the photon energy, $h\nu$, equals the sum of the kinetic (KE_{max}) and potential (Φ) energies of the bound electron. KE_{max} can be written as the product of the electron charge, e, and the magnitude of V_S. We can then rearrange terms to yield Equation 1.

Since we can write the maximum electron kinetic energy, KE_{max} as $e|V_S|$, there is a direct proportionality between V_S and KE_{max}.

II. EXPERIMENTAL SETUP

A. Apparatus

To investigate the photoelectric effect, we build our apparatus in a dark box isolated from external light sources. We use a Mercury lamp to excite the Cs_3Sb photo-cathode of an RCA 935 vacuum photo-tube. Mercury lamps produce photons by arcing electricity across vaporized Mercury [5]. The spectrum of photon emissions is well understood with certain dominant wavelengths as shown in Figure 1. The vacuum photo-tube is a simple photo-detector; photons excite electrons from the metal photo-cathode toward the anode via the photoelectric effect, resulting in a measurable, but weak photo-current, which we can measure with a picoammeter, a highly-sensitive current meter [6].

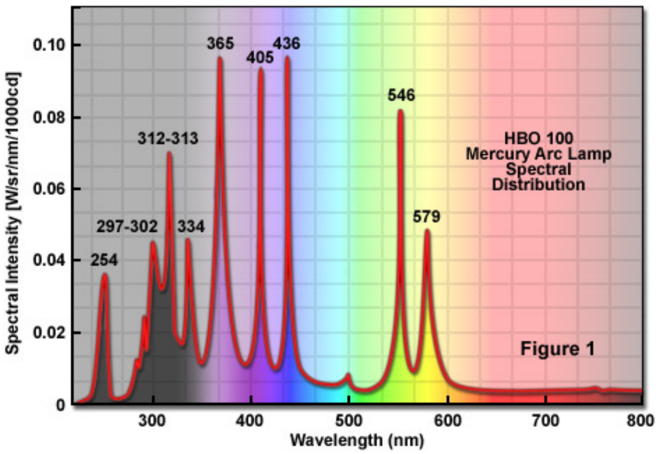

FIG. 1: The photon emission spectrum of a Mercury vapor lamp. Notice several clear peaks with varying widths; photons are emitted in many wavelength bands at a high probability with a low probability of other wavelengths [5].

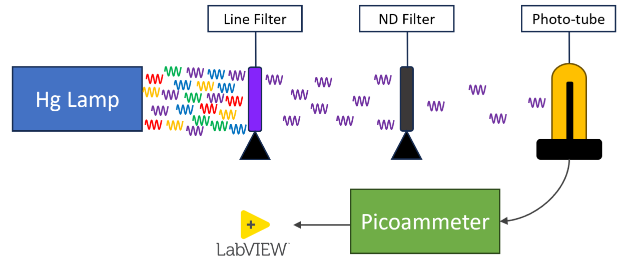

FIG. 2: A schematic of our experimental apparatus. A Mercury (Hg) lamp emits photons of many wavelengths as shown in Figure 1. A line filter selects only desired wavelengths to pass while absorbing all others. These photons then reach a vacuum photo-tube, producing a small current, read by a picoammeter and stored as a text document using LabView. For testing the effect of intensity, we inserted an ND filter between the line filter and the photo-tube.

In order to isolate the effect of photon wavelength on observed photo-current, we isolate four peaks using spectral line filters with ratings 365-375, 395-415, 431-440, and 548 nm. These correspond to the 365, 405, 436, and 546 nm peaks as shown in Figure 1. Ideal spectral line filters allow photons from a certain band of wavelengths to pass through while absorbing all others. This effectively isolates the photons we are interested in investigating so that no other photons hit the detector. The resultant photo-current is read by a National Instruments USB-6361 X Series Data Acquisition Device and processed by `PhotoElectricEffect.vi`, a stable public LabView file which reads the current repeatedly, stores the values in a text file, and presents the data visually.

To test the hypothesis that electron emission does not depend on photon energy, we use the same apparatus with the insertion of several neutral density (ND) filters, special optics characterized by an optical density (OD). These filters diminish the intensity of light, I, from the non-attenuated intensity I_0 via the relation $I = I_0 10^{-\mathrm{OD}}$, reducing the number of photons that reach the photo-detector. We used four ND filters of OD ratings 0.1, 0.3, 0.5, 0.9 to determine the effect of intensity on V_S. To mitigate the dependence of V_S on the wavelength of light irradiation, we additionally inserted the 548 nm line filter for all trials. A diagram of our complete setup is shown in Figure 2.

B. Data Collection

To determine Planck's constant and the work function of our photo-cathode, we first investigate the relationship between wavelength and voltage applied to the vacuum photo-tube. For each spectral band, we repeatedly scan the voltage applied to the photo-tube and record the resultant photo-current. This produces a trace of photo-currents which is approximately 0 until the applied voltage equals the stopping potential, V_S, where the photo-current begins to increase linearly. This point is important for our calculation of Planck's constant and the photo-cathode work function as described by Equations 1. An example trace is shown in Figure 3. Notice that the transition from 0 photo-current to a linearly increasing photo-current is not sharp. We believe this is due to fluctuations in photon energy as the line filters are not perfectly monochromatic. Additionally, we noticed a negative photo-current of small-magnitude and approximately linear slope where we should have seen 0 photo-current; we believe this is due to photo-electric emission from the anode to the photo-cathode. We repeat this experiment several times for each wavelength and notice that the approximate location of V_S does not change between trials of the same spectral band, but it becomes slightly smaller in magnitude as the wavelength increases.

To qualify the relationship between light intensity and electron emission, we repeat the experiment, inserting a neutral density filter into the apparatus and holding the wavelength constant. Since we hypothesize V_S to depend on wavelength, it is important to hold this factor constant to isolate the effect of light intensity. We repeat the experiment several times for each ND filter to reduce uncertainty. We notice that our traces appear to have the same V_S with diminished photo-current as the OD increases.

C. Data Analysis

When analyzing our traces from the trials determining the relationship between V_S and wavelength, we were unable to observe a sharp transition from 0 to linearly increasing photo-current. To determine V_S, we first attempted to choose a point at which the trace begins to increase from 0 nA. However, this yielded extremely inaccurate results. After consulting existing literature, we fit a linear model to the data preceding V_S and a separate linear model to the data succeeding V_S. Ideally the former model should be constant, but we fit a linear model to account for the observed negative photo-current. Then,

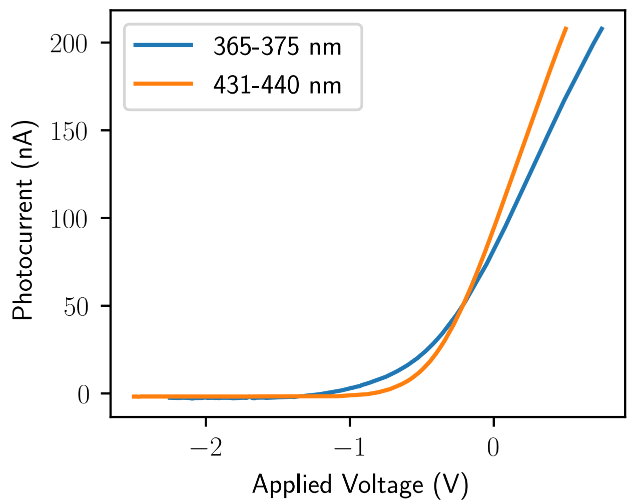

FIG. 3: Example traces from two different wavelengths. Notice that both traces start at 0 current, and the shorter wavelength trace appears to start increasing at a lower voltage. This suggests V_S increases in magnitude as wavelength decreases.

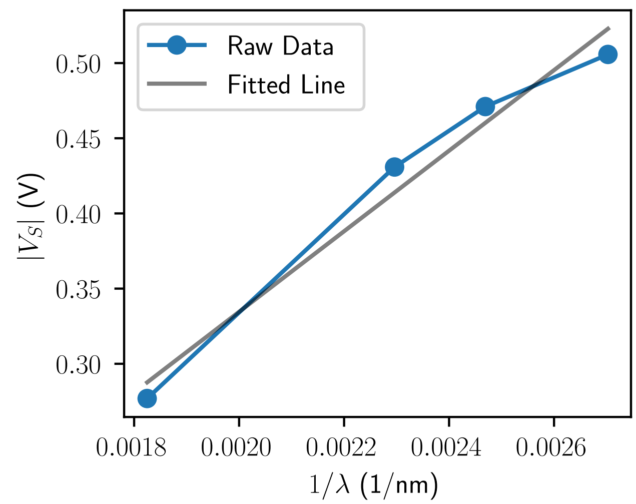

FIG. 5: Illustrating the approximately linear relationship between $1/\lambda$ and $1/|V_S|$ with a linear model overlaid. The fitted line parameters allows us to calculate Planck's constant and the work function as described by Equation 1.

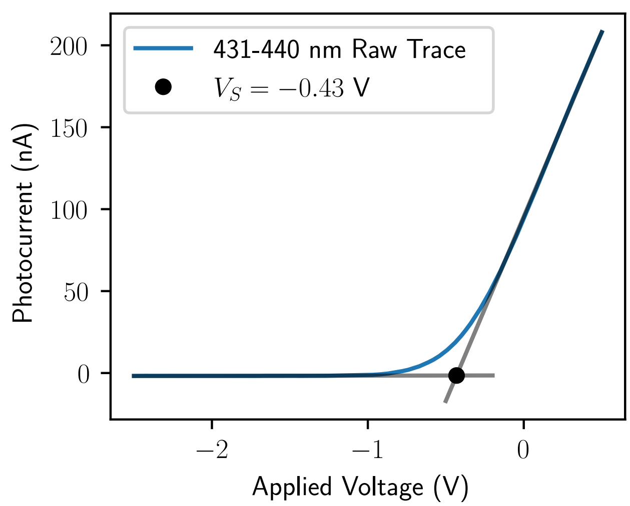

FIG. 4: The average trace from the 431-440 nm trials with linear models overlaid. V_S is the intersection of two fitted lines: one to the data before the photo-current begins to increase, and the other to the data once the photo-current appears to linearly increase.

we determined the intersection of the two models which we defined as V_S [4]. To implement this method, we scaled the traces such that they had the same maximum photo-current; the slope of the second linear model depends upon the maximum photo-current, and the intersection of the two models depends on the slope. Figure 4 shows an example of the resultant V_S as determined using this method overlaid on the raw trace. Using this method, we increase the accuracy of each estimated V_S.

To determine Planck's constant and the work function of Cs_3Sb, we used Equation 1. Using `scipy.optimize.curve_fit` — a Python function to fit data to a theoretical function using least squares regression — we fit a linear model for $1/\lambda$ vs $1/|V_S|$. Our fit determined Planck's constant as $(1.43 \pm 0.17) \times 10^{-34}$ Js and the work function as $(-3.2 \pm 1.2) \times 10^{-20}$ J. Parameter uncertainty was found by calculating the fitting error using `scipy` and propagating the parameter errors for the linear fits used in calculating V_S. To determine h and Φ from our fit, we use $c = 299792458$ m/s and $e = 1.60217663 \times 10^{-19}$ C. Since these values are well established, we did not propagate the error for these terms. Figure 5 illustrates our resultant graph of $1/\lambda$ vs $1/|V_S|$ with the fitted line overlaid.

When we tested the dependence of photo-current on photon intensity, we observed a similar V_S for each trial, with diminished amplitude of the linear photo-current. To support our claim that increased photon intensity increases maximum photo-current via the OD factor, we overlaid the graphs by applying a scaling factor to each trace. This scaling factor was chosen by dividing each trace by the ratio of its maximum photo-current to the maximum photo-current of the first trace. Theoretically, this should produce scaling factors of 1.00, 1.58, 2.51, 6.31 for traces corresponding to OD 0.1, 0.3, 0.5, 0.9. These predicted factors were calculated by dividing the ratio of intensities $(10^{-0.1}/10^{-OD})$. However, our algorithm determined scaling factors of 1.00, 1.31, 1.73, 2.53 respectively. Therefore, our ND filters are likely not attenuating light according to their specifications. The traces overlap, with each V_S — determined using the aforementioned method — at approximately the same point, -257.9 ± 7.7 mV. Additionally, each point aligned with a standard deviation of 0.55 ± 0.15 nA. Therefore, we can claim that electron kinetic energy does not depend on light intensity.

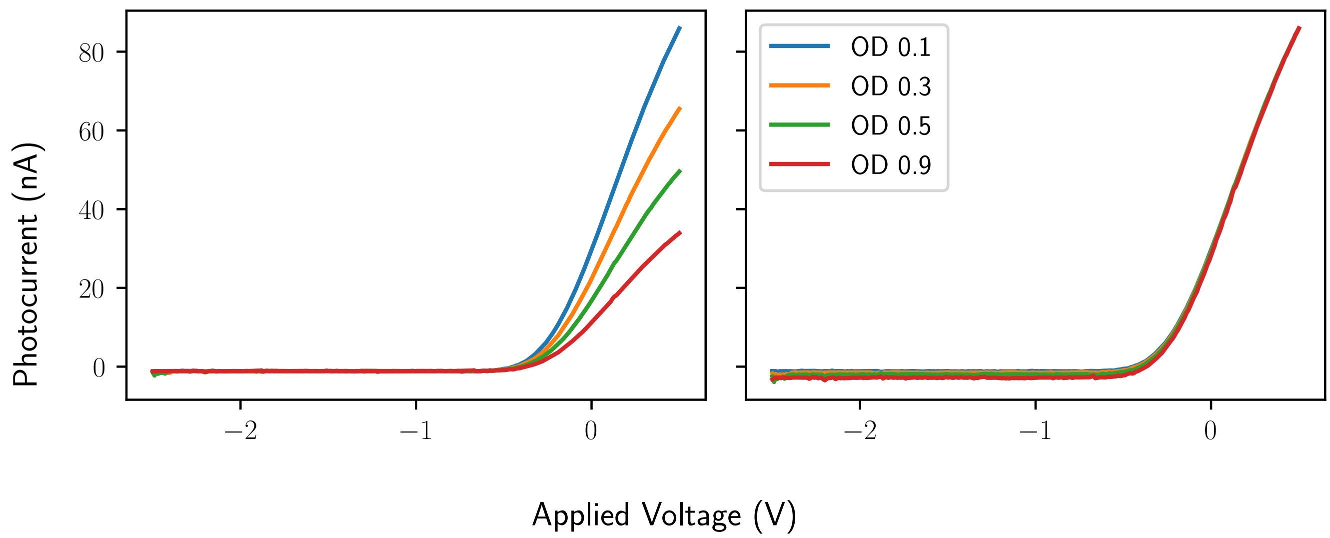

FIG. 6: Graphing photo-current vs voltage applied to vacuum photo-detector. Left: pre-correction traces showing approximate overlap of V_S with vertical attenuation. Right: post-correction traces showing approximate overlap of entire trace. Since there is a scaling factor we can apply to approximately match the traces of each OD test, we can claim that the Vs is the same for all traces.

III. DISCUSSION

By measuring V_S for different wavelengths of light incident a vacuum photo-tube, we determined Planck's constant as $(1.43 \pm 0.17) \times 10^{-34}$ Js and the work function of our photo-cathode as $(-3.2 \pm 1.2) \times 10^{-20}$ J, indicating the minimum energy to release an electron from the potential of the Cs_3Sb photo-cathode.

Planck's constant is a widely-accepted constant with value $6.62607015 \times 10^{-34}$ Js. Additionally, the theoretical minimum energy to release an electron from the conduction band to vacuum for Cs_3Sb is 0.5 eV [7], or approximately 8×10^{-20} J. Therefore, our confidence intervals did not include the accepted value for either calculation.

We believe our primary source of possible error is discrepancies in our spectral line filters allowing photons of different wavelengths to reach the detector. Other possible sources of error include (1) impurities in the photo-cathode causing fluctuations in the work function, prematurely releasing electrons, (2) photo-electron emission from the anode toward the cathode causing a negative current in the highest magnitude applied voltages, and (3) light contamination from the lab penetrating the dark box.

Comparing V_S for different intensities of light, holding wavelength constant, allowed us to isolate the relationship between electron kinetic energy and photon intensity. Since each intensity overlapped well and produced the same stopping potential (within one standard deviation), we concluded that photon intensity did not affect ejected electron kinetic energy. This agrees with Einstein's photoelectric theory. We predict that the discrepancies between predicted and true scaling factors were due to our neutral density filters' true attenuation coefficient disagreeing with their specified attenuation coefficient.

IV. CONCLUSIONS

We tested the photoelectric effect by observing the dependence of light wavelength and intensity on electron ejections from a metal. Using a Mercury lamp and a vacuum photo-tube, we estimated the stopping potential of the metal for each wavelength of light. Through relating the stopping potential and wavelength, we measured Planck's constant and the work function of the Cs_3Sb cathode. We then tested the stopping potential for 548 nm light at different intensities to test the quantized interpretation of light.

We calculated Planck's constant to be $(1.43 \pm 0.17) \times 10^{-34}$ Js. Our value disagreed with the standard accepted value but agreed to the same order. Possibly, our apparatus allowed for light contamination to enter our experiment or our optics were not accurate to their specifications. The measured work function was $(-3.2 \pm 1.2) \times 10^{-20}$ J, disagreeing with theoretical values for an electron ejected from the conduction band of Cs_3Sb, but agreeing to the same order. Finally, by varying the intensity of light radiation while holding wavelength constant, we determined no correlation between light intensity and electron energy, showing that light behaves as a particle.

Classical dynamics predicts a linear dependence between photon intensity and photo-current regardless of wavelength since continuous electromagnetic waves transfer energy constantly [1]. However, quantum mechanics predicts that photons are individual particles of definite energy depending on their wavelength. They are absorbed entirely or not at all [3]. Therefore, metals can only emit electrons if the photon energy exceeds the magnitude of the work function. Since we observed no photoelectric emission below the stopping potential and no dependence of light intensity on photo-current, our results agree with the quantum mechanical interpretation of light predicted by Einstein.

I would like to thank my lab partner, Adrian, for his invaluable assistance during the experiment. Additionally, I would like to thank Dr Greg Sitz for assisting our efforts in and outside of the lab. I would also like to thank the creators of Python, Pandas, Numpy, Scipy, Matplotlib, and PowerPoint who helped make possible the analysis and figures in this paper. This paper was written and compiled in LaTeX using the Overleaf online editor.

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