Franck-Hertz and Photoelectric Effect

Lab Report 4

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Abstract

In this experiment we used the Franck-Hertz method and photoelectric effect to demonstrate the quantization of energy. In the Franck-Hertz apparatus, electrons are accelerated by an electric field and their energy is absorbed by Argon atoms at discrete potential intervals. These intervals were used to determine the excitation potential of Argon. The photoelectric effect was observed by passing the light from a halogen source through various wavelength filters and measuring the stopping potential at which the photocurrent vanished. The relationship between the wavelength and stopping potential was used to estimate the value of Planck's constant.

Introduction

In 1887, Heinrich Rudolf Hertz observed that when UV light falls on a metal cathode held at a lower potential with respect to an anode, the light can cause a change in the potential due to the production of a measurable flow of current between the electrodes. This effect was dubbed the "Hertz effect" and later, the "photoelectric effect". An explanation of this effect was provided in 1905 by Einstein, who theorized that light carried energy in discrete packets called "photons" whose energy is determined entirely by the frequency of the light. Hence, light can only transmit energy in discrete amounts and therefore stimulates the excitation of electrons beyond a threshold frequency. This explanation eventually earned him the Nobel prize in 1921.

Shortly after Einstein's explanation of the photoelectric effect, Neils Bohr proposed a model for the hydrogen atom with a concept of quantized energy levels in 1913. The very next year, James Franck and Gustav Hertz observed the quantized excitation of mercury atoms which won them a Nobel Prize as well. Their experiment showed that electrons moving through a mercury vapour would lose exactly 4.9eV of energy after colliding with mercury atoms and electrons carrying energy below this threshold would collide elastically and fail to stimulate the excitation of the mercury atoms. This provided valuable evidence for Bohr's model and the quantisation of energy levels.

The aims of this experiment are to:

- Measure the excitation potential of Argon using the Franck-Hertz method.
- Estimate Planck's constant using the photoelectric effect by measuring the stopping potential at which the photocurrent vanishes for various wavelengths of light.

Theoretical Background

Photoelectric Effect

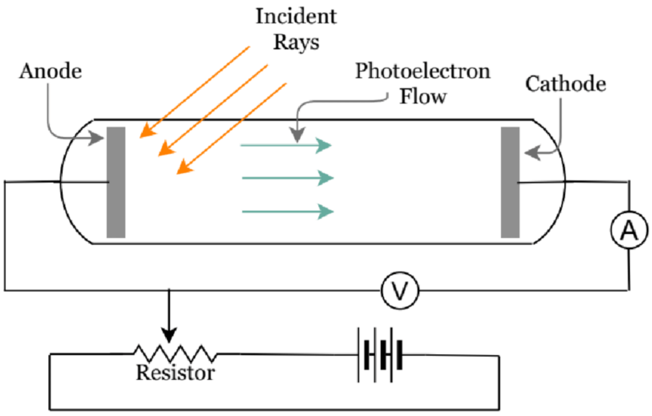

Figure 1: Schematic diagram of the experimental setup to observe the photoelectric effect. Source: Scientific Figure on ResearchGate, A Set of Virtual Experiments of Fluids, Waves, Thermodynamics, Optics, and Modern Physics for Virtual Teaching of Introductory Physics

The photoelectric effect refers to the liberation of electrons from the surface of a material by absorption of energy from incident light. According to Einstein's explanation, each photon of light with frequency ν carries energy equal to $h\nu$ where $h = 6.626 \times 10^{-34}$ Js, which is Planck's constant. In order to free a single electron from an atom, the photon must impart a minimum energy of Φ, known as the work function of the material on which the light is incident. Hence, from the conservation of energy, the maximum kinetic energy gained by an electron is:

$$K_{max} = h\nu - \Phi \tag{1}$$

If the anode is given a reverse potential (or stopping potential) V_s such that all the electrons are prevented from reaching the collector and the photocurrent is zero, then the maximum kinetic energy of the electrons will be $K_{max} = eV_s$. Hence,

$$V_s = \frac{h\nu}{e} - \frac{\Phi}{e} \tag{2}$$

If we plot the stopping potential against the wavelength of incident light, we expect the slope of the graph to be equal to h/e and the intercept to be Φ/e.

Franck-Hertz Experiment

The Franck-Hertz apparatus consists of a tetrode filled with Argon gas (figure 2). The four electrodes are - a filament-heated cathode which acts as the electron source, two grid plates (G_1 and G_2) which minimize space charge effects and accelerate the electrons, and a collecting plate which is held at a slightly lower potential relative to the second accelerating grid, thereby decelerating the electrons between them. V_{G1K} and V_{G2A} are held constant throughout the experiment and the current is detected as a function of V_{G2K}.

As the second grid's voltage V_{G2K} is increased, the electrons gain enough kinetic energy to overcome the retarding potential of the collecting plate and a current is detected in the circuit. As predicted by Bohr's model, energy is absorbed and emitted by atoms in discrete quantities. In the case of Argon, only an electron with energy greater than 11.83eV is capable of stimulating energy absorption and excitation. Hence, electrons below this threshold undergo elastic collisions with the gas atoms and continue with the same energy as before.

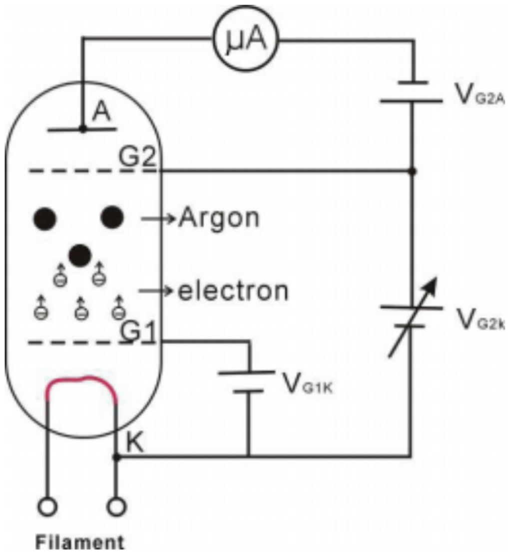

Figure 2: Schematic diagram of experimental setup for the Franck-Hertz apparatus.
Source: Gammel & Horn, Determining lowest excitation energy using the Franck-Hertz experiment

If kinetic energy of the electrons surpasses the excitation energy of the Argon atoms, they collide inelastically with the atoms and lose their energy. This causes a sharp dip in the current detected at the collecting plate since most of the electrons will undergo inelastic collisions between the cathode and $G2$ and are unable to overcome the retarding potential. Upon increasing V_{G2K} further, the current will increase until the electrons gain exactly twice the excitation energy, at which point they suffer exactly two inelastic collisions before losing all their energy. This is detected as a second dip in the current. These dips continue to appear at discrete intervals of 11.83V, each one corresponding to an integer number of inelastic collisions with Argon atoms present in the tube. Hence, the excitation potential of argon can be determined by measuring the distance between the current dips.

Experimental Setup

Photoelectric Effect

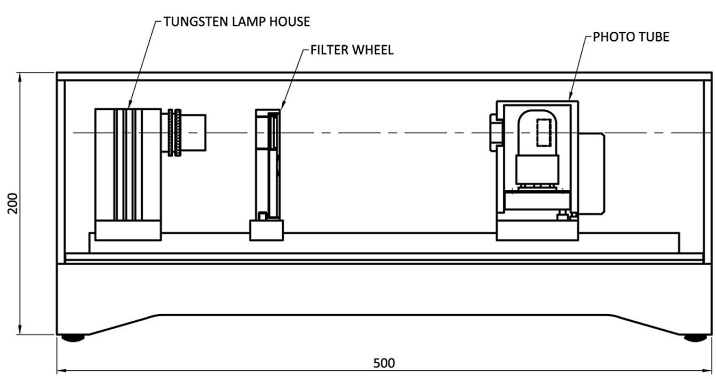

Figure 3: Experimental setup for the Holmarc Photoelectric Apparatus (Model No: HO-ED-EM-02)
Source: Apparatus for the study of Photo Electric Effect, Holmarc

The Holmarc Photoelectric Apparatus (Model No: HO-ED-EM-02) consists of a halogen light source mounted on a rail with a wavelength filter wheel and phototube. The filter wheel contains 5 narrow band filters which allow the following wavelengths to pass - 404nm, 450nm, 505nm, 546nm, and 578nm. As a single wavelength is allowed to pass into the vacuum phototube, the stopping potential and photocurrent are read by an electronic control unit. The ammeter has a sensitivity of 10^{-11}A and the stopping potential has a range of 0-2V.

Least count of Ammeter = 0.01 nA
Least count of Stopping Voltage = 0.01 V

Franck-Hertz Experiment

Figure 4: Experimental setup for the Holmarc Franck-Hertz Apparatus (Model No: HO-ED-EM-04)
Source: Franck-Hertz Experiment, Holmarc

The Holmarc Franck-Hertz Apparatus (Model No: HO-ED-EM-04) contains an tetrode tube filled with Argon gas. The Argon tube is encased behind a metal screen to block the emission of harmful X-rays produced by the excitation of Argon atoms. The apparatus has control knobs for filament voltage, V_{G1K}, V_{G2K}, V_{G2A}, as well as the current multiplier selector. An LCD display shows the values of V_{G1K}, V_{G2K}, V_{G2A} and the current detected at the collecting plate.

V_{G1K} range: 1.20-5.00 V
V_{G2K} range: 0.00-80.00 V
V_{G2A} range: 1.30-12.00 V
Filament voltage range: 2.80-3.40 V

Least count of V_{G2K} = 0.01 V
Least count of Ammeter = 1 nA

Procedure

Photoelectric Effect

1. Connect the phototube to the electronic control unit and plug in the power supply for the halogen lamp. As the lamp heats up, a photocurrent should be detected by the phototube.

2. Cycling through the filter wheel, select the filter which produces the highest photocurrent. This corresponds to the light with the highest energy and therefore lowest wavelength (i.e. 404nm).

3. Starting with the 404nm filter, adjust the stopping voltage until the photocurrent goes to zero. Record this value of V_s. Repeat this step for the four other filters, making note of their wavelength and stopping voltage. Take 3-5 sets of readings to average across and minimize error.

4. Convert the wavelength into frequency using $c = \nu\lambda$ and plot the stopping voltage against the frequency. Use equation 2 and the value of e to find Planck's constant.

Franck-Hertz Experiment

1. Before plugging in the power supply of the instrument, ensure that all the knobs are set to zero. Turn on the apparatus and set the filament voltage to some intermediate position since its value is not displayed on the LCD screen.
2. Set the current multiplier selector to 10^{-7} and toggle the auto-manual switch to manual mode.
3. Choose a value of V_{G2A} such that it is held at a lower potential throughout the range of V_{G2K} over which the experiment is being conducted. V_{G1K} should be set below both these values. For our experiment we chose $V_{G1K} = 2.00$V, $V_{G2A} = 5.00$V and V_{G2K} was varied between $8.00 - 60.00$V.
4. While gradually increasing V_{G2K}, note down the current detected at intervals of 1V. Plot a graph of the current against the accelerating voltage and determine the position of each dip. Find the average spacing between the dips and determine the excitation potential of Argon.

Observations and Analysis

Photoelectric Effect

Least count of Stopping potential = 0.01V
Least count of Ammeter = 0.01 nA

Using $c = \nu\lambda$, the frequency of each wavelength was determined. This was plotted against the corresponding stopping potential at which the photocurrent detected at the collecting plate was zero (figure 5). Since 5 sets of readings were taken, the mean value of the stopping voltage was found:

$$\langle V \rangle = \frac{\sum_{i=0}^{5} V_i}{5}$$

The error in each value was taken to be one standard deviation of the values:

$$\sigma_V = \sqrt{\frac{\sum_{i=0}^{5} (V_i - \langle V \rangle)}{5}}$$

The mean value of the stopping voltage was plotted against the frequency of the incident light.

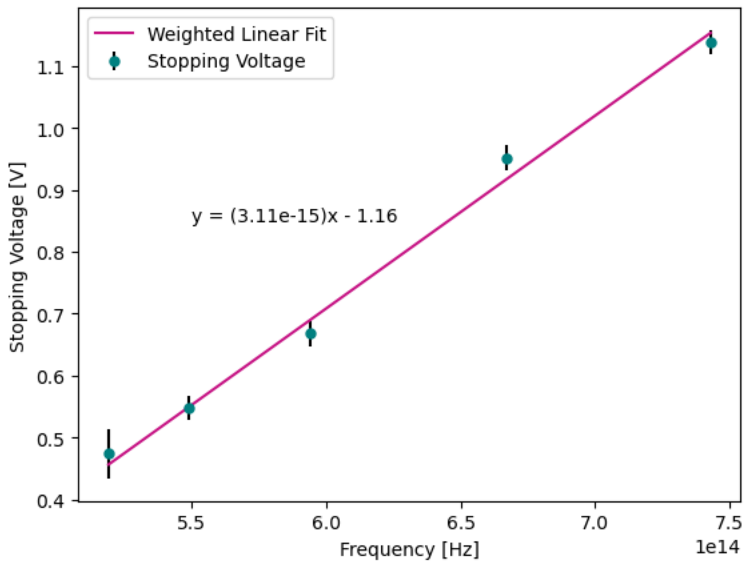

Figure 5: The stopping potential appears to vary linearly with respect to the frequency of incident light

We fit the data with a weighted curve-fit function from the `scipy.optimize` package using the two parameter model function $y = ax + b$ and the standard deviation error in the stopping voltage as Δy. This gave us a value of $a = (3.11 \pm 0.03) \times 10^{-15}$ Vs (where the error in a was determined from the covariance matrix calculated by the curve-fit function). Using equation 2, we expect the slope of the graph to be $a = h/e$, so taking $e = 1.602 \times 10^{-19}$C we find:

$$h = 4.98 \times 10^{-34} \text{ Js}$$

Franck-Hertz Experiment

$V_{G1K} = 2.00$V
$V_{G2A} = 5.00$V
V_{G2K} range $= 8.00 - 60.00$V
Ammeter Current Multiplier $= 10^{-9}$A

The above values were chosen by trial and error such that the current dips appeared to be sharper as V_{G2K} was increased. The current vs accelerating voltage graph was plotted using the mean and standard deviation of the current values from 5 sets of readings (figure 6).

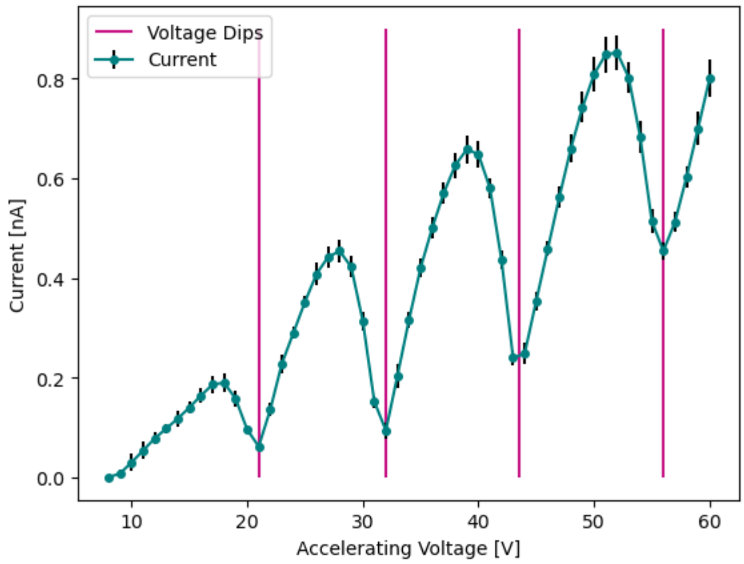

Figure 6: Each dip in the current corresponds to a whole number of inelastic collisions between the electrons and Argon atoms which cause the electrons to lose their energy and therefore cannot overcome the retarding potential of the collecting plate.

The position of the current dips were estimated to be at - 21V, 32V, 43.5V and 56V. The average interval between the current dips corresponds to the excitation potential of Argon since the electrons carry energy equal to $E = eV$ so the energy difference between the dips is $\Delta E = e(V_2 - V_1)$. This is the energy difference between exactly one inelastic collision and two inelastic collisions between the electrons and Argon atoms (i.e. the excitation energy of a single Argon atom):

$$E^* = 11.67 \text{ eV}$$

Error Analysis

The error in Planck's constant comes from the error of the slope of the graph, by quadrature:

$$\frac{\Delta h}{h} = \sqrt{\left(\frac{\Delta \text{slope}}{\text{slope}}\right)^2} = \frac{\Delta \text{a}}{\text{a}}$$

The error in the slope was determined from the covariance matrix of the weighted linear fit to be $\Delta a = 0.03 \times 10^{-15}$ Vs. So,

$$\Delta h = 0.04 \times 10^{-34} \text{ Js}$$

The error in the excitation energy of Argon originates from the measurement of accelerating voltage. Since we take the average of the potential dip intervals, we can assume that the standard deviation of the intervals is equal to the error:

$$\Delta V = \sqrt{\frac{\sum_{i=0}^{N}(\delta V_i - \langle \delta V \rangle)}{N}}$$

Where δV is the difference between consecutive current dips. Hence,

$$\Delta V = 0.6 \text{ V}$$

$$\implies \Delta E^* = 0.6 \text{ eV}$$

Results and Discussion

From the photoelectric effect was used to estimate the value of Planck's constant:

$$h = (4.98 \pm 0.04) \times 10^{-34} \text{ Js}$$

The known value of Planck's constant is $h_{\text{real}} = 6.626 \times 10^{-34}$Js. From the formula of percentage error, we find:

$$\text{Percentage error in } h = \left(1 - \frac{h_{\text{measured}}}{h_{\text{real}}}\right) \times 100 = 24.77\%$$

We noticed that the photocurrent detected by the phototube was extremely sensitive to the angle at which the halogen lamp was placed with respect to the axis of the setup. We are note certain why the angle of the incident light is relevant but we chose to angle the lamp such that the photocurrent was maximized. This was done to ensure that the light fell perpendicular to the filter and error was minimized. However, since the lamp had a limited degree of movement, the lamp may not have been angled perfectly, introducing error into our reading.

The Franck-Hertz apparatus was used to determine the excitation energy of Argon:

$$E^* = 11.67 \pm 0.6 \text{ eV}$$

The known value of Argon's excitation energy is $E^*_{\text{real}} = 11.83$eV. From the formula of percentage error, we find:

$$\text{Percentage error in } E^* = \left(1 - \frac{E^*_{\text{measured}}}{E^*_{\text{real}}}\right) \times 100 = 1.38\%$$

This value of E^* is within the acceptable margin of error.

References

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[5] Franck-Hertz Experiment, Ashoka University Lab Handout

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