Physics 405 - Experiment 3

Dillon Walton

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Introduction

James Franck and Gustav Hertz were the first to show, through experimentation, the quantization of atomic energy levels in 1914. Their results were in agreement with the Bohr Model and were pivotal in strengthening the acceptance of early quantum theory. Upon viewing the experimental results, Einstein is to have said they were "so lovely it makes you cry."[1] For their work, Franck and Hertz would go to win the 1925 Nobel Prize for "their discovery of the laws governing the impact of an electron upon an atom."

Theory

The theory governing the Franck-Hertz experiment is simple, analytically speaking. The experiment has three electrodes aligned plano-parallel in a tube of mercury vapor. Electrons are emitted from the first cathode, which is heated by current running through a filament as seen in figure (1) which diagrams the apparatus. A positive voltage is applied to a mesh-like metal anode which causes the electrons to accelerate and pass through the anode (given its grid-like structure). Electrons which pass through the grid then face a negative (retarding) potential before reaching a collector, from which a current is measured. Inside the tube, the mercury vapor is heated to a temperature

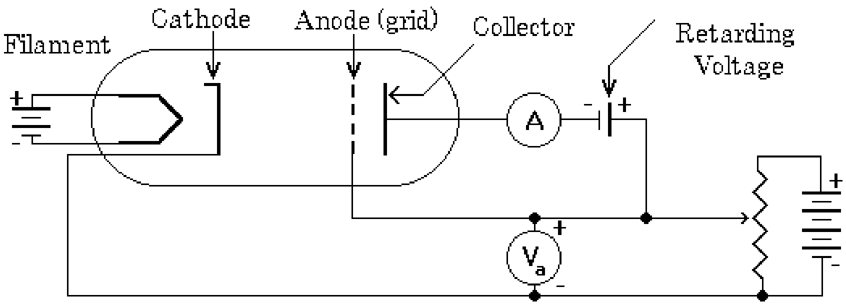


Figure 1: Diagram of Franck Hertz Apparatus (Foothill.edu)

of 180°C, increasing the vapor pressure within the tube and causing emitted electrons to undergo several collisions with the mercury atoms before finally reaching the collector. This is where the theory starts. The collisions which occur will either be elastic or inelastic depending on the energy

[1] S. A. Rice and J. Jortner, James Franck, A Biographical Memoir (National Academy of Sciences, 2010)

of the emitted electron. In the case of an elastic collision, the mercury atom is much larger than the electron and the electron will simply change directions but maintain the same kinetic energy. In the case of an inelastic collision, the energy of the electron is absorbed by the mercury atom, leaving the atom in an excited state and the electron with not enough energy to overcome the retarding voltage before reaching the collector. Therefore, inelastic collisions cause the collector to record a lower current. Inelastic collisions with the mercury atom occur when electrons have an integer multiple of energy $4.9eV$ (this value was determined by Franck-Hertz and confirmed by many after them). As we increase the applied voltage to the grid anode, we see drops in the measured current at each energy multiple of $4.9eV$. By continuing this process, we observe drops in the measured current at regular intervals, which we can then use to calculate the energy required to excite the mercury atom. Since the current drops at regular intervals, we are observing a linear relationship. To calculate the energy required to excite the mercury atom, we find the accelerating voltage points at which the current displayed a maxima and we calculate difference between them.

$$V_{max}(n) = V_x n + b \tag{1}$$

Equation (1) shows the equation we use to find V_x, the energy of the ground states of the mercury atom. The b in the equation is a correction for the background noise.

Experimental Setup

The experimental setup is split into two parts. First, we configure the circuit to measure the anode current as a function of time. The Franck-Hertz apparatus is pre-configured, so this circuit is designed to apply a ramping voltage, a retarding voltage and measure an output current through an instrumental amplifier. In Figure (2), we see the experimental setup for this part of the data

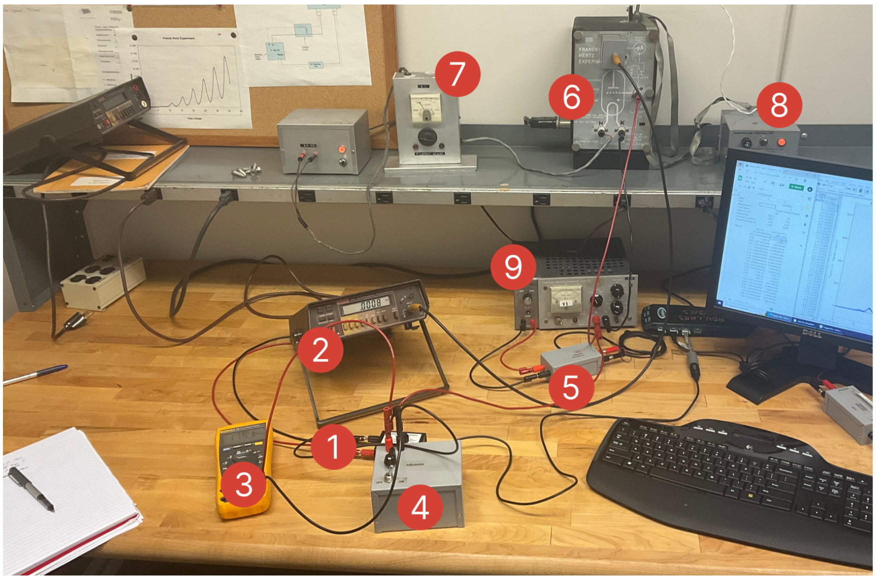


Figure 2: Experimental setup for measurement of anode current

collection. The labeled items and their purpose are explained below:

1. instrumental amplifier - amplifies output current from the picometer as input to logger pro
2. picometer - measures output current from Franck-Hertz apparatus
3. voltmeter - measures retarding voltage
4. adjustable voltage supply - supplies retarding voltage to circuit
5. DC blocking circuit - serves as a filter for DC signals which trigger data collection
6. Franck-Hertz apparatus - heated tube with anode / cathode configuration and mercury vapor
7. filament current supply - controls current to the filament inside the Franck-Hertz apparatus
8. temperature controller - sets and measure temperature of Franck-Hertz tube in (C°)
9. ramping power supply - supplies accelerating voltage to anode grid inside Franck-Hertz apparatus

The circuit is especially sensitive to configuration tweaks. In adjusting the filament current, the output current read through the picometer will display a signal with more or less noise depending on whether you decrease or increase the current, respectively. The ramping power supply additionally can be adjusted to reach a specific maximum power supply over a given interval, it is important to hold this constant. The retarding voltage supply can be altered to change the maxima of the output signal. The higher the retarding voltage, the lower the maxima will be, and less pronounced the effect of the background will be as well. Finally, adjustments in the temperature will have a dramatic effect on the output signal as well, which has been examined in more recent literature.

Second, we reconfigure the circuit to measure the ramping voltage as a function of time. This circuit is dramatically more simple than the first circuit and only measures the ramping voltage supply against time. It is important to hold everything on the ramping supply constant between circuits.

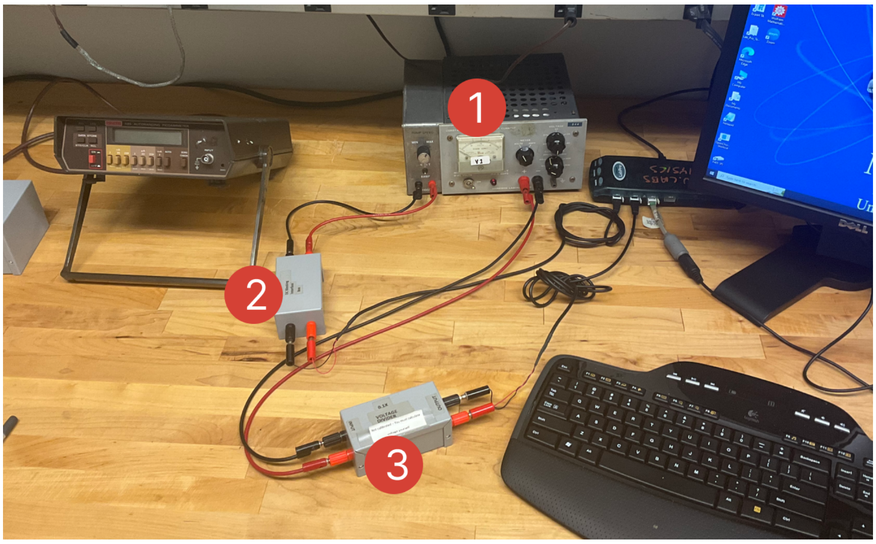


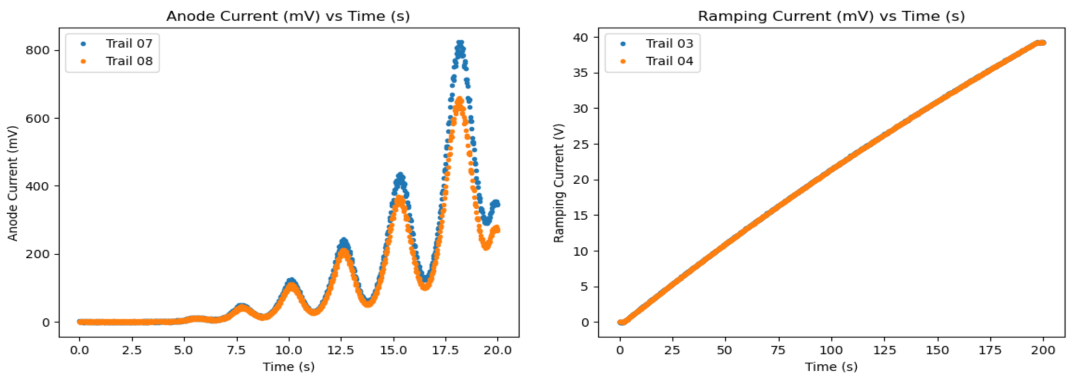
Figure 3: Experimental setup for measurement of ramping voltage

Figure (3) shows the experimental setup. The labeled items and their purpose are below:

1. ramping power supply - supplies power straight to the logger pro to be recorded as if it was going to the Franck-Hertz apparatus
2. voltage divider - lowers the total voltage by 0.10x being supplied to the logger pro to prevent damage
3. DC blocking circuit - serves as a filter for DC signals which trigger data collection

This setup is not specifically sensitive at all. Since the ramping power supply should be consistent with the previous circuit setup, there should be no reason to adjust any aspects of this circuit.

Measurement and Data Analysis



(a) Graph of anode current vs time

(b) Graph of ramping current vs time

Figure 4: Graph of the data sets used for analysis

For the data analysis, two trails, *trail 07* and *trail 08*, were used from the measurement sets of anode current and one trail, *trail 04*, was used from the measurement of the ramping voltage. As seen in figure (4b), the difference between *trail 03* and *trail 04* were negligible. Each of the data sets had identical circuit parameters which are listed below.

Trial	T_{start}	T_{finish}	$I_{filament}$	V_{retard}
07	180	178	0.23	1.753
08	181.5	179.3	0.23	1.753

Table 1: Circuit parameters

For both *Trial 07* and *Trial 08*, I followed the same procedure to calculate a value for the ground state energy of the mercury atom.

1. Separate minima and fit the background polynomial
2. Separate maxima and fit the individual Gaussian curves
3. Use the parameters from individual fits to calculate model fit with 18 total parameters

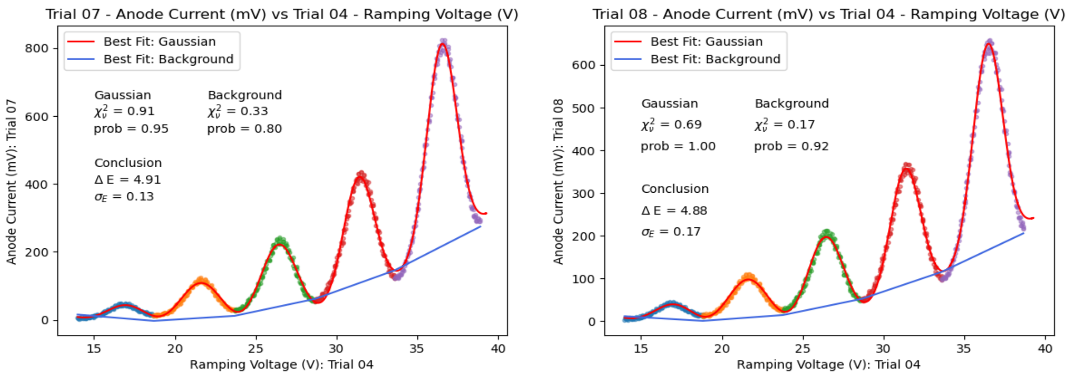
4. Separate maxima from model fit and calculate ΔE between each point
5. Average over the set of ΔE and take standard deviation to derive final values

The uncertainty in the measurements primarily came from systematic sources. As mentioned in the conclusion, changes in the outcome of the results can be achieved by altering the parameters of the circuit configuration. Though new theory accounts for the relationship which describes how the changes are reflected in the data, that is beyond the scope of this experiment, and conclusions can be drawn almost entirely from curve fitting.

There is an uncertainty in the current measurements which results from the heat of the oven. After turning the oven off for *Trial 07* and *Trial 08*, the noise was negligible.

Additionally, data points with a ramping voltage $\approx 14V$ were removed from the data analysis as finding the minima proved extremely difficult. Therefore the curve fit and derived parameters were calculated from data with a ramping voltage of $14V$ and above.

To calculate the final uncertainty, the standard deviation between the five ΔE measurements were taken. To justify the use of this value as the uncertainty, the curve fit had to be in strong agreement with the data. Once the parameters were found which satisfied this requirement, I was confident using the maxima derived from the curve to calculate the values for ΔE. With several values for ΔE, taking the average and standard deviation was a given, which is how I arrived at my final value.



(a) Final conclusion for Trail 07

(b) Final conclusion for Trail 08

Figure 5: Graph of the final conclusions for Trial 07 and Trail 08

Trial 07	$4.91 \pm 0.13eV$
Trial 08	$4.88 \pm 0.17eV$
Final	$4.89 \pm 0.15eV$

Table 2: Final value for ΔE with uncertainty

Conclusion

In conclusion, the experiment produced data which agreed with theory and showed the discrete energy levels of the mercury atom. The experiment required several rounds of calibration in order to get data which was not drowned out by noise or saturated at peak current levels. Calculating the effect on the energy levels of each calibration would likely reveal insights into the behavior of the atom in under different conditions. Further, recent experiments have shown the Franck-Hertz curve to display energy levels of non equal distances which can be fit to a more precise linear relationship. Finally, it has become common to calculate the voltage difference between minimum current values as well, which this experiment overlooked. Such methods leave much to learn from the Franck-Hertz experiment in the future. Overall, the Franck-Hertz experiment is an elegant method of viewing quantum phenomena.

Question 1

$$m_{Hg} = 3.330877587E - 25(kg)$$
$$m_e = 9.1093837E - 31(kg)$$

To calculate this we just find what the transfer of kinetic energy would be in the circumstance that the electron transfers all its kinetic energy to the Hg atom.

$$\begin{aligned}
\frac{\Delta K_f}{k_i} &= \frac{m_{2f} v_{2f}^2}{m_{1i} v_{1i}^2} \\
&\textit{Solve for } v_{1i} \textit{ using conservation laws} \\
&= \frac{m_{2f} v_{2f}^2}{m_{1i} \frac{1}{4} (\frac{m_1+m_2}{m_1})^2 v_{2f}^2} \\
&= \frac{4m_2 m_1}{(m_1+m_2)^2} \\
&= 0.00001
\end{aligned} \tag{2}$$

Question 2

An electron volt is the energy gained by an electron when it is under a potential of one volt. The value of $1eV$ is $1.602 \cdot 10^{-12}$ $ergs$.[2]

Question 3

The excited mercury atom does not stay excited for very long and soon decays back into the ground state, emitting a photon of wavelength $253.6nm$ as mentioned in the original Franck-Hertz paper.[3] This could be detected with a spectroscope or some spectroscopy equipment.

Question 4

I am not completely sure that I read this question correctly, I believe this effect is due to the fact that below the energy of the ground state, there mercury atom will not accept any energy from the

[2] https://www.britannica.com/science/electron-volt
[3] James Franck, Gustav Hertz, Nobel Prize, 1925

electron. However, as the accelerating voltage provides the electron with a higher minimum energy than needed for the ground state of mercury, are more and more electrons which can undergo a collision and still make it across. In other words, there is more electrons which have sufficient energy as the accelerating voltage rises. However, I am not sure I answered this question correctly.