Franck-Hertz experiment using Neon tube

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Our experiment employed a neon-filled Franck-Hertz tube to examine the quantized energy states of neon atoms. We gradually increased the accelerating voltage applied to the tube and observed corresponding fluctuations in the current. Peaks in the current occurred at specific voltages, indicating the points where electrons lost energy through inelastic collisions with neon atoms. The spacing between these peaks allowed us to determine the excitation energy of neon, providing empirical evidence for the quantized nature of atomic energy levels.

I. OBJECTIVE

Study of quantized excitation of Neon atoms by inelastic scattering and determine the excitation energy.

II. THEORY

Franck and Hertz conducted a pioneering experiment in 1914 that offered the first tangible proof of quantized energy levels in atoms. They bombarded mercury vapor with electrons of varying energies and found a significant threshold: electrons with less than 4.9 electron volts (eV) could only undergo elastic collisions, whereas those with 4.9 eV or more could excite mercury atoms, resulting in the emission of light at a specific wavelength (253.6 nm). This observation provided strong support for Bohr's quantum theory, which posited that electrons could only occupy certain discrete energy states within an atom.

In this experimental arrangement, the excitation of neon atoms is investigated by observing inelastic collisions between electrons and neon atoms within a tetrode filled with neon gas. As electrons, emitted from a heated cathode and accelerated by an applied electric field, collide with neon atoms, the excited atoms release visible light. To determine the excitation energy of neon, the distance between the equidistant maxima of the electron current is measured under varying opposing electric fields. This analysis allows for a precise calculation of the energy required to excite neon atoms.

Principle

Electrons are emitted from the cathode and accelerated towards the grid by applying a potential difference U_{KG} between the cathode and the grid.The cathode in the tube is heated by a filament to emit electrons in a process called thermionic emission with an appplied voltage of U_F.

When electrons with insufficient energy (less than the excitation energy of the gas atoms) collide with the gas atoms, they do not transfer energy to the atoms. The collisions are elastic, meaning the electrons merely bounce off without losing kinetic energy.

When the electron energy equals or exceeds the excitation energy of the gas atoms, the electrons can transfer part of their energy to the atoms. This energy transfer causes the atom to move from its ground state to an excited state. The energy required to excite the atom is quantized,

$$E_{\text{exc}} = \frac{hc}{\lambda} = eV \tag{1}$$

Excitation of Ne Atoms

The most likely excitation in neon occurs when electrons collide inelastically, promoting atoms from the ground state to the ten $3p$ states, which are 18.4 to 19.0 eV above the ground state. The four lower $3s$ states, between 16.6 and 16.9 eV, are less likely to be excited. De-excitation from the $3p$ states back to the ground state happens through the $3s$ states, emitting photons in the process. The emitted light, visible to the naked eye, falls within the red to green range.

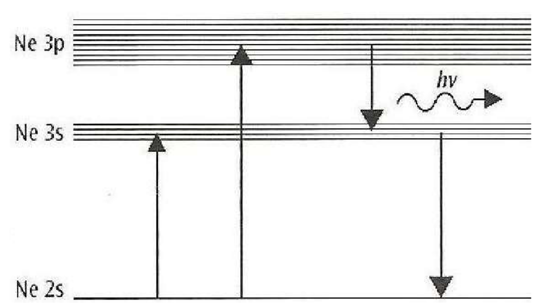

FIG. 1: Energy level diagram for Ne

III. EXPERIMENTAL SETUP

Apparatus

1. Franck-Hertz tube
2. Franck-Hetrz Operating Unit

3. Banana wires for connecting sockets for the heater, control grid and anode grid voltages

Electrons are accelerated from the cathode (K) to the anode (A) by the applied voltage, denoted as U_A. A retarding potential, U_{AE}, is established between the anode (A) and the collector electrode (E), allowing only those electrons with sufficient kinetic energy to reach electrode E and contribute to the collector current.

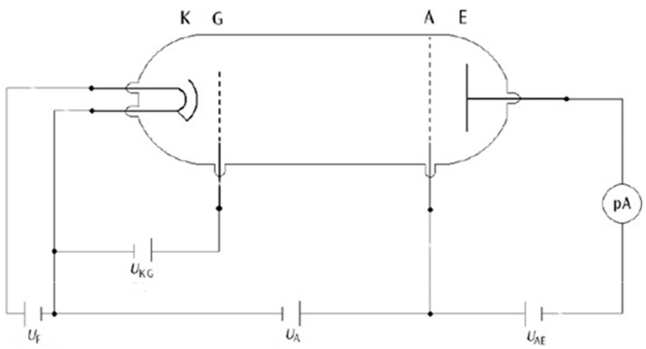

FIG. 2: Schematic of the experimental set-up and circuit diagram. Here, K is the cathode, G is the control grid, A is the anode and E is the collector electrode

As the accelerating voltage U_A increases, the kinetic energy of the electrons rises. When this kinetic energy reaches the excitation energy of the gas atoms, inelastic collisions occur, causing electrons to lose energy and resulting in a decrease in the collected anode current. As U_A continues to increase, electrons that have lost energy can be reaccelerated towards the anode. At even higher voltages, multiple inelastic collisions may occur, leading to a series of equidistant peaks and troughs in the anode current. By measuring the voltage difference between successive maxima in the anode current, the excitation energy of the gas can be determined,

$$E_{\text{exc}} = e\Delta U_A \tag{2}$$

IV. PROCEDURE

1. Set the Franck Hertz operating unit to manual mode, with all control knobs turned to their extreme anticlockwise positions.
2. Adjust voltage settings U_{KG} and U_{AE} to approximately 4-6 V and 4-8 V, respectively such that there can be three peaks of current in the whole measurement.
3. Slowly vary acceleration voltage U_A from 0 to 80 V, and record the corresponding collector current.
4. Repeat the experiment for 3 different sets of filament and grid voltages.

V. OBSERVATION AND CALCULATIONS

Least count of the instrument = 0.5 V. Using data from table I, we have plotted I_C vs. U_A for 3 different datasets as follows.

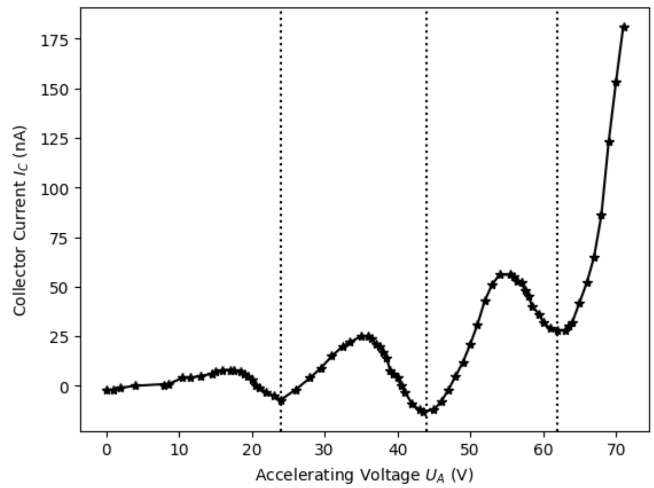

FIG. 3: I_C vs. U_A for $U_F = 8.5$ V, $U_G = 4$ V, $U_E = 4$ V

From the first 2 minima, $\Delta U_1 = (20.0 \pm 0.5)$ V
From the 2nd and 3rd minima $\Delta U_2 = (18.0 \pm 0.5)$ V
So, $\Delta U_{\text{avg}} = (19.0 \pm 0.4)$ V

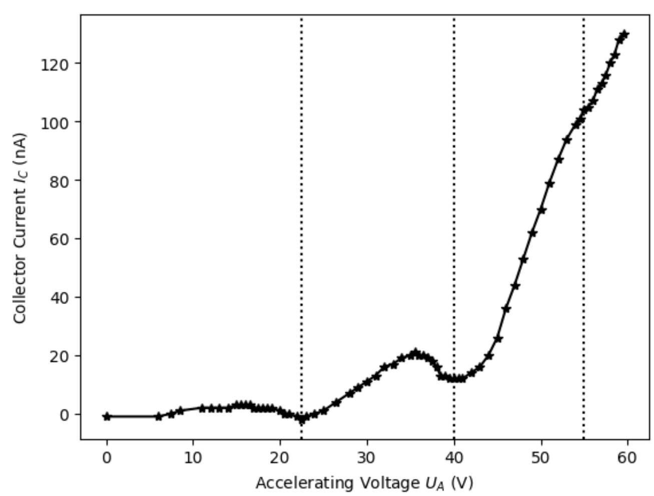

FIG. 4: I_C vs. U_A for $U_F = 8.5$ V, $U_G = 4.8$ V, $U_E = 5$ V

From the first 2 minima, $\Delta U_1 = (17.5 \pm 0.5)$ V
From the 2nd and 3rd minima $\Delta U_2 = (15.0 \pm 0.5)$ V
So, $\Delta U_{\text{avg}} = (16.3 \pm 0.4)$ V

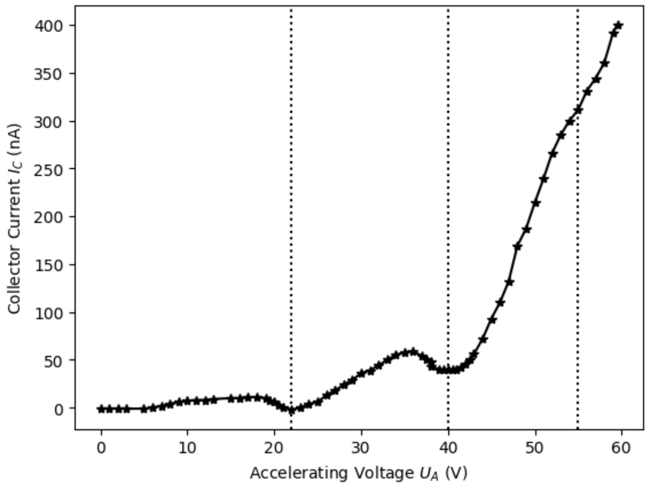

FIG. 5: I_C vs. U_A for $U_F = 8.5$ V, $U_G = 5$ V, $U_E = 4.5$ V

From the first 2 minima, $\Delta U_1 = (18.0 \pm 0.5)$ V
From the 2nd and 3rd minima $\Delta U_2 = (15.0 \pm 0.5)$ V
So, $\Delta U_{\text{avg}} = (16.5 \pm 0.4)$ V

VI. DISCUSSION AND CONCLUSION

The Franck-Hertz experiment, conducted with a neon-filled tube, successfully demonstrated the quantized nature of energy levels in atoms. By analyzing the graph of current versus accelerating voltage, distinct peaks were observed, corresponding to the specific excitation energies required to elevate electrons in neon atoms to higher energy levels. The results obtained show the average excitation energy as $\Delta U = (17.3 \pm 0.3)$ eV, which falls quite close to the theoretical range of $(18.0 - 19.5)$ eV.

The measured excitation energy closely corresponded to the theoretical value for neon's first excitation level, reinforcing the quantum mechanical model of discrete energy states. Slight deviations between the experimental and theoretical results could be attributed to experimental factors such as contact resistance, impurities in the neon gas, or variations in the applied voltage. In some cases, identifying the third minima was more difficult, which may have also contributed to the error. Nevertheless, the experiment successfully demonstrates the quantized nature of atomic energy levels and the fundamental principles governing electron-atom collisions.

VII. PRECAUTIONS

1. Make sure that the circuit is connected properly before switching on the set-up.
2. Make sure that the values of U_F, U_G and U_E fall within the specified range.
3. Before taking measurements, check if the collector current does not saturate before obtaining 3 extremum values.

[1] SPS, *Franck-Hertz experiment using Neon tube*, NISER (2023).

U_A (V)	I_C (nA)	U_A (V)	I_C (nA)	U_A (V)	I_C (nA)	U_A (V)	I_C (nA)	U_A (V)	I_C (nA)
$U_F = 8.5$ V, $U_G = 4$ V, $U_E = 4$ V									
0.0	-2	20.0	3	38.0	17	52.0	43	65.0	42
1.0	-2	20.5	0	38.5	14	53.0	51	66.0	52
2.0	-1	21.0	-1	39.0	8	54.0	56	67.0	65
4.0	0	22.0	-3	39.5	6	55.5	56	68.0	86
8.5	1	23.0	-5	40.0	4	56.0	55	69.0	123
8.0	0	24.0	-7	40.5	0	56.5	53	70.0	153
10.5	4	26.0	-2	41.0	-3	57.0	52	71.0	181
11.5	4	28.0	4	42.0	-9	57.5	48	72.0	208
13.0	5	29.5	9	43.0	-12	58.0	45	73.0	245
14.5	6	31.0	15	43.5	-13	58.5	40	74.0	271
15.0	7	32.5	20	45.0	-12	59.5	36	75.0	315
16.0	8	33.5	22	46.0	-8	60.0	32	76.0	351
17.0	8	35.0	25	47.0	-2	61.0	29	77.0	399
17.5	8	36.0	25	48.0	5	62.0	28	78.0	400
18.5	7	36.5	24	49.0	12	63.0	28	80.0	400
19.0	6	37.0	21	50.0	21	63.5	30		
19.5	5	37.5	20	51.0	31	64.0	32		
$U_F = 8.5$ V, $U_G = 4.8$ V, $U_E = 5$ V									
0.0	-1	16.0	10	28.0	24	39.5	40	50.0	214
1.0	-1	17.0	11	29.0	29	40.0	40	51.0	239
2.0	-1	18.0	11	30.0	36	40.5	40	52.0	266
3.0	-1	19.0	10	31.0	39	41.0	40	53.0	285
5.0	-1	19.5	8	32.0	44	41.5	42	54.0	300
6.0	0	20.0	6	33.0	50	42.0	46	55.0	311
7.0	2	20.5	3	34.0	55	42.5	50	56.0	331
8.0	4	21.0	0	35.0	58	43.0	56	57.0	344
9.0	6	22.0	-2	36.0	59	44.0	72	58.0	360
10.0	7	23.0	0	37.0	54	45.0	93	59.0	391
11.0	8	24.0	4	37.5	51	46.0	110	59.5	400
12.0	8	25.0	6	38.0	48	47.0	132	60.0	400
13.0	9	26.0	13	38.0	43	48.0	169		
15.0	10	27.0	18	39.0	40	49.0	187		
$U_F = 8.5$ V, $U_G = 5$ V, $U_E = 4.5$ V									
0.0	-1	20.0	1	35.5	21	47.0	44	59.0	128
6.0	-1	20.5	0	36.0	20	48.0	53	59.5	130
7.5	0	21.0	0	36.5	20	49.0	62	60.0	137
8.5	1	22.0	-1	37.0	19	50.0	70	61.0	148
11.0	2	22.5	-2	37.5	18	51.0	79	62.0	165
12.0	2	23.0	-1	38.0	16	52.0	87	63.0	177
13.0	2	24.0	0	38.5	13	53.0	94	64.5	202
14.0	2	25.0	1	39.0	13	54.0	99	65.0	226
15.0	3	26.5	4	39.5	12	54.5	101	67.0	266
15.5	3	28.0	7	40.0	12	55.0	104	68.5	310
16.0	3	29.0	9	40.5	12	55.5	105	70.5	383
16.5	3	30.0	11	41.0	12	56.0	107	71.5	400
17.0	2	31.0	13	42.0	14	56.5	111		
17.5	2	32.0	16	43.0	16	57.0	113		
18.0	2	33.0	17	44.0	20	57.5	116		
18.5	2	34.0	19	45.0	26	58.0	120		
19.0	2	35.0	20	46.0	36	58.5	123		

TABLE I: Corresponding U_A and I_C values for 3 sets of data