The Photoelectric Effect: Two Steps Forward One Step Back

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Innovation is not always as constructive as it may seem. The discovery and consequences of the photoelectric effect contradict classical wave theory, as well as open a window into the world of quantized physics. This paper follows one of many stories that led to the restructuring of the classical physics canon.

Physics was once thought to be nearing completion. Classical physics could seemingly predict any observable phenomenon with incredible precision. But as with the spirit of curiosity, more and more physicists began discovering more and more phenomena to test. Around the middle of the nineteenth century, scientists began to experiment with a new phenomenon called cathode rays. Under certain conditions, these rays seemed to spontaneously emit from a cathode hence their name. At the beginning of the twentieth century, Philipp von Lenard discovered something strange about these mysterious cathode rays. The rays he was studying were generated via the photoelectric effect, meaning that the cathode of a vacuum tube containing a potential difference was subjected to an incident light source, which caused the rays to be emitted. If the light was responsible for the cathode ray's creation, then it would be reasonable to assume that the energy in the light would be related to the energy of the ray. When Lenard measured the energy of the incident light in accordance with classical physical principles he found that the energy of the cathode ray was not dependent on the light's energy. This came as a huge shock to Lenard who was devoted to Classical Wave Theory [2].

The first experiment in this lab is a recreation of Lenard's famous experiment. A cathode ray tube is a vacuum chamber containing a cathode and anode separated by a small gap of free space. A potential difference is then applied across this gap. Under certain conditions, incident light on the cathode will produce a cathode ray and a corresponding current across the gap, which is now known as a photocurrent. It is now known that the cathode ray is actually a current of negatively charged particles called electrons, but this was debated at the time [2]. Classical physics related the energy of a wave to its amplitude, which in the case of light is proportional to the measure of its intensity. All Lenard had to prove was that the energy of the photocurrent was somehow related to the intensity of the incident light that created it. The experiment consists of measuring the resultant photocurrent at a fixed intensity while varying the potential difference across the gap. The experiment is then repeated at a different intensity in order to observe its effects.

The design of this lab's apparatus consists of an ultraviolet mercury lamp light source (253.7nm), and a Leybold Didactic GmbH model 558 77 photocell [1]. The 558 77 photocell has a circular potassium cathode plate with a silver oxide coating, which will be important later. The anode is shaped like a ring parallel to the cathode plate. The light source is directed via a color filter through the anode ring toward the cathode plate. At the same time, a potential difference is applied across the cathode-anode gap by a variable DC power supply. The value of this potential difference can be carefully controlled using the power supply's adjustment feature. Finally, The current of the whole system is measured by an ammeter positioned on the cathode side of the current loop. Fig 1 shows a schematic of the lab apparatus.

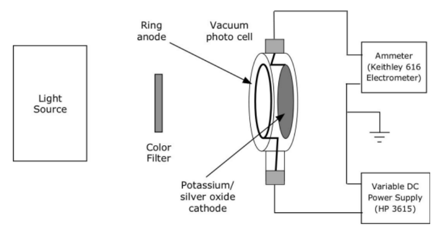

FIG. 1. Apparatus diagram for experiments one and two. The photocell is contained in a metal box with a filter mounted on the window. Cables for connecting external meters and power supplies are attached using BNC connectors. An external power supply is attached to the anode, and an ammeter is connected between the cathode and ground wire. This configuration insures electron flow off of the photocathode will register as a positive current. The potential difference across the gap between the cathode and the anode will be varied in both experiments. The wavelength used to illuminate the cathode will also be varied in experiment two [1].

Using the power supply to vary the potential difference, one can measure the resultant current caused by the light source on the ammeter. This current is a photocurrent just like what Lenard was studying. The potential difference acts like a controlled resistor. As the potential is decreased it becomes harder for the current to flow until eventually, the current does not have enough energy to cross the gap. This is known as the stopping potential. The experiment consists of plotting the range of resultant current values against the potential difference they occurred for in order to form a curve. Another curve is formed in the same way, but this time the intensity of the light source is changed by increasing the distance between the source and the photocell. One can use the inverse square law to calculate the difference in inten-

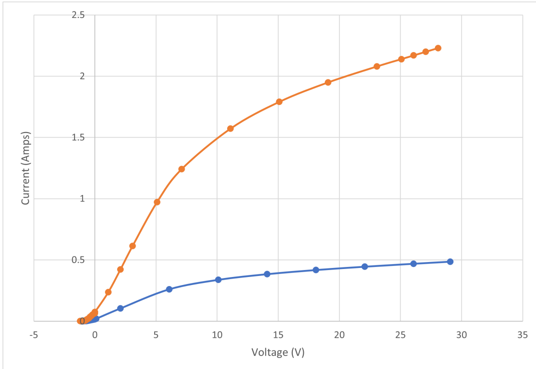

FIG. 2. Photocurrent vs Anode Potential for high intensity 130mm distance (orange) and low intensity 230mm distance (blue) stopping potential graph. As the potential increases, the graph saturates at photocurrent values proportional to the intensity. The intercept of the photocurrent axis (stopping potential) is the same for both lines.

sities. Studying the relationship between these curves allows one to determine the effects that intensity has on the photocurrent. FIG 2 shows the results of this experiment.

Classical Wave Theory would have one believe that the intensity of the incident light determines the photocurrent's energy. As far as the upper limit on the graph is concerned this appears to be true, however, the lower bound tells a different story. The upper bounds show asymptotic limits at values proportional to the incident light's intensity, but the lower bounds do not behave as such. As if it were meant to be, the smallest values of this graph will later lead someone to conclude that the quantum world exists. The stopping potential (the voltage value at which no current is able to cross the gap between the cathode and anode) does not depend on intensity. Both curves drop to zero at the same value despite having different intensities. The logic behind this quantum mystery will involve a new theory; something which Lenard neither anticipated nor excepted easily. Classical physics was not complete, and more discoveries that questioned the canon were flowing in by the year. Around the time of Lenard's famous experiment, J.J. Thomson postulated that cathode rays were made of a previously undiscovered negatively charged particle which became known as the electron. Lenard's work provided further evidence that this was the case rather than contradicting it as he had hoped. Eventually, Lenard along with many others was forced to accept that a new era of physics was on the rise [2].

The photoelectric effect would later inspire another famous physicist to question Classical Wave Theory even further. In 1905, Albert Einstein proposed that light was corpuscular rather than a classical wave. He proposes that light consists of individual "photons", which carry the energy of light, and intensity is simply proportional to the number of these photons present per area per time. He also proposes that photons are indivisible or quantized[3]. Einstein's theory suggests that the energy of a quantized photon is equal to Planck's constant times the frequency of that photon. The dimensional analysis of this operation produces a unit of energy. Rather than the classical theory of amplitude being related to energy, here it is the frequency that determines the energy. In the case of the photoelectric effect, the freed electrons that make up the cathode ray receive their kinetic energy from individual photons in the light. The second experiment of this lab investigates the relationship between the free electron kinetic energy and the frequency of light. If the electron receives its energy by absorbing a photon of a certain frequency then its energy should be related to that frequency.

Einstein goes on to suggest that the kinetic energy of the electrons in the photocurrent is equal to the energy absorbed by a photon minus the energy it takes to free the electron from the material of the cathode [4]. The energy required to free an electron from a given material is called the work function of that material:

$$eV = h\nu - \omega_0, \tag{1}$$

The omega term is the work function here. This simple equation is the basis for the second experiment of the lab. Originally performed by Robert Millikan, the experiment focuses on the relationship between the stopping potential and light frequency. Solving Einstein's equation for the stopping potential gives:

$$V_0 = \frac{h\nu}{e} - \frac{\omega_0}{e}, \tag{2}$$

Millikan decided to test Einstein's hypothesis by investigating equation 2. This equation represents a special case of the minimum kinetic energy required for an electron to cross an *unfavorable* potential. More specifically, it describes the voltage value this occurs at. Millikan designed an experiment in which he could measure the stopping potential for a known frequency of light. He then repeated this experiment for different frequencies. Finally, he plotted each frequency with its corresponding stopping potential on a graph to investigate the relationship [4]. According to equation 2, the stopping potential is related to the frequency by a factor of Planck's constant over the electron charge. This means that the slope of Millikan's graph should be Planck's constant over the electron charge, and this is exactly what he found to be true [4]. In reality, this value is something like $4.1375e^{-15}$eV. Since equation 2 is of the form y=mx+b, the intercept of the graph should be related to the work function of the cathode by a factor of one over the electron charge. This also turned out to be true. Experiment two of this lab is a recreation of Millikan's experiment.

Experiment two is designed to measure the stopping potential for a given frequency of light using a similar procedure to experiment one. Unlike experiment one,

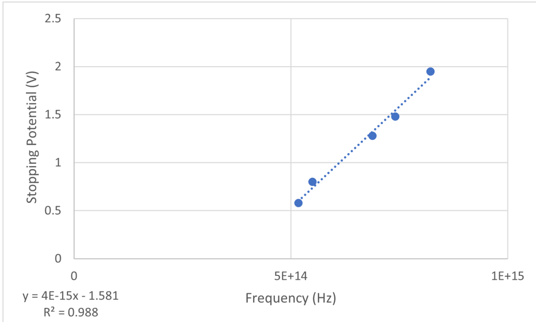

FIG. 3. Linear estimate of stopping potentials plotted against frequency. The uncertainty of slope is estimated to be 2.685E-16 and the uncertainty of y-intercept is estimated to be 0.18. When the data points are entered into Excel's linear regression feature, the slope is calculated to be $4.21869e^{-15}$.

however, the light source is now kept in a fixed location for all trials in order to keep the intensity constant. This time, the frequency is changed between trials by changing the color filter. The wavelengths of the color filters are as follows: 579.1nm (yellow), 546.1nm (green), 435.8nm (blue), 404.7nm (violet), and 365.0nm (ultraviolet). For each filter trial, the potential difference is slowly varied until the current on the ammeter reads zero (i.e. the stopping potential is reached). Each measured stopping potential is plotted against the frequency it was measured for. Based on Einstein's modified equation 2 one should expect a line such that its slope is Planck's constant over the electron charge, and its intercept is the work function of the cathode over the electron charge. Earlier it was mentioned that the cathode was made of potassium with a silver oxide coating. This composition is responsible for the work function value in this experiment. FIG 3 shows the results of this experiment.

The slope of the graph in FIG 3 is $4.21869e^{-15}$ with an uncertainty of $2.685e^{-16}$. Just like Millikan's experiment, the design of this experiment suggests that the slope of this line is Planck's constant over the electron charge. Using this information, one can multiply the slope value by the electron charge in order to estimate Planck's constant. Calculating Planck's constant becomes:

$$4.218e^{-15} \pm 2.685e^{-16} * 1.602e^{-19} = 6.749e^{-34} \pm 4.301e^{-35} \tag{3}$$

With today's excepted value being $6.602e^{-34}$, we see that the results easily fall within the uncertainty. Planck's constant appears almost out of nowhere, but the evidence is plain to see. The frequency of incident photons is responsible for the kinetic energy of the electrons in the current. Planck's constant is just a constant of proportionality between the two. The results of this experiment suggest the idea of quantized light is unavoidable, and classical physics required many new innovations as a consequence.

The process of innovation is not always a story of constant progress. Sometimes a small but humbling fact can set back centuries of effort in constructing a physical model. Though classical physics might have failed to describe everything, it is certainly not a failure in its own right. The story of physics must constantly evolve in pursuit of the truth. Just like in one of its own principles, the net force of the physics canon points forward though sometimes components within may act to slow it down.

[1] J. McCoy, C. Conover, D. Tate, L. Lessard. The Photoelectric Effect. (Lab Manual) (2022)

[2] NobelPrize.org, Philipp-Lenard–Biographical. https://www.nobelprize.org/prizes/physics /1905/lenard/biographical/ (1905)

[3] NobelPrize.org, Albert Einstein Facts. https://www.nobelprize.org/prizes/ physics/1921/einstein/facts/ (2022)

[4] R. Eisberg and R. Resnick, Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles (John Wiley and Sons, New York, 1985)