Electron energy loss investigated through the Nobel Prize winning Franck-Hertz Experiment

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Quantum mechanics has come a long way since Planck introduced the idea of quantization of energy in 1900. Later, Bohr proposed his theory of atomic structure also based on quantization, positioning electrons in discrete orbits around the nucleus, called *energy levels*. This discretization of energy levels within an atom can be observed in various ways. Franck-Hertz's classic experiment is one such technique. It was first performed in 1914 by German physicists James Franck and Gustav Ludwig Hertz aimed at experimentally probing Bohr's model of the atom. The experiment won the 1925 Nobel Prize in Physics for elegantly validating Bohr's hypothesis and for its contribution towards the understanding of quantum theory and atomic structure.

KEYWORDS

Elastic collision · inelastic collision · cathode · gate · collector · first excitation energy · mean free path · accelerating potential · collisional cross section.

1   Objectives

In this experiment, we will:

1. understand the difference between elastic and inelastic collisions between subatomic particles,

2. learn how the energy of a free electron can be controlled by maintaining an electric field,

3. indirectly observe the discrete nature of energy levels in an atom, and

4. finally, we will perform a Nobel prize winning experiment, which is considered to be a landmark in the history of modern physics.

References and Essential Reading

[1] Adrian C. Melissinos, Jim Napolitano, "Experiments in Modern Physics", Academic Press, 2003, pp. 10-19.

[2] John R. Taylor, Chris D. Zafiratos, Michael A. Dubson, "Modern Physics for Scientists and Engineers", 2nd Edition, Pearson Education, Inc., 2007, pp. 97-102, 162-164.

[3] G. Rapior, K. Sengstock and V. Baev, "New features of the Franck-Hertz experiment", Am. J. Phys. 74 (5), 2006.

2 Introduction

Q 1. Can you recall a daily-life phenomenon that is a direct result of discretization of energy?

It is well known since the time of Niels Bohr that the electrons revolve around the nucleus only in discrete orbits and their energy is quantized. From magnetism to street lights filled with sodium, it is the quantized structure of atom at play. The Franck-Hertz experiment employs a simple method to demonstrate this fact. Franck and Hertz were awarded the 1925 Nobel prize in physics for the contribution that their experiment made to the understanding of quantum structure of the atom.

2.1 Observing quantization

To observe an evidence of quantization of the energy levels of an atom, any process that transfers energy to an atom, or detects the energy emitted from it, is suitable. Energy that is absorbed or emitted in discrete amounts implies some sort of quantization. In the case of the Franck-Hertz experiment, energy transfer to atoms is achieved by letting them collide with electrons that are being accelerated in an electric field. These collisions may be of two types: elastic and inelastic collisions [2].

2.1.1 Elastic collisions

In an elastic collision between an electron and an atom, the electron is deflected away and the incident kinetic energy is subsequently shared by the deflected electron and the atom that is hit by the electron. These types of collisions are dominant when the impinging electrons have energies lesser than the minimum amount of energy needed to excite an atom (smaller than the first excitation energy).

Q 2. When an electron, with initial kinetic energy K_0, scatters elastically from a stationary atom, there is no loss of total kinetic energy. Nevertheless, the electron loses a little kinetic energy to the recoil of the atom. (a) Use conservation of momentum and kinetic energy to prove that the maximum kinetic energy of the recoiling atom is approximately $(4m/M)K_0$, where m and M are the masses of the electron and atom. The collision is one dimensional.

(b) If a 3 eV electron collides elastically with a mercury atom, what is its maximum possible loss of kinetic energy? (Your answer should convince you that it is a good approximation to say that the electrons in the Franck Hertz experiment lose no kinetic energy in elastic collisions with atoms.)

Q 3. If the first excitation energy of mercury is 5.0 eV, how much energy will an electron with 4.0 eV of kinetic energy transfer to a mercury atom?

Before collision

K_{ei}

Electron

Atom

After collision

K_{ef}

Electron

K_{af}

Atom

Elastic collision: K_{ei} = K_{ef} + K_{af}

K_{ei}

Electron

Atom

K_{ef}

Electron

E

Atom

Inelastic collision: K_{ei} = K_{ef} + E
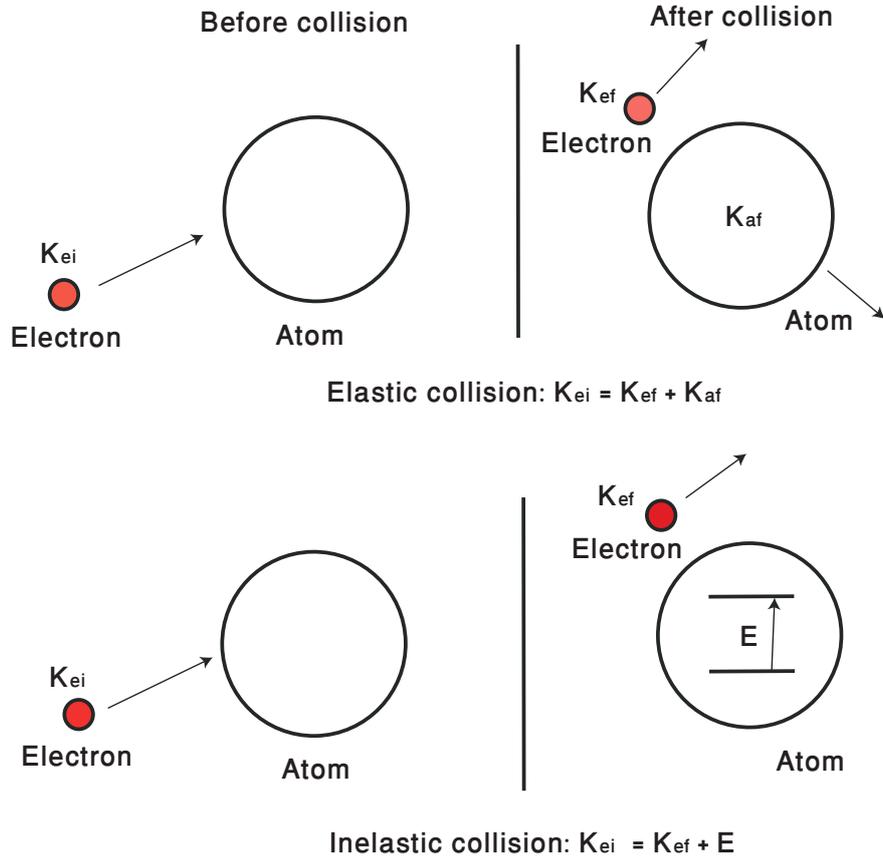
Figure 1: Kinetic energy is conserved in elastic collisions, while in inelastic collisions a part of it is used in exciting an electron in the atom. K_a and K_e is the kinetic energy of the atom and electron respectively, while the subscripts i (initial) and f (final) refere to before and after the collision. We assume that the atom is at rest before the collision.

2.1.2 Inelastic collisions

When an electron collides with an atom inelastically, it imparts a significant amount of its energy to the atom resulting in excitation of the electrons of the atom to a higher energy level. As the description suggests, this happens only when the incident electron has an energy more than, or at least equal to, the first excitation energy of the atom.

If the energy of the incident electron is denoted by K_{ei} and the first excitation energy of the atom as $E = E_2 - E_1$ (where E_1 and E_2 denote the energies of the first and the second energy levels respectively), collisions will be elastic with high probability when $K_{ei} < E$ and inelastic when $K_{ei} \geq E$ respectively. These two kind of processes are illustrated in Figure (1).

3   Preparation for the Experiment

3.1   The Franck-Hertz experimental arrangement

The Franck Hertz setup consists of a glass tube filled with mercury vapor and fitted with three electrodes: a thermionic tube with a cathode, an anode (also called gate or grid) and collector (counter electrode), as shown in Figure 2. By heating the filament, electrons are emitting
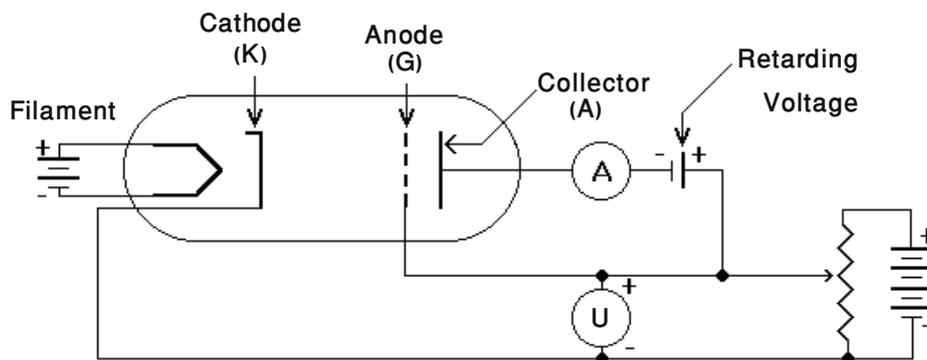
Figure 2: Schematic diagram of the Franck-Hertz tube.

thermionically, which pass through the cathode (K) and are then accelerated by the anode (G) that is kept at a positive potential with respect to the cathode. The anode is perforated and the electrons pass through it to be collected at the collector (A). As the accelerating potential increases, the number of electrons reaching the gate increases and so does the current between the cathode and collector. Remember that electrons may be colliding with the mercury atoms present inside the tube, but the collisions will be elastic as long as the accelerating potential is less than the first excitation potential of mercury.

Q 4. Write down the expression for energy of an electron inside an electric field. If the electron is free to move, what type of energy does it possess?

Q 5. Increasing the accelerating potential increases the kinetic energy of the electrons. Is this the reason that collector current also increases? If not, identify the cause for this increase in current with increasing accelerating potential.

When the accelerating potential is increased and reaches the first excitation potential E_1, then the electrons have just enough energy to excite the mercury atoms from the ground state ($^1S_0$) to an excited state ($^3P_0$), ($^3P_1$) or ($^3P_2$). Inelastic collisions commence due to which many electrons lose their energy and cannot reach the collector. At this point, there is an abrupt drop of collector current as the number of electrons reaching the collector sharply decreases.

A series of peaks (dips) is observed as the voltage is continually increased (Figure 3). The first peak at E_1 is displaced by the contact potentials in the system from its expected value. Due to this displacement the absolute value E_1 is not the exact excitation potential.

Q 6. How can you explain the repetition of dips in current in Figure 3? Discuss with the lab demonstrator.

4 The Experiment

Figure 5 shows the apparatus used for Franck-Hertz experiment. It consists of a Franck-Hertz tube and an electronic control and monitoring unit (TEL-Atomic Inc.) that is used to provide the required voltages and measure the resulting current through the tube by converting it to a voltage and then amplifying it. A schematic of the components of the control and monitoring unit is shown in Fig. (6). To observe and record the measurements, a 60 MHz BK Precision digital storage oscilloscope is interfaced with the computer via a USB cable. The waveforms are displayed in a graphical user interface.
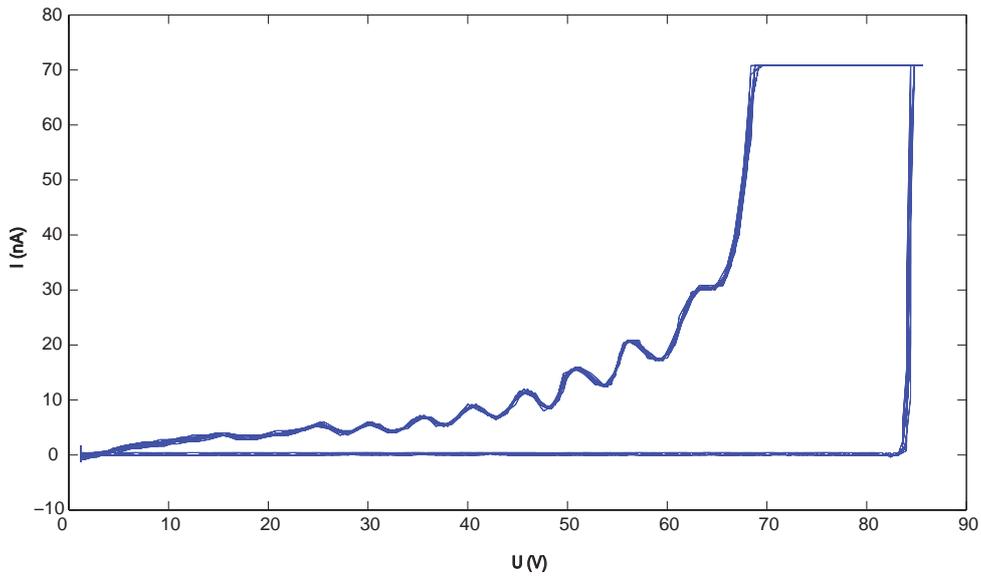
Figure 3: Anode (grid) potential U vs. cathode-collector current I. Periodic dips in the current are observable at 170 °C . The separation between the dips is a measure of the first excitation potential.
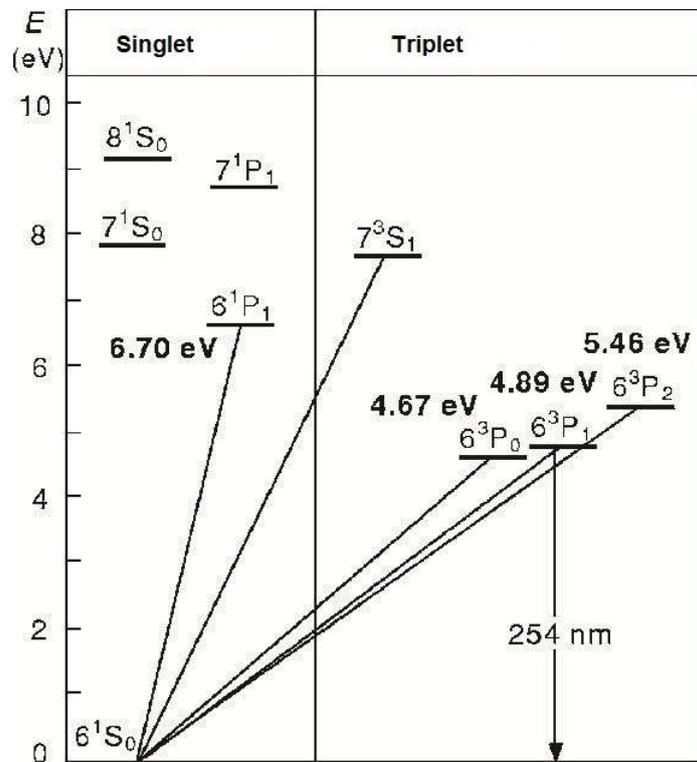
Figure 4: Energy level diagram of mercury [3]. The first excited state comprises three states denoted as 6^3P_0, 6^3P_1 and 6^3P_2.
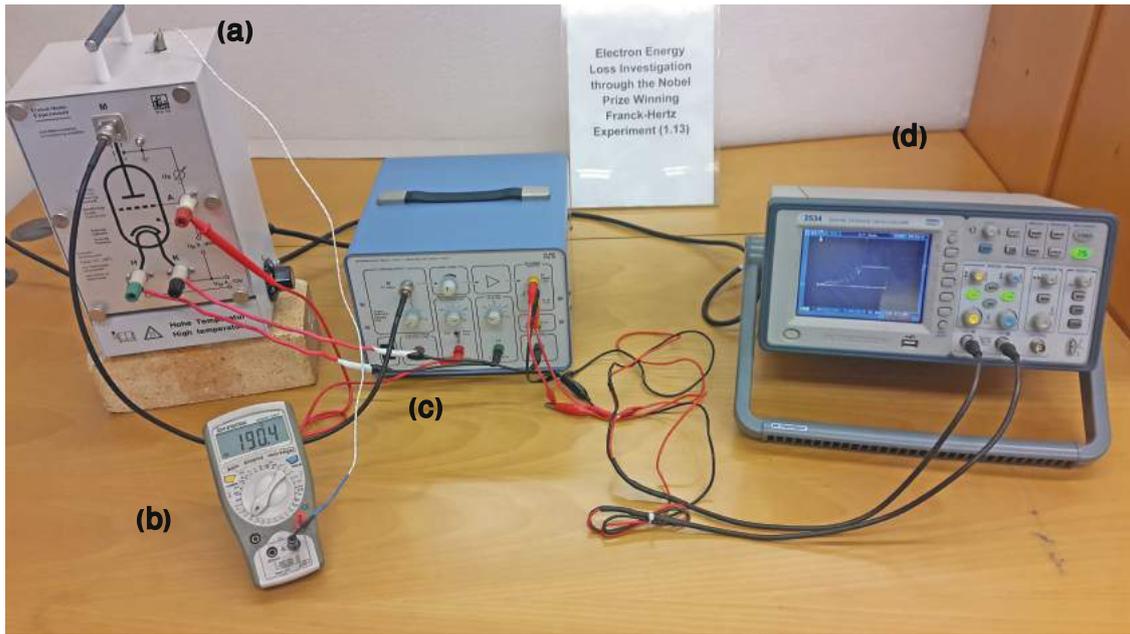
Figure 5: An overall view of the Franck-Hertz apparatus. (a) Franck-Hertz tube, (b) temperature monitor, (c) control and monitoring unit, (d) digital oscilloscope.
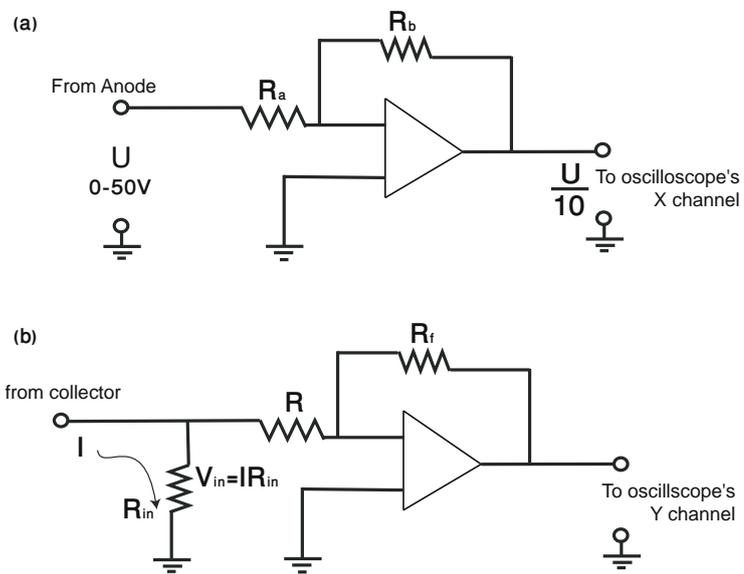
Figure 6: A schematic of electronic control and monitoring unit. (a) shows the accelerating potential scaling circuit of the control and monitoring unit while (b) shows the current measurement branch that converts the collector current into a voltage and then amplifies it.
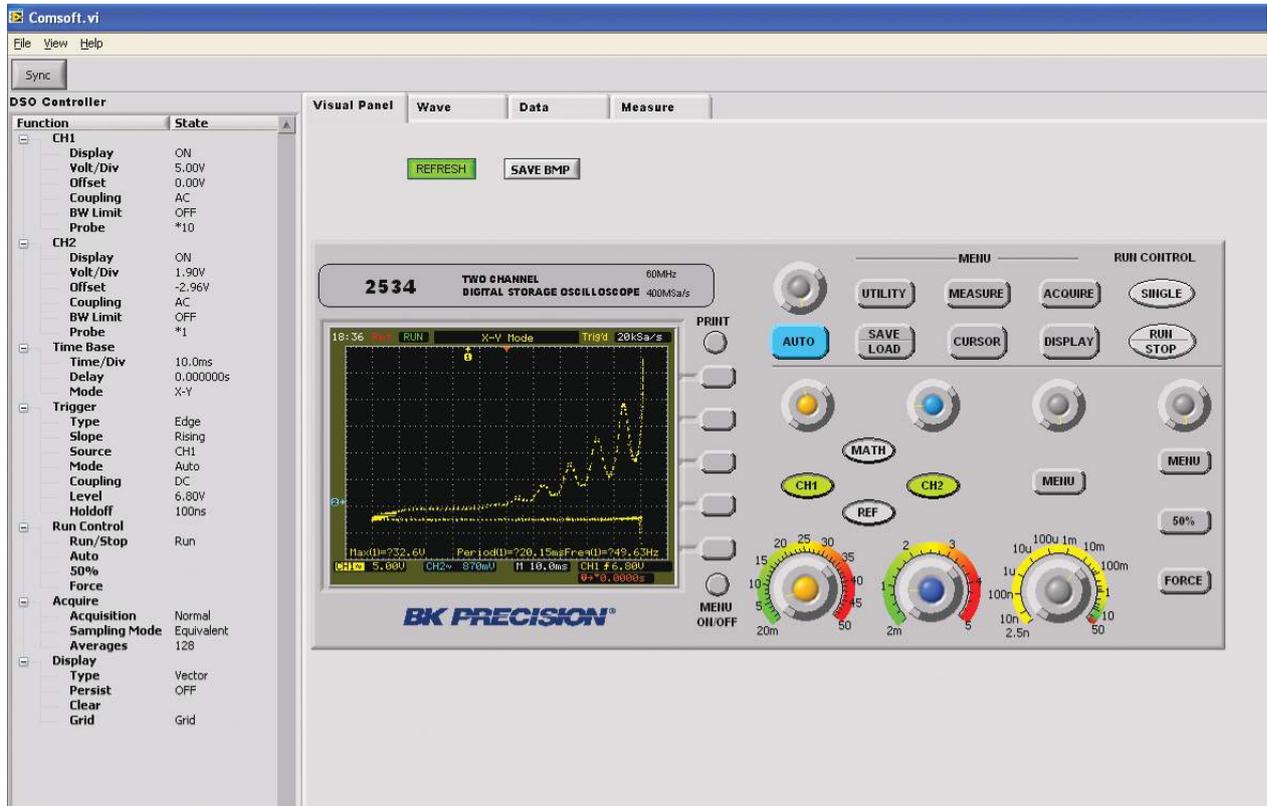
Figure 7: Comsoft GUI. You can switch between scope and X-Y mode using the virtual controls and use the tabs on the top to see the data as a waveform or a table.

4.1 Quantization and first excitation potential

1. Connect the inputs to the Franck-Hertz tube, making sure the correctness of connections from the labels of the terminals. You may consult the copy of the manual of the apparatus. At this juncture, show your connections to the instructor.

2. Connect the two outputs of the control unit to the two channels of the oscilloscope according to the indications on the panel of the unit.

3. Keeping the power supply to the control unit off, switch on the heater power, adjust the temperature dial on the tube casing to 180 °C and wait for about half an hour.

4. Don't heat above 200 °C. Turn off thermostat if temperature raises above 200 °C.

   Q 7. Why is it necessary to heat the tube? Why can't the experiment be done at room temperature?

5. Turn all the controls to the minimum and switch on the control unit. Now increase the heater current to 6 mA and the accelerating potential to about 30 V, keeping the select switch at "Ramp 60 Hz".

6. Start the **Comsoft.vi** program on your computer. Your output should look similar to Figure 7 once you configure the scope to XY mode.

   Remember don't heat above 200 °C. Turn off thermostat if temperature raises above 200 °C.

   Q 8. Explain the output. How many dips do you see? What does each dip correspond to?

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7. Measure the first excitation potential of mercury from the graph. Also express the first excitation energy in Joules.

4.2 Temperature dependence and mean free path

Q 9. What kind of changes in Franck-Hertz graph are expected due to temperature variation? What will happen to the mean free path of the electrons with increase or decrease in temperature?

1. Let the tube heat up to 200 °C and wait until the response has stabilized.

2. Allow the tube to cool down and record your observations for 180, 170, 160, 150 and 140 °C. You should be able to interpret the variations in terms of the electron's mean free path. You will be assessed on the basis of the soundness of a logical argument, not necessarily quantitative.