PHY324: The Franck-Hertz Experiment

Idil Yaktubay

4 April 2022

Abstract

In this experiment, the collisions between vaporized mercury atoms and electrons were studied in order to determine the energy required to excite a mercury atom. By measuring the current set up by the incident electrons across different accelerating voltages, the energy required to excite vaporized mercury atoms was found to be $5.1\,eV \pm 0.8\,eV$. This value was found to agree to within one uncertainty interval of the theoretical value of 4.9 eV.

1 Introduction

The Franck-Hertz experiment has contributed greatly to the establishment of modern atomic theory by showing that atoms can only absorb discrete amounts of energy (Hanne 1987, 696). In the experiment, mercury atoms are bombarded with a beam of electrons accelerated through a varying voltage. The electron beam sets up a measurable current that changes based on the nature of the mercury-electron collisions. If an incident electron has a high enough kinetic energy (i.e., the accelerating voltage is high enough), the mercury-electron collision will be elastic. In other words, the incident electron will lose no energy and the measured current will remain undisturbed. However, when the electron energy is too low for an elastic collision to occur but high enough to meet an energy threshold, the mercury atom will absorb some of the electron energy and move to the next excited state. The measured current will then decrease due to the loss in electron kinetic energy. Specifically, in the case where the accelerating voltage is slowly increased, the overall current will keep increasing. However, the decreased electron flow due to the occasional inelastic collisions will manifest itself as a series of dips in a current versus accelerating voltage graph, as shown on Figure 1. The first dip will correspond to electrons that lost all their kinetic energy after a single inelastic collision, the second dip will correspond to those that lost all their kinetic energy after two inelastic collisions and so on (Hanne 1988, 696).

Further, it is relevant to note that in order for an excited mercury atom to return to its ground state, it must release a photon with the same energy that was initially absorbed to move to the excited state. The energy of this photon is given by the equation:

$$E = hf \tag{1}$$

where E is the photon energy, h is Planck's constant, and f is the photon frequency. To find the wavelength of the released photon, we can use the following known equation:

$$c = \lambda f \tag{2}$$

where c is the speed of light, λ is the photon wavelength, and f is the photon frequency. Combining equations 1 and 2, we have:

$$\lambda = \frac{ch}{E}. \tag{3}$$

The purpose of this experiment is to experimentally determine the energy required to excite a vaporized mercury atom by analyzing the described mercury-electron collisions. Specifically, the accelerating voltage of the incident electrons will be slowly increased, and a current versus voltage graph will be accumulated using software. Then, the difference in voltage between the adjacent current dips in this graph will be optimized using a linear function. Lastly, the optimized value will be converted to the discrete amount of energy required to excite the vaporized mercury atoms using the equation:

$$E = Ve \times \frac{1\,eV}{1.602 \times 10^{-19} J} \tag{4}$$

where V the difference in voltage between the dips, e is the known charge of an electron $1.602 \times 10^{-19}\,C$, and E is the energy in eV.

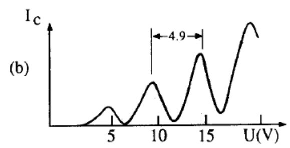

Figure 1: The expected current versus voltage graph recorded in a Franck-Hertz experiment with vaporized mercury, taken from literature (Hanne 1988, 696). As shown, the voltage difference between the dips is 4.9 eV. This theoretical value will be discussed in proceeding sections.

2 Experimental Setup and Procedure

The main part of the apparatus consists of a tube that contains an electron emitting filament, grids for accelerating the electrons to variable energies, and an anode that collects the electrons. The tube is evacuated except for the vaporized mercury atoms. Using an oven, the tube can be heated up to appropriately regulate the pressure of vapor mercury. To keep the oven at a specific temperature, an electrometer and a voltmeter are used. Further, the apparatus has various power supplies that are used to heat up the electron emitting filament and to produce the accelerating voltages. A schematic circuit diagram of the apparatus is shown on Figure 2.

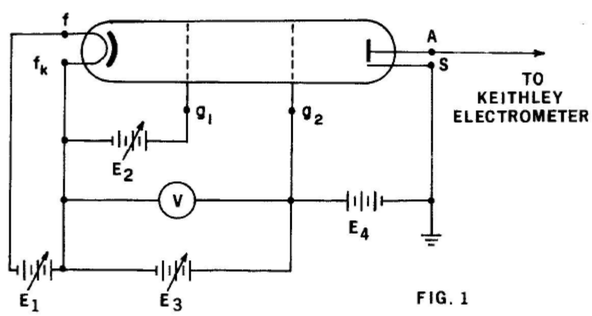

Figure 2: A schematic diagram of the Franck-Hertz apparatus. E1 is the filament supply, E2 is the screen grid voltage, E3 is the accelerating voltage, E4 is a fixed voltage to repel low energy electrons.

The first step of the experiment was to place the evacuated tube inside the oven and heat it up to 170^oC. Before collecting data, it was ensured that the knob that controls the accelerating voltage was at its lowest value. Then, the data acquisition software was opened on a computer connected to the apparatus. Data was collected as the voltage knob was slowly and steadily dialed to increase the potential difference. Once the knob was turned all the way, the data collection was stopped. Lastly, to avoid poor data sets, data was collected four more times in the same manner.

3 Data and Analysis

In order to decide which of the five data sets will be used for analysis, each data set was plotted. The third data set was observed to have the least amount of noise, and therefore chosen for analysis. Figure 3 shows the variation of the current set up by the accelerated electrons with respect to varying accelerating voltage as described by the third data set. Evidently, Figure 3 closely resembles the expected curve from Figure 1.

Further, to determine the energy required to excite the vaporized mercury atoms, a few steps were followed. First, the values of voltage at which the current dips occurred were found. The data points corresponding to these voltage values are explicitly marked on Figure 3. The uncertainty associated with each voltage value was taken to be the width of the dip at which the value is located, for reasons included as further discussion in section 4. Then, shown on Figure 4, a graph of voltage versus dip number was created, the first minimum from the left being dip number one, the second minimum from the left being dip number two and so on. Since the slope of this graph gives the difference in voltage between the adjacent current dips, it was optimized by fitting the graph to a model function of form:

$$f(x, a, b) = ax + b \tag{5}$$

where a is the parameter of interest. The optimized value of parameter a was found to be $5.1\,V \pm 0.8\,V$. The reduced χ^2 for this fit was found to be 0.01. The implications of this value are discussed in the next section. Finally, using equation 4, the discrete amount of energy required to excite the vaporized mercury atoms was found to be $5.1\,eV \pm 0.8\,eV$.

As further investigation, the wavelength of the photon that must be released in order for an excited vaporized mercury atom to return its ground state was found using equation 3. Using the known values $c = 2.9979 \times 10^8\,\frac{m}{s}$ and $h = 6.626 \times 10^{-34}\,Js$, the photon wavelength was found to be $240\,nm \pm 40\,nm$ by error propagation. This is in the ultraviolet range.

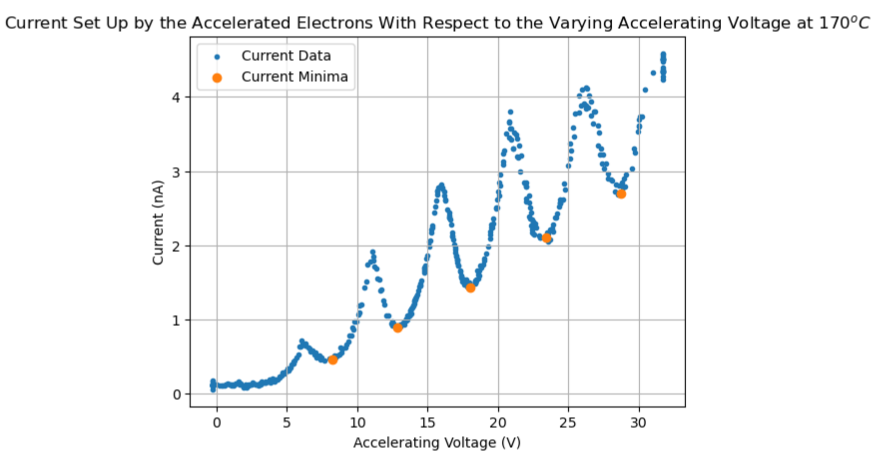

Figure 3: Raw data collected by the data acquisition software connected to the experiment apparatus. This graph shows the variation of the current set up by the accelerated electrons collected by the anode with respect to varying accelerating voltage. The orange points represent the data points at which current minima, or "dips", occur.

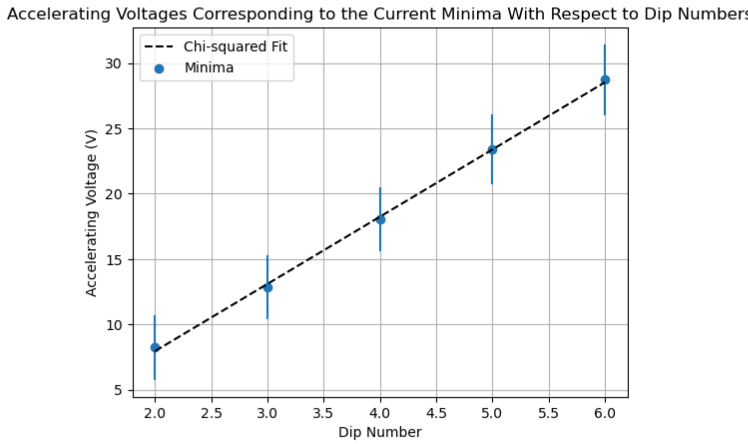

Figure 4: Accelerating voltage values at minima with respect to dip numbers. The error bars are shown as vertical blue lines, and the chi-squared fit, which was performed using equation 5, is shown in black. The reduced χ^2 value for this fit was found to be 0.01. Evidently, the curve is linear. Hence, the slope of the line was used to extract the energy required to excite mercury atoms.

4 Discussion and Conclusion

In this experiment, the collisions between accelerated electrons and vaporized mercury atoms were used to explore the quantized energy states of atoms. Specifically, after accelerating a beam of electrons across a slowly increased potential difference and bombarding some vaporized mercury atoms with these electrons, the current set up by the electrons that reached the anode after collision was recorded using a data acquisition software. The difference in voltage between the adjacent dips of the current data was optimized using a linear fit. This optimized value then yielded $5.1\,eV \pm 0.8\,eV$ as the energy required to excite a vaporized mercury atom, or as the amount of energy transferred from an electron to a mercury atom in an inelastic collision. This experimental value was found to be both accurate and precise, as it agrees with the theoretical value of $4.9\,eV$ (Hanne 1988, 696), to within one uncertainty interval, which is good agreement.

An important topic of discussion in this experiment is the shape of the current versus voltage graph. Because of the quantization of atomic states, one might expect the curve to be shaped as a sharp sawtooth pattern. However, the electrons with higher energies than the minimum required energy to excite a mercury atom were able to reach the anode with their remaining energies, still inducing a current. Hence, the reduced electron flow due to these inelastic collisions was able to manifest itself as a series of spread-out dips, whose widths were used as the uncertainties mentioned in the previous section.

One might be curious as to why mercury atoms were preferred in this experiment over other gases such as hydrogen. This is because when gases such as hydrogen that tend to form molecules are bombarded with electrons, it is possible for the energy transfer to almost seem continuous rather than discrete due to the transfer of energy to molecular energy levels (Melissinos 1966, 13). Therefore, the quantization of atomic energy states is best shown through monatomic gases such as mercury. In our case, we showed that the monatomic mercury atoms can only be excited by absorbing quantized amounts of energy, and only decay back to the ground state by emitting a photon that has the same energy as this discrete amount. We also found the wavelength of this released photon to be $240\,nm \pm 40\,nm$.

As previously mentioned, the reduced χ^2 value associated with the fit performed in the analysis section was 0.01, which is small compared to the ideal value of 1. This is due o the relatively large uncertainties associated with the voltage values at which the current dips occur. To improve our results, we could run the experiment at various temperatures of the oven, which will produce different graphs. This will help reduce the errors, which will improve our fit.

In conclusion the amount of energy required to excite a mercury atom was found to be $5.1\,eV \pm 0.8eV$, which deviates from theory by only 4%, and contains the theoretical value within its uncertainty range. Therefore, this this experiment was successfully able to analyze the quantized energy states of atoms.

5 References

Hanne, G. F. 1988. “What Really Happens in the Franck–Hertz Experiment with Mercury?” American Journal of Physics 56 (8): 696–700. https://doi.org/10.1119/1.15503.

Melissinos, Adrian Constantin. 1966. Experiments in Modern Physics. New York: Academic Press.