Birla Institute of Technology & Science, Pilani
Pilani Campus

PHY F244 : Modern Physics Laboratory

Franck and Hertz Experiment

1. **Aim and Objectives** : The objective of this experiment to measure the ionization potential of the Argon using the Franck and Hertz experimental setup.

2. **Keywords** : Bohr's atomic model, quantization of energy levels, inelastic collision.

3. **Theory** :

   As we all know, the Bohr quantization, introduced by Niels Bohr in 1913 as part of his atomic model, represents a pivotal step in developing quantum mechanics. It offers a framework to describe the behavior of electrons in atoms, bridging classical and quantum physics before the full formalism of quantum mechanics was developed. Core Ideas of Bohr Quantization are as follows

   (a) **Quantized Orbits**: Electrons revolve around the nucleus in specific, discrete orbits (energy levels) without radiating energy. These orbits are stable and characterized by quantized angular momentum. The angular momentum L of the electron in an allowed orbit is given by:$L = n\hbar$, where n is a positive integer (the principal quantum number), and $\hbar$ is the reduced Planck constant.

   (b) **Energy Quantization**:
   Each orbit corresponds to a specific energy level. Electrons can transition between these levels by absorbing or emitting energy in the form of photons.
   The energy difference between the two levels is:$\Delta E = E_{\text{final}} - E_{\text{initial}} = h\nu$ where: ν is the frequency of the emitted or absorbed radiation.

   If the energy levels are quantized, one can also excite the atom by transferring the kinetic energy of the electrons to the atom. In this experiment, we will be using the Argon gas. These Argon atoms will be excited from the ground state by varying the kinetic energy of the electrons. The energy level diagram of the Argon is shown in Figure 1.

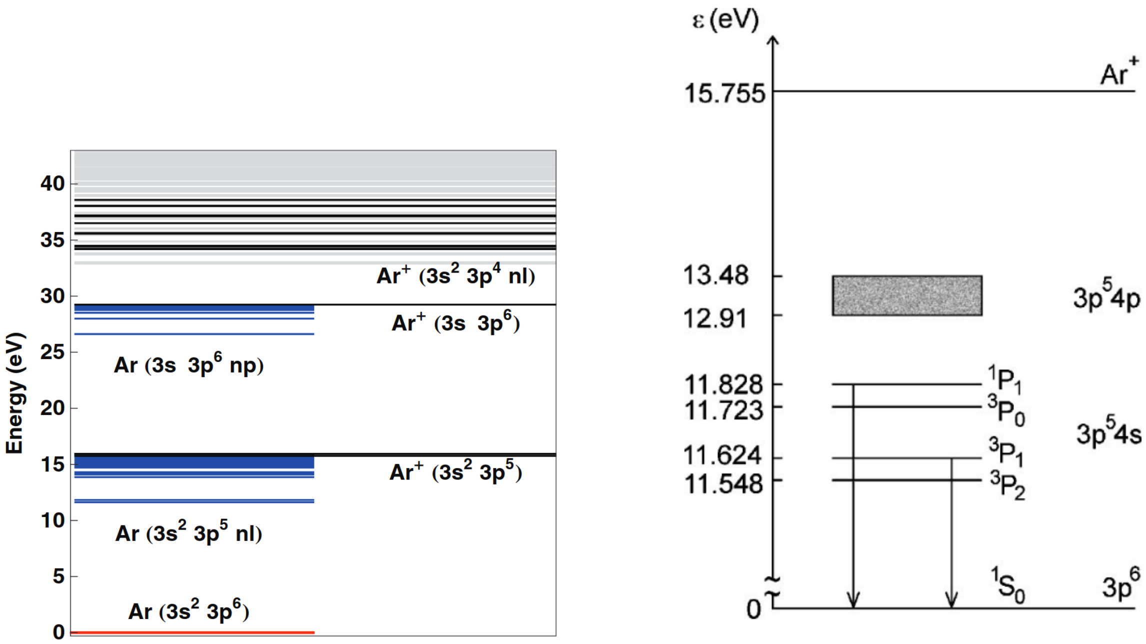

Figure 1: The energy level diagram of the Argon.[Image Courtsey: J. Appl. Phys. 87, 7652–7659 (2000) and Phys. Rev. A 87, 023420, (2013)]

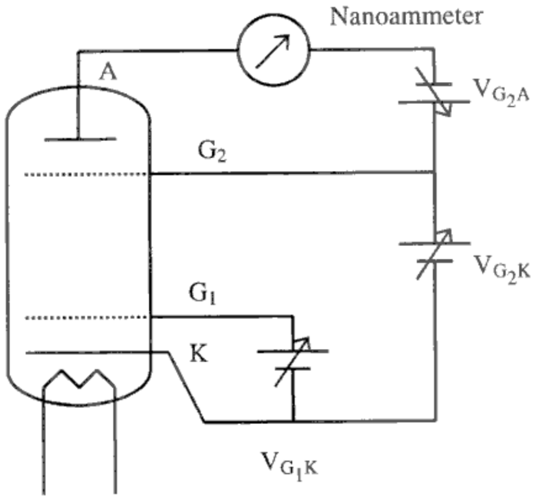

Figure 2: Franck-Hertz exerperimental setup.

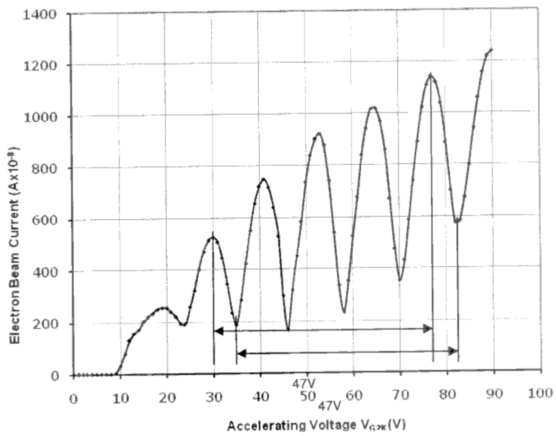

Figure 3: The variation of the anode current as a function of the V_{G2K} for a fixed V_{G1K} and V_G2A.

It can be seen from Figure 1 that the first excited energy level of the Argon is the range of $\sim 11.55 - 11.83$ eV. So if the electron having energies in this range undergoes an inelastic collision with the neutral Argon atom. The atom can be excited to those energy levels, so the electron will lose its energy.

The Franck-Hertz experiment, conducted by James Franck and Gustav Hertz in 1914, confirmed quantum theory by demonstrating that atoms absorb energy discretely. This experiment is considered one of the critical early validations of the quantum nature of atomic structure. The Franck-Hertz experiment was the first direct proof of quantized energy levels in atoms, supporting the Bohr model of the atom and the broader principles of quantum mechanics. It also demonstrated that atomic transitions require specific energy values, helping solidify the concept of discrete energy levels in atomic physics. In recognition of their work, Franck and Hertz received the Nobel Prize in Physics in 1925. Their experiment remains a foundational demonstration in quantum mechanics and is still a staple experiment in physics education.

4. **Experimental Procedure** :

A thermionic emitter (cathode), typically made of a heated filament, produces electrons. When heated, the filament released free electrons via thermionic emission. The electrons were accelerated toward a grid (anode) by applying a variable potential difference (V_{G1K}) between the cathode and the grid 1. Toward the end of the tube, another potential is applied (V_{G2K}) to accelerate the electrons with desired energies. This voltage (V_{G2K}) determined the kinetic energy of the electrons as they traveled through the tube. After passing through the tube filled with Argon gas, the electrons encountered a retarding grid that slowed them down before they reached the collector plate. A small retarding voltage (V_{G2A}) was applied to filter out low-energy electrons, ensuring only sufficiently energetic electrons reached the collector. The non-ammeter then records the current. There is also an auto mode available in the setup, which scans the V_{G2K} and measures anode current, and we can see the desired graph on the CRO.

(a) Set $V_{G1K} = 1.5$ Volts and $V_{G2A} = 7.5$ Volts.

(b) Vary the V_{G2K} and measure the current in nano-ampere.

(c) Set $V_{G1K} = 2.5$ Volts and $V_{G2A} = 7.5$ Volts, and repeat step 2.

(d) Set $V_{G1K} = 1.5$ Volts and $V_{G2A} = 5$ Volts, and repeat step 2.

(e) The typical graph between the current and the V_{G2K} for fixed values of V_{G1K} and V_{G2A} is shown in Figure 3. It can be seen that as we increase the V_{G2K}, the kinetic energy of the electrons increases; if it attains sufficient energy to excite the neutral Argon atom, then the inelastic collision of an electron with the atom results in a reduction of the electron energy which no longer can overcome the the retarding voltage and hence sudden drop in the current is seen. When the electron's energy is increased further, the current also increases as even after the collision with the atom; it has some energy left; however, again, we see the sudden drop in the current. If the energy of the electron is in the multiple of the excitation energy, then because of the inelastic collision, the electron loses all its energy in exciting even more than one argon atom, and a sudden drop in the anode current is registered.

5. **Tasks** :

   (a) Prepare appropriate observation tables.

   (b) Plot the graphs between V_{G2K} vs the I_A (anode current) for different V_{G1K} and V_{G2A} values.

   (c) Estimate the separation between the consecutive dips in the graph and find its average, which would be equivalent to the excitation energy of the Argon atom as shown in Figure 1.

   (d) Estimate the error in the excitation energy of the Argon.

   (e) Explain how and why the nature of the graph changes if we change the V_{G1K} and V_{G2A} voltages.

   (f) Switch the knob to auto mode and see the graph on the CRO. Create an appropriate observation table to note down the position of the dips in the graph and then estimate the average excitation energy of the Argon atom from this information.

6. **Observations and Results** :

   (a) $V_{G1K} = 1.5$ V, $V_{G2A} = 7.5$ V

S.N.	V_{G2K} (Volts)	I (nA)
1		
2		
$\cdots$		

   (b) $V_{G1K} = 2.5$ V, $V_{G2A} = 7.5$ V

S.N.	V_{G2K} (Volts)	I (nA)
1		
2		
$\cdots$		

   (c) $V_{G1K} = 1.5$ V, $V_{G2A} = 5.0$ V

S.N.	V_{G2K} (Volts)	I (nA)
1		
2		
$\cdots$		

The instruction manual for the experimental setup is also appended.

INTRODUCTION

From the early spectroscopic work it is clear that atoms emit radiations at discrete frequencies. From Bohr's model, the frequency of the radiation ν is related to the change of energy levels through $\Delta E=h\nu$. It is then to be expected that transfer of energy to atomic electrons by any mechanism should always be in discrete amounts. One such mechanism of energy transfer is through inelastic scattering of low-energy electrons.

Frank and Hertz in 1914 set out to verify these considerations.

(i) It is possible to excite atoms by low energy electron bombardment.

(ii) The energy transferred from electrons to the atoms always had discrete values.

(iii) The values so obtained for the energy levels were in agreement with spectroscopic results.

Thus the existence of atomic energy levels put forward by Bohr can be proved directly. It is a very important experiment and can be performed in any college or University level lab.

OPERATING PRINCIPLE

The Frank-Hertz tube in this instrument is a tetrode filled with the vapour of the experimental substance Fig. 1 indicates the basic scheme of experiment.

The electrons emitted by filament can be accelerated by the potential V_{G_2K} between the cathode and the grid G_2. The grid G_1 helps in minimising space charge effects. The grids are wire mesh and allow the electrons to pass through. The plate A is maintained at a potential slightly negative with respect to the grid G_2. This helps in making the dips in the plate current more prominent. In this experiment, the electron current is measured as a function of the voltage V_{G_2K}. As the voltage increases, the electron energy goes up and so the electron can overcome the retarding potential V_{G_2A} to reach the plate A. This gives rise to a current in the ammeter, which initially increases. As the voltage further increases, the electron energy reaches the threshold value to excite the atom in its first allowed excited state. In doing so, the electrons lose energy and therefore the number of electrons reaching the plate decreases. This decrease is proportional to the number of inelastic collisions that have occurred. When the V_{G_2K} is increased further and reaches a value twice that of the first excitation potential, it is possible for an electron to excite an atom halfway between the grids, loose all its energy, and then again gain enough energy to excite atoms and this lead to a second dip in the current. The advantage of this type of configuration of the potential is that the current dips are much more pronounced, and it is easy to obtain five fold or even larger multiplicity in the excitation of the first level.

Experiment consists of the following :

- Argon filled tetrode
- Filament Power Supply : 2.6 - 3.4V continuously variable
- Power Supply for V_{G_1K} : 1.3 - 5V continuously variable
- Power Supply for V_{G_2A} : 1.3 - 12V continuously variable
- Power Supply for V_{G_2K} : 0 - 95V continuously variable
- Saw tooth waveform for CRO display
  Scanning Voltage : 0 - 95V
  Scanning Frequency : 115 ± 20Hz.
- Multirange Digital Voltmeter
  Range : 0 - 100V, with 100% over
  Display: 3 ½ digit 7-segment LED with auto polarity and decimal indication
- Multirange Digital Ammeter
  Range : 0 – 100, 0-10 μA & 0-1μA
  Display: 3 ½ digit 7-segment LED with auto polarity

All the above are housed in a single cabinet and operates at 220V ±10%, 50Hz power source.

The instrument can not only lead to a plot of the amplitude spectrum curve by means of point by point measurement, but also directly display the amplitude spectrum curve on the oscilloscope screen. This instrument can thus be used as a classroom experiment as well as for demonstration to a group of students.

ANALYSIS OF THE DATA

Data obtained for the excitation potential point by point are shown in Fig. 3. The readings are taken for 1V changes on grid 2 (V_{G_2K}). A significant decrease in electron (collector) current is noticed every time the potential on grid 2 is increased by approximately 12V, thereby indicating that energy is transferred from the beam in (bundles) quanta of 12 eV only. Indeed, a prominent line in the spectrum of argon exists at 1048 Å corresponding to eV=11.83.

The location of the peaks is indicated in Fig. 3. Average value of spacing between peaks is 11.75 eV compared with the accepted value of 11.83V.

UNPACKING

Unpack the instrument carefully and check the accessories with the packing list. The instrument is checked thoroughly before dispatch, damage/shortage, if any should be reported immediately.

Take out the Frank-Hertz Tube from its window-marked 'Frank-Hertz Tube Window' by removing its cover.

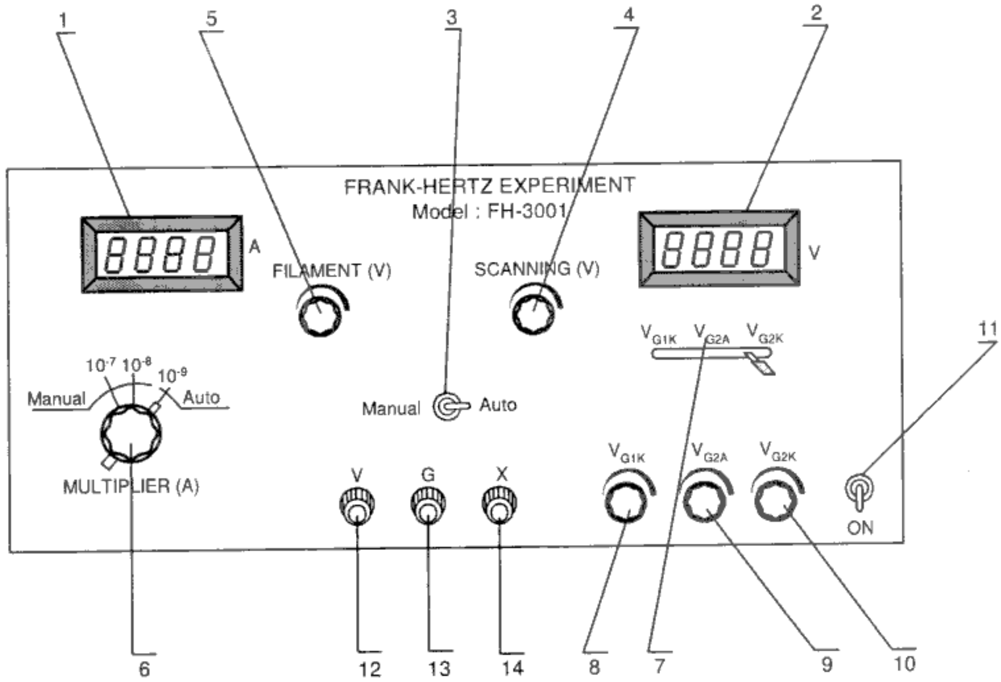

Fig.5 : Panel diagram of Frank-Hertz Experiment, FH-3001

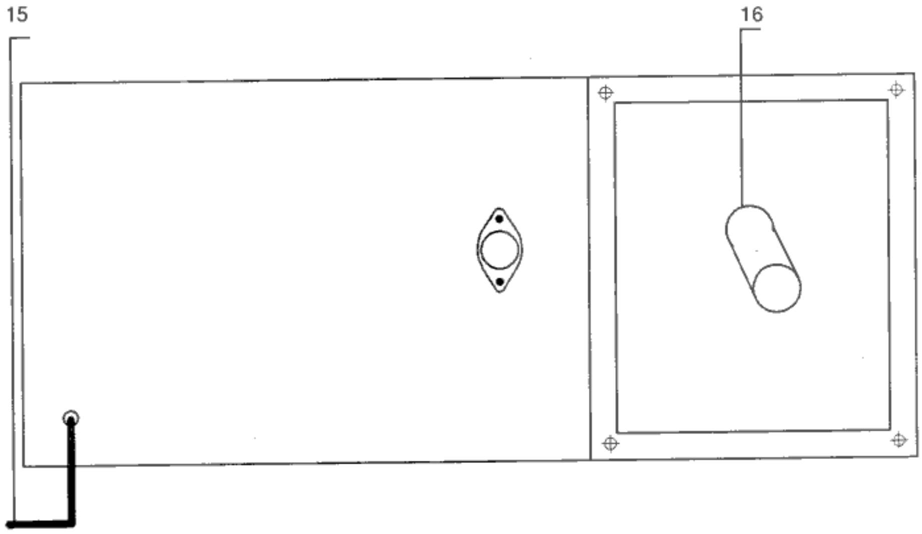

Fig.6 : Back side of Frank-Hertz Experiment, FH-3001

PACKING LIST

1. Frank Hertz, FH-3001 (Main Unit) : One
2. Frank Hertz Tube (Inside its Chamber- not Connected)
3. Dust Cover : One

PANEL CONTROLS AND THEIR FUNCTIONS

1) Ammeter
2) Voltmeter
3) Manual - Auto Switch
4) Scanning Voltage Knob
5) Filament Voltage Knob
6) Current Multiplier Knob
7) Voltage Display Selector: V_{G_1K}, V_{G_2A} or V_{G_2K}
8) V_{G_1K} Adjust knob : 1.3 - 5V
9) V_{G_2A} Adjust Knob : 1.3 - 15 V
10) V_{G_2K} Adjust knob : 0 - 80V
11) Power Switch
12) Y-Output Terminal
13) Ground Terminal
14) X-output Terminal
15) Power Lead
16) Frank Hertz Tube

INSTALLATION

Before the Frank-Hertz tube is put in its socket, make sure the power supplies-'V_{G_1K}, V_{G_2A} & V_{G_2K} are working properly. For this proceed as follows.

1. Put all the control knobs (Scanning Voltage V_{G_1K}, Filament Voltage V_{G_2A} & Accelerating Voltage V_{G_2K} Knobs) to their minimum position by rotating anticlockwise.
2. Turn the Manual-Auto switch to Manual
3. Turn Voltage Display Selector to V_{G_1K} and rotate the V_{G_1K} knob clockwise to see if the power supply is working properly. Similarly turn the Voltage Display Selector to V_{G_2A} and V_{G_2K} and check if these power supplies are also O.K.
4. Switch 'OFF' the power and put Frank-Hertz tube in the socket. **As the tube is delicate and very expensive this operation must be handled very carefully and by a trained technical hand only.**

The instrument is now ready for operation

OPERATING INSTRUCTIONS

1) Ensure that the Electrical power is 220V ±10%, 50Hz.

2) Before the power is switched 'ON' make sure all the control knobs are at their minimum position and Current Multiplier knob at 10^{-7} position.

3) Switch 'ON' the power.

4) Turn the Manual-Auto Switch to Manual, and check that the Scanning Voltage Knob is at its minimum position.

5) Turn Voltage Display Selector to V_{G_1K} and adjust the V_{G_1K} knob until voltmeter reads 1.5V.

6) Turn Voltage Display Selector to V_{G_2A} and adjust the V_{G_2A} knob until the voltmeter read 7.5.

When you have finished step 1-5, you are ready to do the experiment with following parameters.

Filament voltage	: 2.6 V (minimum position)
V_{G_1K}	: 1.5 V
V_{G_2A}	: 7.5 V
V_{G_2K}	: 0 V
Current multiplier	: 10^{-7}A

These are suggested values for the experiment. The experiment can be done with other values also.

7) Rotate V_{G_2K} knob and observe the variation of plate current with the increase of V_{G_2K}. The current reading would show maxima and minima periodically. The magnitude of maxima could be adjusted suitably by adjusting the filament voltage and the value of Current Multiplier. Now take the systematic readings, V_{G_2K} vs. plate current. For better resolution, the reading may be taken at a interval of 1V. Plot the graph with output current on Y-axis and accelerating voltage V_{G_2K} at X-axis.

8) Turn the Manual-Auto switch to 'Auto', connect the instruments Y, G, X sockets to Y, G X of oscilloscope. Put the Scanning Range switch of oscilloscope to X-Y mode/external 'X'. Switch on the power of oscilloscope, adjust the Y and X shift to make the scan base line on the bottom of screen. Rotate the 'Scanning Knob' of the instrument and observe the wave-form on the oscilloscope screen. Adjust the 'Y-gain' and 'X-gain' of oscilloscope to make wave-form clear and Y amplitude moderate. Rotate the scanning potentiometer clockwise to end. Then the maximum scan voltage is 85V. Measure the horizontal distance between the peaks. The distance of two consecutive peaks (count the grids) and multiply it by V/grid factor (X-gain) of oscilloscope. This would give the value of argon atom's first excitation potential in eV.

PRECAUTION

1) Before taking the systematic readings, gradually increase the value of V_{G2k} to a maximum. Adjust the filament voltage if required such that max. readings is about 1000 on $X10^{-8}$ range. This will insure that all the readings could be taken in the same range.

2) During the experiment (manual), when the voltage is over 60V, please pay attention to the output current indicator, If the ammeter reading increases suddenly, decrease the voltage at once to avoid the damage of the tube.

3) Whenever the Filament Voltage is changed, please allow 2/3 minutes for its stabilisation.

4) **When the Frank-Hertz Tube is already in the socket, please make sure the following before the power is switched 'ON' or 'OFF', to avoid damage to the tube.**

   a) Manual - Auto switch is on Manual and Scanning and Filament Voltage knob at its minimum position (rotate it anticlockwise) and Current Multiplier knob at 10^{-7}.

   b) V_{G_1K}, V_{G_2A}, and V_{G_2K} all the three knobs are at their minimum position.