BS 192: Undergraduate Science Laboratory (Physics)

A
Laboratory Report
on

Franck-Hertz Experiment

by

Jaskirat Singh Maskeen
Nishchay Bhutoria
Kavya Lavti
Kanhaiyalal

Indian Institute of Technology Gandhinagar

Index

Experiment No. 2

Franck-Hertz Experiment

I. Aim:

To determine the first excitation potential of argon ($^{39.9}_{18}Ar$) atom using Franck-Hertz tube.

II. Theory:

The Franck-Hertz experiment, carried out by James Franck and Gustav Hertz in 1914, played an essential role in validating Niels Bohr's atomic model, which introduced the notion of quantized energy states for electrons. Bohr's proposal in 1913 asserted that electrons within atoms could only occupy specific and discrete energy levels. The objective of the Franck-Hertz experiment was to confirm this idea.

The experimental setup involves a glass tube containing a low-pressure mercury gas and three electrodes: a cathode emitting electrons, a mesh grid for acceleration, and an anode. However, we use Argon instead of mercury because it eliminates the heating of the tube. The anode is held at a slightly negative electric potential relative to the grid (although positive compared to the cathode so that the electrons have a small amount of kinetic energy to reach it after passing through the grid), creating a potential difference to accelerate electrons through the gas. The experiment relies on inelastic scattering of electrons by gas atoms.

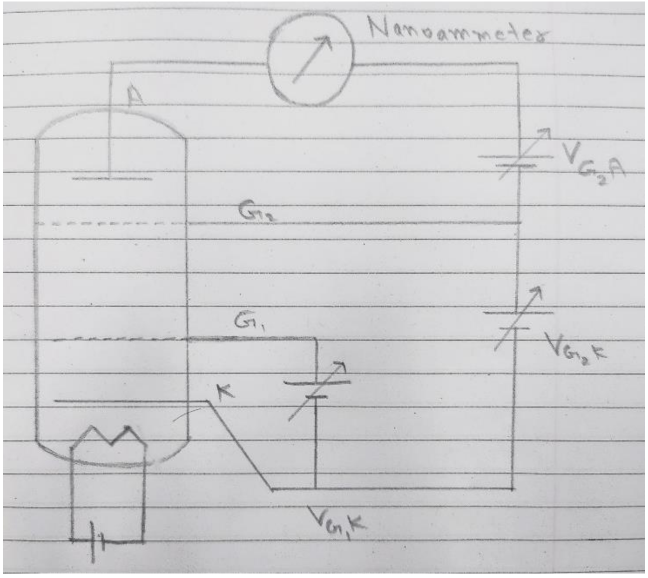
As the accelerating voltage increases, more electrons reach the anode, causing an increase in current. However, when the accelerating voltage equals the excitation potential of the gas atoms, there is a sudden drop in current. This drop is attributed to inelastic collisions between the accelerated electrons and the atomic electrons of the gas. The sudden onset indicates that the gas electrons can only accept energy once they reach the threshold for elevating them to an excited state.

Franck and Hertz observed quantized excitation in 1914, providing evidence for Bohr's theory. Electrons with energy greater than a critical value could excite the mercury (here, Argon) spectrum, while those with lower energy bounced elastically without exciting any electromagnetic emission.

The Franck-Hertz experiment thus supports Bohr's atomic model and demonstrates that electrons orbit the nucleus with specific and discrete energies. For their work, James Franck and Gustav Hertz were awarded the Nobel Prize in Physics in 1925.

III. Apparatus:

Franck-Hertz tube, cathode ray oscilloscope, digital ammeter (with multiplier), digital voltmeter, continuously variable power supply [V_{G1K} $(1.3 - 5V)$, V_{G2A} $(1.3 - 15V)$, V_{G2K} $(0 - 80V)$].



IV. Procedure:

1. Before turning on the equipment, check that all the knobs are at their minimum values and set the current multiplier value at 10^{-9}.
2. Now turn on the equipment and set the Manual-Auto switch to manual. Set the values of $V_{G1K} = 1.5\,V$, $V_{G2A} = 7.5\,V, V_{G2K} = 0\,V$ and wait for 10-15 min so that the filament is heated enough for our reading.
3. Then increase the value of V_{G2K} by 2 volts, wait for 2-3 minutes and note down the average value of the fluctuating current readings corresponding to V_{G2K} .
4. Repeat this process until V_{G2K} reaches 60V and plot the graph between current and voltage.
5. Slowly decrease V_{G2K} voltage to its minimum, followed by V_{G1K} , V_{G2A} , and filament voltage knobs.
6. Set the oscilloscope to X-Y mode and adjust the scanning range switch.
7. Turn on the oscilloscope and adjust the Y and X shifts to align the scan baseline at the bottom of the screen.
8. Rotate the scanning knob, observe the waveform, and adjust Y-gain and X-gain for clarity.
9. Rotate the scanning potentiometer clockwise to its end. Wait 2-4 minutes for the waveform to develop completely.
10. Mark voltage differences between consecutive peaks or consecutive valleys on the traced waveform.
11. Slowly minimize V_{G2K} voltage again, followed by V_{G1K} , V_{G2A} , and filament voltage knobs to their least values.
12. Switch off the equipment.

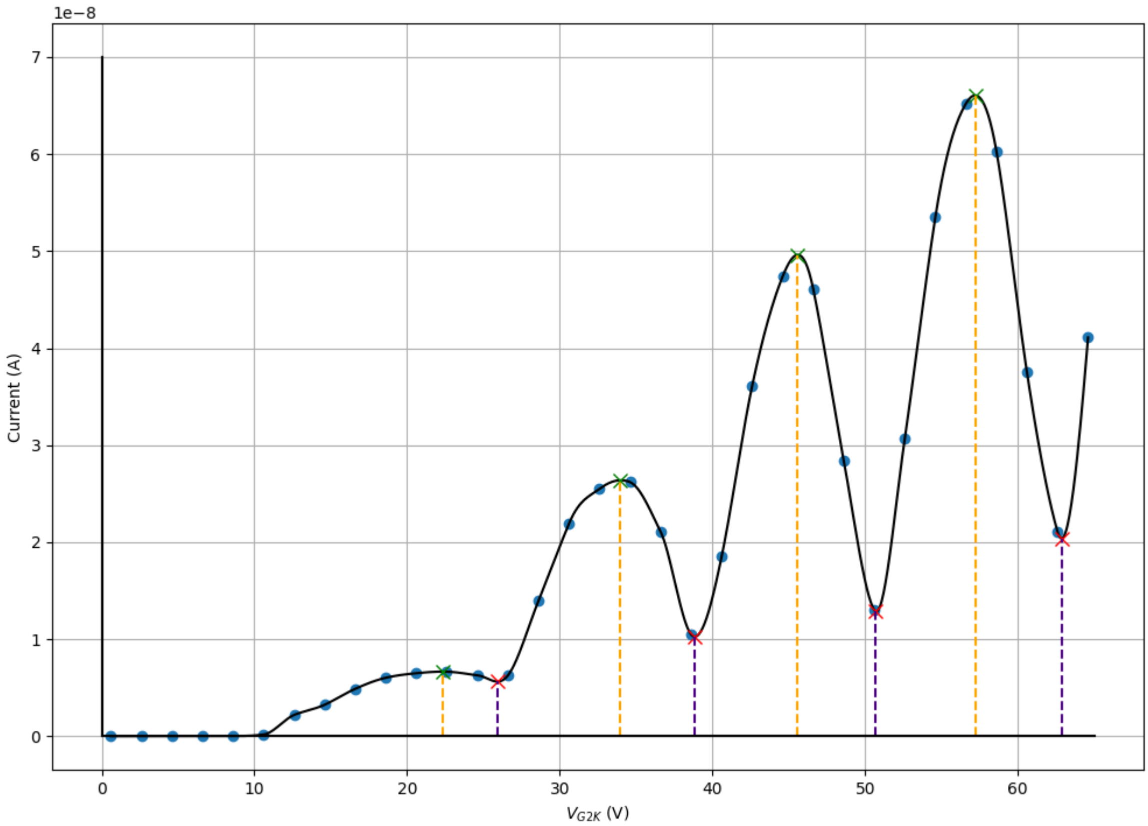
V. Observations:

- Manual mode:

VG2K (V)	Current (I x 1e-9)
0.6	0.01
2.6	0.02
4.6	0.02
6.6	0.02
8.6	0.02
10.6	0.18
12.6	2.20
14.6	3.25
16.6	4.89
18.6	6.03
20.6	6.50
22.6	6.66
24.6	6.30
26.6	6.26
28.6	13.94
30.6	21.90
32.6	25.50
34.6	26.20
36.6	21.10
38.6	10.50
40.6	18.50
42.6	36.10
44.6	47.40
46.6	46.10
48.6	28.40
50.6	13.00
52.6	30.70
54.6	53.50
56.6	65.20
58.6	60.30
60.6	37.50
62.6	21.10
64.6	41.10

(Images of these readings are in Section VIII)

- Plot between I vs V_{G2K} :



1. At low V_{G2K}, up to 10 volts, the current in the tube was almost zero ($0.2 \times 10^{-9} A$). As the voltage was increased, the current steadily increased up to a certain value, then dipped down. Similarly, we obtain several dips in the graph.
2. Upon doing a curve fitting with these datapoints, we obtain local maximums and local minimums.
3. The peak values of the current are as follows:

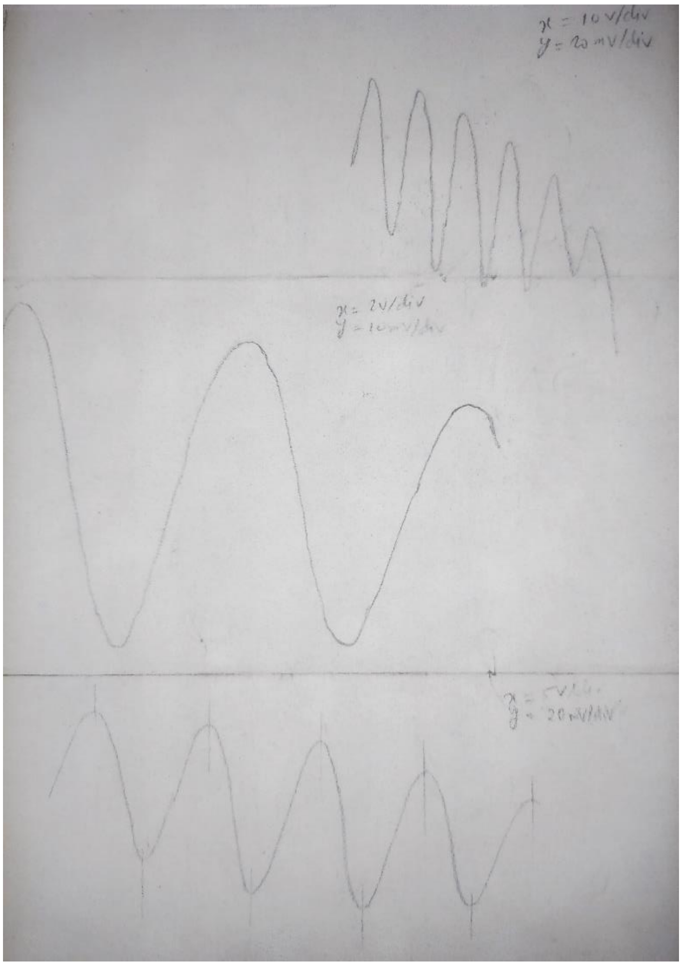
Current ($\boldsymbol{I \times 10^{-9}}$)	$\boldsymbol{V_{G2K}}$ ($\boldsymbol{V}$)
6.67	22.32
26.39	33.98
49.62	45.57
66.05	57.23

4. The dip values of the current are as follows:

Current ($\boldsymbol{I \times 10^{-9}}$)	$\boldsymbol{V_{G2K}}$ ($\boldsymbol{V}$)
5.64	25.91
10.27	38.85
12.85	50.70
20.39	62.87

5. To obtain the excitation potential, we compute the difference between two consecutive values of peaks or valleys (dips).

- Auto mode:
  1. On switching to auto mode and connecting the oscilloscope, we obtain a similar graph to manual mode.
  2. Choosing a suitable scale, we compute the difference between two consecutive peaks or two consecutive valleys.



VI. Result, Discussion and Error Analysis:

To make a continuous curve which fits the collected data from the manual mode, we used the "Akima spline" method.

Between each of the points (x_i, y_i) and (x_{i+1}, y_{i+1}), we can construct a cubic polynomial of the form,

$$P_i(x) = a_i + b_i(x - x_i) + c_i(x - x_i)^2 + d_i(x - x_i)^3$$

The coefficients a_i, b_i, c_i, d_i are computed by determining the values and slopes at neighbouring data points.

$$s_i \ = \text{weighted average of nearby slopes of points } (m)$$

$$m_i = \frac{y_{i+1} - y_i}{x_{i+1} - x_i}$$

The coefficients are chosen such that, the four conditions of continuity of spline together with its first derivative are satisfied, to give a smooth curve passing through all the data points.

i. $P(x_i) = y_i$
ii. $P(x_{i+1}) = y_{i+1}$
iii. $P'(x_i) = s_i$
iv. $P'(x_{i+1}) = s_{i+1}$

- Manual mode:

	VG2K (V)	Vo (V)	Vi-Vo (V)	(Vi-Vo)^2 (V^2)
Peak	22.32	11.66	-0.32	0.10
	33.98	11.59	-0.39	0.15
	45.57	11.66	-0.32	0.10
	57.23			
Dip	25.91	12.94	0.96	0.92
	38.85	11.85	-0.13	0.02
	50.70	12.17	0.19	0.04
	62.87			
	Mean Vo	11.98		
	σ	0.47		

1. Compute difference between two consecutive peaks and two consecutive valleys.
2. Get the average value of excitation potential.

$$V_0 = \frac{\Sigma V_i}{N}$$

3. Compute the standard deviation from mean.

$$\sigma = \sqrt{\frac{(V_i - V_o)^2}{N}}$$

$$V_o = 11.98\, V$$

$$\sigma = 0.47\, V$$

4. Error percentage comes out to be:

$$\frac{\Delta V_o}{V_o} = \frac{0.47}{11.98} \times 100 = 3.92\%$$

- Auto Mode:

Scale	x-axis	5 V/cm		
	Distance (cm)	Vo (V)	Vi-Vo (V)	(Vi-Vo)^2 (V^2)
Peak	2.3	11.5	0.4	0.1
	2.3	11.5	0.4	0.1
	2.1	10.5	-0.6	0.4
	2.2	11.0	-0.1	0.0
Dip	2.2	11.0	-0.1	0.0
	2.3	11.5	0.4	0.1
	2.2	11.0	-0.1	0.0
	Mean Vo	11.1		
	σ	0.3		

1. Mark the peak points and the valley points.
2. Get the distance between two consecutive peak points and two consecutive valley points.
3. Multiply that distance by the scale for *x-axis*.
4. Get the mean value of excitation potential.

$$V_0 = \frac{\Sigma\, V_i}{N}$$

5. Compute the standard deviation from mean.

$$\sigma \;=\; \sqrt{\frac{(V_i - V_o)^2}{N}}$$

$$V_o = 11.1\,V$$

$$\sigma \;=\; 0.3\,V$$

6. Error percentage comes out to be:

$$\frac{\Delta \mathrm{V_o}}{\mathrm{V_o}} = \frac{0.3}{11.1} \times 100 = 2.7\%$$

- Possible sources of errors:

We see a difference between the readings of manual mode and the auto mode. The reasons for this might be as follows:

1. We did not use enough valley points in manual mode, to get the mean excitation potential.
2. According to procedure, we had to fix the values of V_{G1K} at $1.50\,V$ and V_{G2A} at $7.50\,V$. But V_{G1K} was fluctuating between $1.49\,V$ and $1.51\,V$. We had to increase V_{G2K} from $0.00\,V$, but the least we could get our V_{G2K} was to $0.06\,V$.

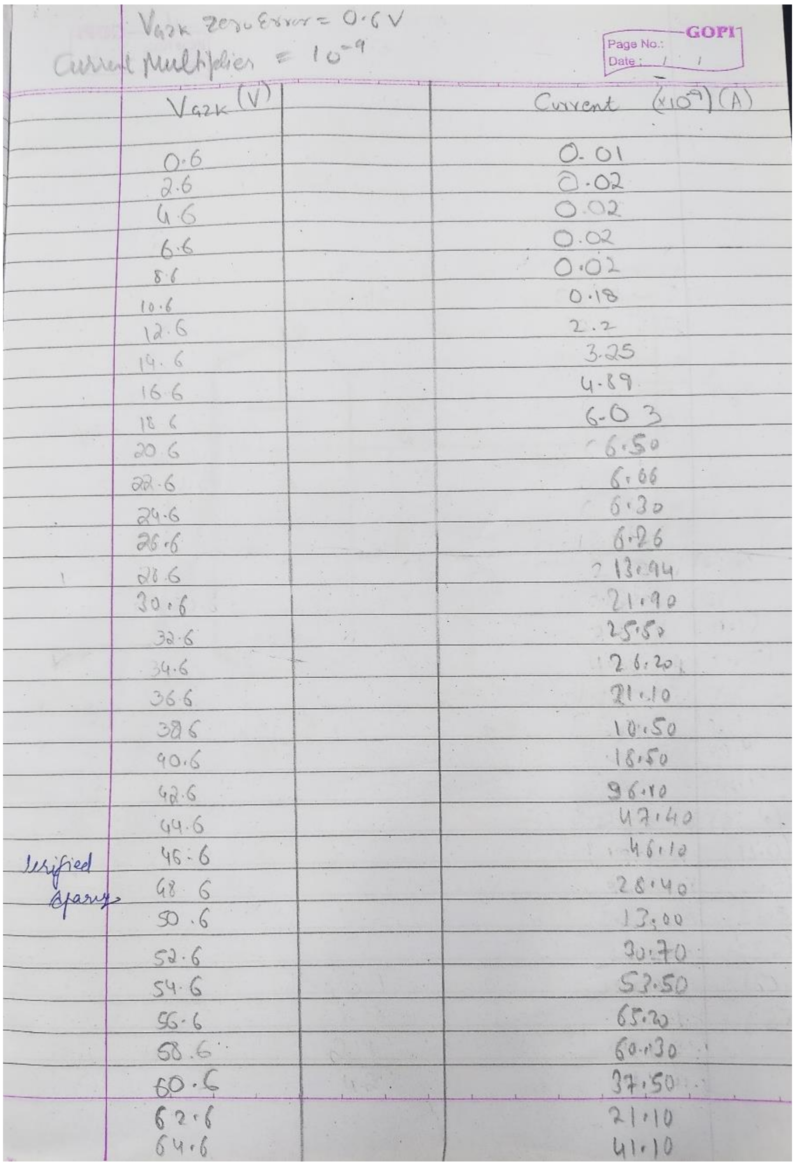
3. While taking the readings, after setting V_{G2K} to a fixed value, the current fluctuated about a value, so we took the average of highest and lowest value at that particular V_{G2K}.
4. There is a substantial human error while tracing the graph from oscilloscope to paper, as it was difficult to estimate where along the *x-axis*, minima or maxima lies.
5. There are huge uncertainties in the peak and dip values from fitting the cubic splines, to the data in order to interpolate the location of maxima and minima.
6. The temperature of the Franck-Hertz tube may have introduced an error, as with decrease in temperature the distance between a maxima and minima increases.
7. The scaling and resolution of the oscilloscope may make the distance between peaks differ by a few millimetres.

VII. Conclusion:

We conducted this experiment to determine the value of the excitation potential of Argon, which comes out to be $11.98\,V$, with a standard deviation of $0.47\,V$ in manual mode and $11.1\,V$, with a standard deviation of $0.3\,V$ in auto mode.

We can also conduct experiment for different temperatures, to obtain an idea of how it affects the excitation potential. We can also take readings at a smaller interval of $1\,V$ to have a more detailed dataset, which will reduce systematic errors from curve fitting. As our data shows, when the accelerating voltage reaches around $23\,V$, the current sharply drops, which indicates existence of a phenomenon that takes away enough energy from the electrons that they cannot reach the collector. The current drop happens because the fast electrons collide with the atomic electrons in argon. These current drops occur at around every $11.98\,V$. This experiment strongly supports the idea of specific atomic energy levels.

VIII. Readings Images:



V_{G2K} Zero Error = 0.6 V
Current Multiplier = 10^{-9}

GOPI
Page No.:
Date: / /

V_{G2K} (V)		Current ($\times10^{-9}$) (A)
0.6		0.01
2.6		0.02
4.6		0.02
6.6		0.02
8.6		0.02
10.6		0.18
12.6		2.2
14.6		3.25
16.6		4.89
18.6		6.03
20.6		6.50
22.6		6.66
24.6		6.30
26.6		6.26
28.6		13.94
30.6		21.90
32.6		25.50
34.6		26.20
36.6		21.10
38.6		10.50
40.6		18.50
42.6		36.10
44.6		47.40
46.6		46.10
48.6		28.40
50.6		13.00
52.6		30.70
54.6		53.50
56.6		65.20
58.6		60.30
60.6		37.50
62.6		21.10
64.6		41.10

Verified
Sparsh

IX. Author Contribution:

Name	Roll Number	Contribution	Signature
Jaskirat Singh Maskeen	23110146	Interpolating datapoints with Akima spline and generating graph (Matplotlib). Doing error analysis, finding possible sources of error and conclusion.	
Nishchay Bhutoria	23110222	Index, Aim, Apparatus, Document structure, taking readings in lab, Cover page, Theory, Tracing the oscilloscope rough curve with Matplotlib.	
Kavya Lavti	23110164	Document structure, Taking readings in lab, Procedure.	
Kanhaiyalal	23110155	Noting readings, Apparatus Diagram.	