The Photoelectric Effect

Nestor Viana
Florida International University

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1 Introduction

In 1887 Heinrich Hertz discovered that ultraviolet light incident 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 named *threshold frequencies* for this to occur, while increasing the intensity of the light did not increase the electrons' kinetic energy. Later work by several other scientists and Einstein 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 (Figure 1). The phenomenon is called the photoelectric effect. The emitted charges were initially called photoelectrons. This discovery led to the quantum revolution in physics and earned Albert Einstein the Nobel Prize in Physics in 1921.

Normally, an ordinary electron on the surface of a conducting material cannot simply leave the surface; if such electron were to escape, it would leave behind a net positive charge, known as an *image charge*, and so attractive forces will redirect the trajectory of the electron back onto the surface. This creates an energy barrier called the *work function* of the metal. The photoelectric effect then occurs when incident light transfers enough energy to the surface atoms and excite electrons enough to overcome the work function. The minimum frequency of light that gives rise to photoemission is known as the *threshold frequency*.

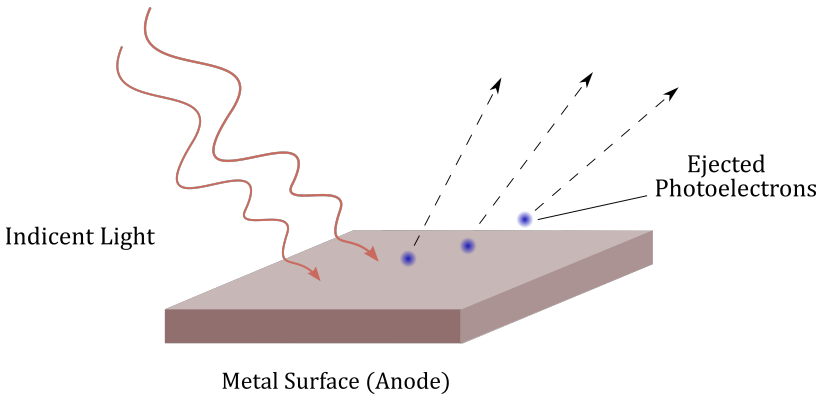


Figure 1: Photoemission.

By conservation of energy, when photon transfers all its energy to an atom, the total energy becomes:

$$h\nu = \phi + K \tag{1}$$

where ν denotes the frequency of light, ϕ represents the work function of the metal, K is the maximum kinetic energy of the ejected photoelectron, and h is Planck's constant.

2 Setup

In this experiment, our goal is to determine Planck's constant h and the work function of the metal anode. We use a Mercury lamp as the light source. A lens focuses the white light along the entrance slit, reaching a monochromator which lets us select a particular range of light from the electromagnetic spectrum. The wavelength adjust specifies what color of light exits the slit toward the amplifier controller. We choose wavelengths corresponding to yellow, green, blue, violet, and ultraviolet light using the built-in milliammeter.

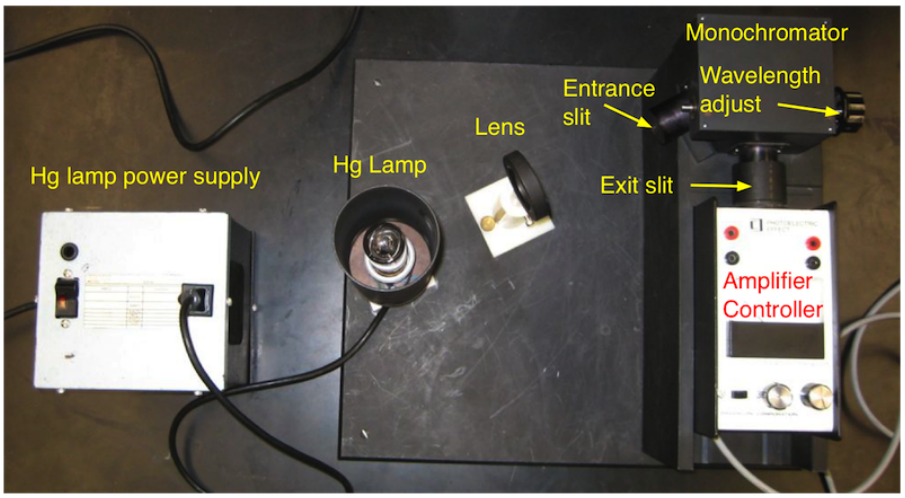


Figure 2: Main parts of the experimental setup.

Next, we set the potential difference between the anode (metal surface) and the cathode to a maximum, which acts as a retarding potential for the photoelectrons. With this configuration, virtually no electrons have enough energy to reach the cathode and thus no appreciable current is detected. As we decrease the retarding potential, the current registered increases gradually at first until a sharp increase is observed. The retarding potential at the sharp current increase is called the *stopping potential*, V_s, which corresponds to the maximum kinetic energy of photoelectrons.

$$h\nu = \phi + eV_s \tag{2}$$

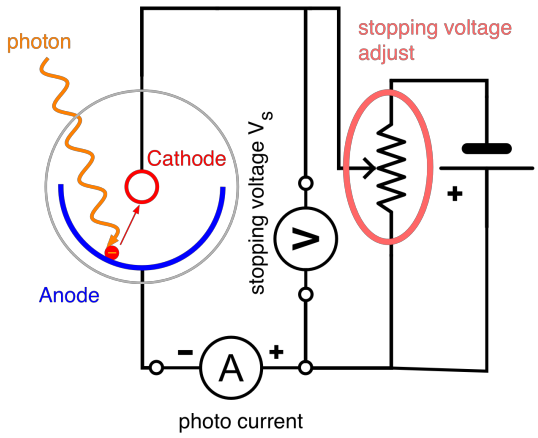


Figure 3: Circuit diagram of setup.

3 Data and Analysis

Below we plot the data sets of photoelectric current vs retarding potential for yellow, green, blue, violet, and ultraviolet light. On each graph we also plot three lines whose intersection determine the range of the stopping voltage V_s. The flat line follows the slow, gradual decrease of current indicating that no electrons are able to reach the cathode, the second line models the "knee" or sharp transition in the current signaling the stopping voltage, and the third vertical line accompanies the steady current decrease corresponding to less electrons continuously reaching the cathode.

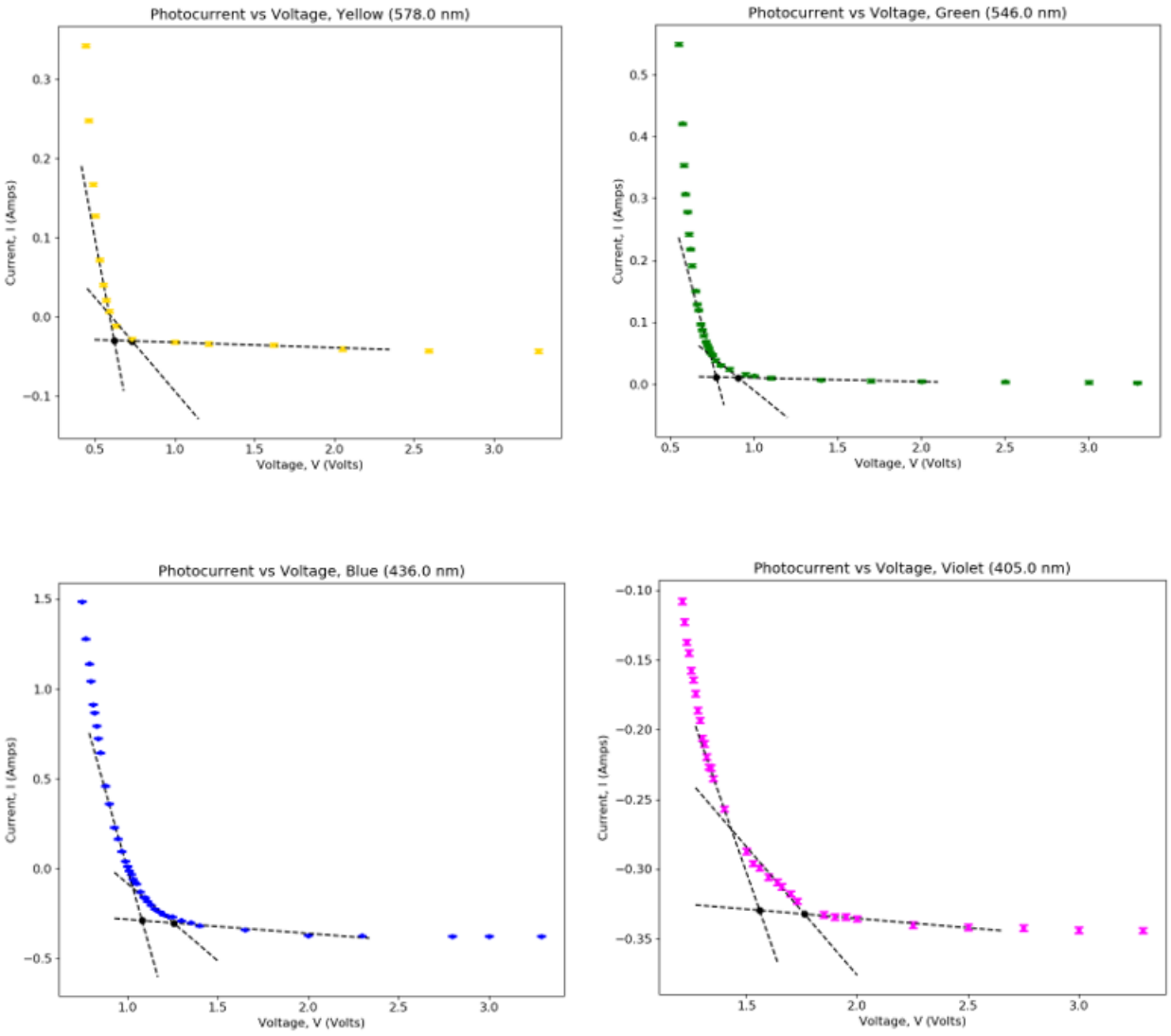


Figure 4: Graphs of current vs voltage for yellow, green, blue and violet wavelengths of light. The regions between the line intersections signaled by two black dots represent the ranges for the possible stopping voltages.

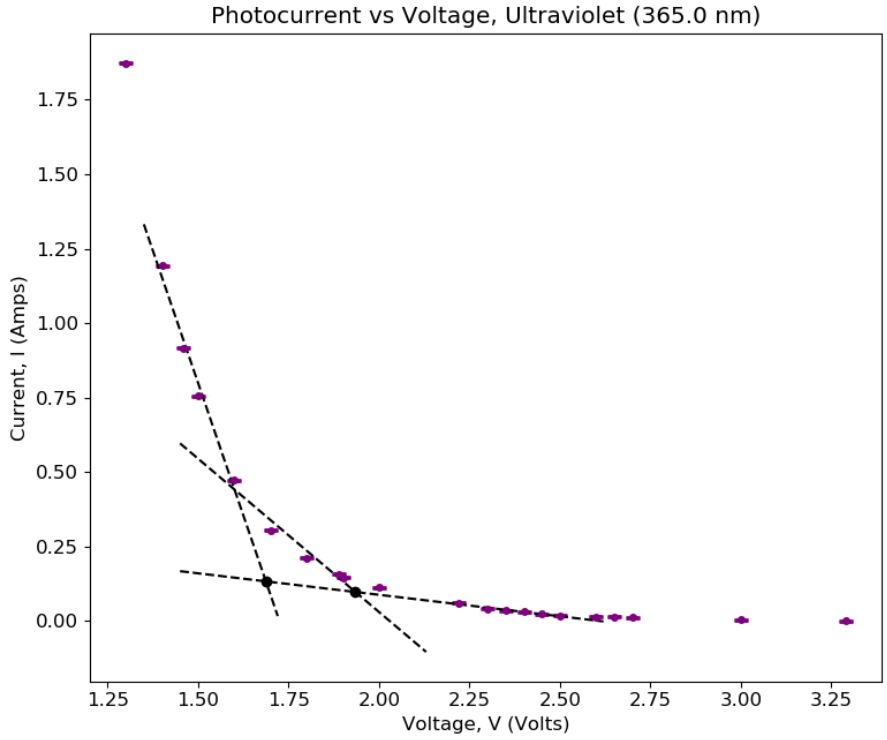


Figure 5: Current vs retarding potential plot for ultraviolet light.

Since there is no clear way of determining where inside the intersection ranges the true value of the stopping voltage is located, we attempt choosing the left endpoint V_{min}, the midpoint V_{mid}, and the right endpoint V_{max} of the ranges as the values for the stopping voltage. In any case, we define the uncertainty to be half the length of the of the intervals; the reasoning behind such seemingly arbitrary choice for the uncertainty is to assure that through repeated runs of this experiment the margin of error defined by σ_{V_s} captures the true value value of V_s a higher percent of the time. In other words,

$$V_{mid} = \frac{V_{max} + V_{min}}{2} \tag{3}$$

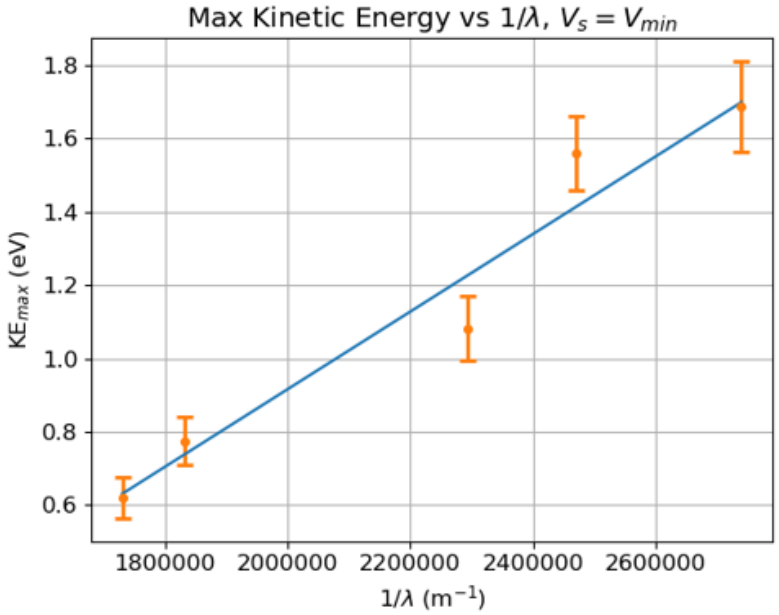
and

$$\sigma_{V_s} = \frac{V_{max} - V_{min}}{2}. \tag{4}$$

The maximum kinetic energy of the photoelectrons is therefore $K = eV_s$, where e is the magnitude of the electron charge. Rearranging Equation 1, we have

$$K_{max} = eV_s = \frac{hc}{\lambda} - \phi. \tag{5}$$

To determine the work function of the anode and to estimate Planck's constant, we plot K_{max} as a function of $1/\lambda$, known as the wavenumber, and perform a linear regression on the data for each three choices of stopping voltage.



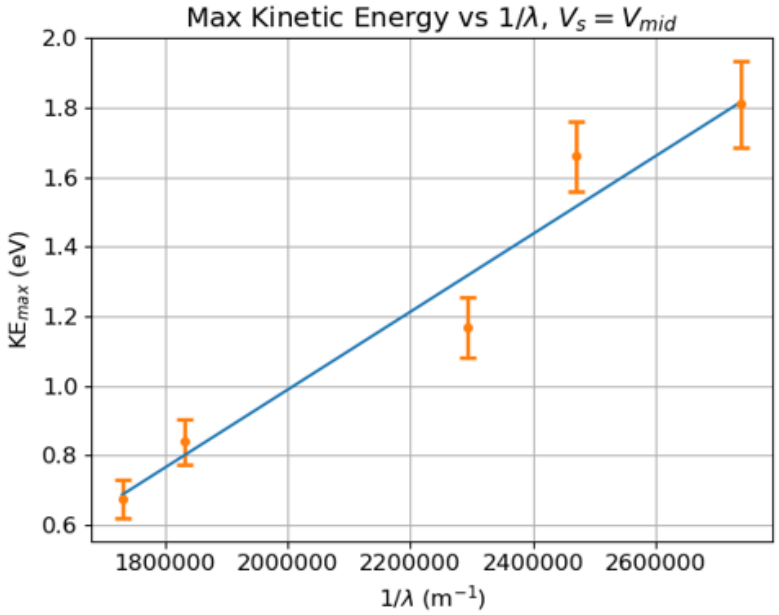


Figure 6: Graphs of maximum kinetic energy of electrons vs wavenumber for $V_s = V_{min}$ and $V_s = V_{mid}$

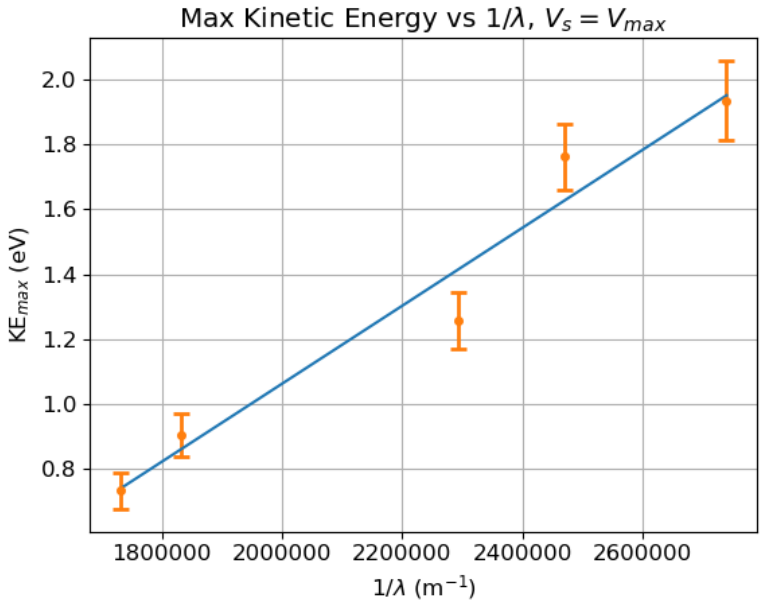


Figure 7: Graph of maximum kinetic energy of electrons vs wavenumber for $V_s = V_{max}$

These are the summaries of the linear regressions:

Planck's Constant h (J·s)	Work Function ϕ (eV)
$V_s = V_{min}$	
$(5.646 \pm 0.538) \times 10^{-34}$	1.19 ± 0.21
$V_s = V_{mid}$	
$(6.410 \pm 0.774) \times 10^{-34}$	1.34 ± 0.33
$V_s = V_{max}$	
$(5.977 \pm 0.518) \times 10^{-34}$	1.24 ± 0.20

Table 1: Linear fit results for parameters h and ϕ for $V_s = V_{min}, V_{mid}$ and V_{max}.

Across Figures 4 and 5, note that the knee of the curves moves to the right as we decreased the wavelength of incident light. This is because wavelength and energy are inversely proportional. Also note that when no photoelectrons reached the cathode (the flat section of the curve) we still measure some current through the ammeter, however. This is due to the fact that since no electrons leave the surface of the anode, photons are still being absorbed by atoms which in turn knock off electrons from the outer shells, increasing the free surface charge of the anode. Electron-electron repulsions increment and therefore some electrons travel in the opposite direction toward the cathode, which reads as negative charge in the ammeter.

4 Conclusion

We attempted several methods to obtain the stopping potential of photoelectrons based on ranges of possible values. Table 1 suggests that using the midpoint of such ranges was the most appropriate method of estimating the stopping potentials based of best calculated value of Planck's constant, namely $(6.410 \pm 0.774) \times 10^{-34}$ Js, 0.28 standard deviations away from the published value of 6.626×10^{-34} Js. Therefore, we are confident that the most accurate estimate of the work function of the anode is (1.34 ± 0.33) eV. Since we tended to underestimate the Planck constant, a better estimator of the stopping voltage would be 3/4 of the way between the possible V_s ranges instead of the midpoint. Compared to the published work functions of other metals such as Aluminum, Mercury, Copper, etc., ranging from about 3-5 eV, our result was appreciably much lower and thus we must conclude that the anode is not solely a metal or alloy and that its composition includes some other molecular compound, and additionally, most metals exhibit the photoelectric effect under ultraviolet light or more energetic light such as X-rays and gamma rays. It is known that photocells have very low work functions since their main functionality is to generate electricity as easily as possible from the photoemission process of the photoelectric effect, and so electrons move more freely on the surface of photocells which are commonly made of layers of Phosphorus and Silicon.
In summary, we demonstrated the process of the photoelectric effect which provides irrefutable evidence of the particle nature of light.

5 References