Experiment 6: The Franck-Hertz Experiment*

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Abstract

In this experiment, you will verify the quantization of atomic energy levels using a Franck-Hertz technique in neon.

1 Introduction

Quantum theory predicts that bound atoms have certain discrete energy states. In 1914, James Franck and Gustav Hertz bombarded mercury atoms with electrons and observed that only discrete amounts of energy were absorbed during inelastic collisions. During such a collision, an electron lost energy to the mercury atom by raising it from a lower to higher energy state. This experiment provided further evidence for the quantization of atomic energy levels.

In the Frank-Hertz (FH) experiment, electrons are thermionically emitted from a cathode filament and accelerated through a rarefied gas[1] towards an anode grid as illustrated in Figure 1. The electrons pass through holes in the anode grid and are then slightly decelerated by a retarding voltage before reaching a collector electrode. Initially, the collisions between electrons and gas atoms occur elastically, without significant energy transfer to the atoms. However, when the accelerating voltage is increased significantly, the electrons kinetic energy is large enough to excite the gas atoms directly in front of the grid anode (the atoms then give off a photon when they de-excite, causing a glowing layer between the cathode and anode). The electrons lose their kinetic energy and can no longer reach the collector electrode against the braking voltage. Thus, the current reading given by the measuring amplifier decreases. When the accelerating voltage is increased further, the collision zone moves closer to the cathode. The electrons braked by collisions are accelerated again. Thus, they can reach the collector electrode until their kinetic energy has become so large they are braked by a second non-elastic collision with a gas atom. This energy transfer recurs periodically with an increasing accelerating voltage.

On the FH curve (see Figure 2), this periodic energy transfer is indicated by the recurrent and equidistant maxima and minima of the collector electrode current as a function of the accelerating

*Adapted from *Operating Instructions for The Franck-Hertz Experiment In Neon No. 32048*, Central Scientific Company.

[1] While the original experiment used a tube containing a drop of mercury that was then heated to produce mercury vapor, we will use a tube filled with neon gas.

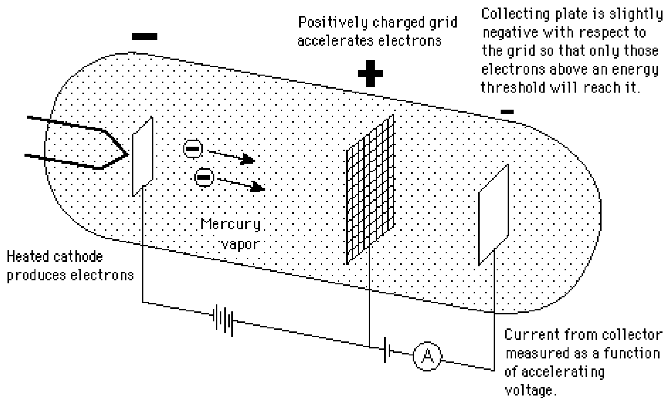

Figure 1: A schematic of the original experiment performed by Franck and Hertz using mercury. The neon tubes used in this experiment are similar.

voltage. The minima are spaced at intervals that are characteristic of the atomic excitation energy of the gas atoms. For neon, three such minima can be observed, corresponding to three distinct glowing layers in the FH tube as in Figure 3.

2 Equipment

The Franck-Hertz Experiment in Neon (No. 32048)	Digital Oscilloscope with X-Y capability
– Neon-filled Fracnk-Hertz tube in housing	Digital Multimeter
– Control unit	BNC to banana connector (2)
– Leads and cables	

Neon Franck-Hertz Tube The connector sockets for the heater, control grid, and anode grid are located in the tube's base plate. Collector current is connected to the amplifiers contained within the control unit via a shielded-BNC cable that connects at the top of the shielding cylinder. A 10 kΩ limiting resistor is permanently installed between the accelerating voltage connector and the tube anode – this serves to protect the tube if it arcs at excessively high voltage. The voltage drop across this resistor can be neglected when measurements are made, since the anode current in the tube is less than 5 μA (so the voltage drop at the protective resistor is about 0.05 V). The neon gas pressure is selected for an optimum characteristic line within production constraints for these tubes.

Control Unit The control unit provides all voltages required for performing the Franck-Hertz experiment. It also contains a highly sensitive DC amplifier for measuring the collector current. The power supply component of the control unit delivers:

- the DC accelerating voltage U_B. When the U_B switch is set to the "Man." position, it is continuously variable (via the acceleration knob) from 0 to 60 V. When the switch is in the sawtooth position, the accelerating voltage ramps from 0 V to the value set by

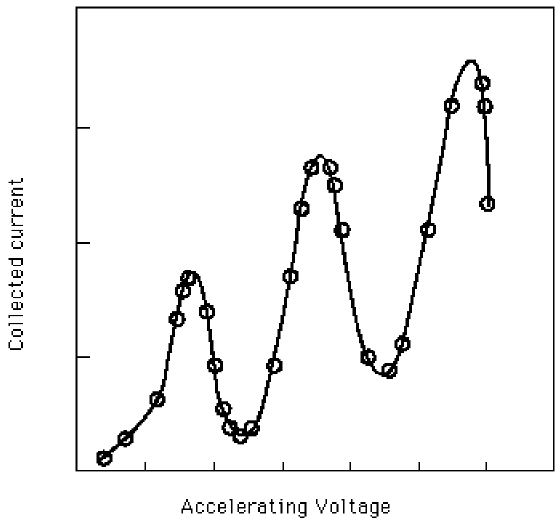

Figure 2: A typical Franck-Hertz collector current versus acceleration voltage curve.

Figure 3: Glow from neon de-excitation.

the acceleration knob repeatedly with a frequency of 60 Hz. This allows the output to be displayed on an oscilloscope with x-y plotting capability.

- the AC filament heating voltage for the tube (labeled U in the "Heater" section of the control unit). The filament voltage is adjustable up to 8 V (or a current of 270-350 mA).
- the opposing voltage (labeled U in the "Reverse Bias" section of the control unit). It is continuously variable from 0 to 1.5 V. Increasing the reverse bias helps to make the FH peaks more distinct when generating a FH curve.
- signal amplification. The DC amplifier included in the control unit consists of two cascaded operational amplifiers (integrated circuits). They serve to amplify the signal and invert it. The output display voltage is proportional to the measured current. A 1-volt output voltage corresponds to a 0.7 μA input current at the minimum sensitivity setting (i.e., the control knob turned to the far left), and to a 7 nA input current at the maximum sensitivity setting (i.e., the control knob turned to the far right).

Digital Oscilloscope The digital oscilloscopes available in the laboratory have x-y plotting capability. That is, they can plot one signal (in our case the voltage at the collector plate – which is directly proportional to the collector current) versus another signal (the acceleration voltage). Refer to the oscilloscope manual for instructions in its usage. (Yes, it will take some getting used to – just remember that it's just a fancy voltmeter.) The oscilloscope must be plotting the collector voltage on the y-axis and the acceleration voltage on the x-axis for this analysis to work.

3 Procedure

Thoroughly read and understand the provided equipment manual *Operating Instructions for The Franck-Hertz Experiment In Neon No. 32048*, Central Scientific Company (hereafter referred to as the *Manual*) before beginning this experiment.

1. Make sure that the power to both the control unit and the oscilloscope are off and that all the knobs on the control unit are fully counterclockwise (their minimum values) before making any connections.

2. Connect the color-coded terminals on the base of the Franck-Hertz (FH) tube to the matching terminals on the control unit. Also, connect the BNC collector plate plug on the top of the tube to the BNC connector M on the control box using the shielded cable provided. None of the operating voltages may be conductively connected to ground, since the experimental apparatus is already grounded through the operating unit.

3. Connect the output terminal "$U_B/10$ x-out" on the control unit to channel 1 on the oscilloscope using a BNC to banana connector. Connect the output terminal "FH Signal y-out" to channel 2 on the oscilloscope using a BNC to banana connector. Ground both oscilloscope channels to the output ground on the control unit.

4. Set the acceleration switch on the control unit to "Man." and turn the heater voltage to about 6 V. Turn on the control unit. Allow the indirectly heated cathode a warm-up time of about 90 seconds before making any observations.

5. Slowly increase the accelerating voltage (starting from 0 V). You should be able to see the progression of glowing regions form as described in Section 1. Increase the accelerating voltage until three distinct glowing regions (and two dark regions) are visible (as in Figure 3). The heating voltage may require adjustment – increasing it will give a larger signal, however, it must be low enough so that no independent discharge occurs for higher acceleration voltages (recognizable by orange/red light between the cathode and control grid).

6. Turn on the oscilloscope. Flip the acceleration switch on the control unit to the sawtooth wave setting. Press the "Display" button on the oscilloscope and put it into x-y mode. Make sure channel 1 (acceleration voltage) is plotted on the x-axis and that channel 2 (collector voltage) is on the y-axis. Use the two voltage scale knobs on the oscilloscope and the reverse bias and amplitude knobs on the control unit to reproduce a plot similar to Figure 2. Your plot should have three minima.

7. Once you have a good plot, push the "Stop" button then the "Cursor/Measure" button on the oscilloscope. Use the reference and difference cursors to determine the difference in accelerating voltage between the beginning of the curve (note that this does not start at zero) and the first minimum, the first and second minima, and the second and third minima. It may require some patience to get the cursors to do what you want. Note that the x and y locations of each cursor are printed on the screen. Record the three voltage differences.

8. Print out your FH curve.

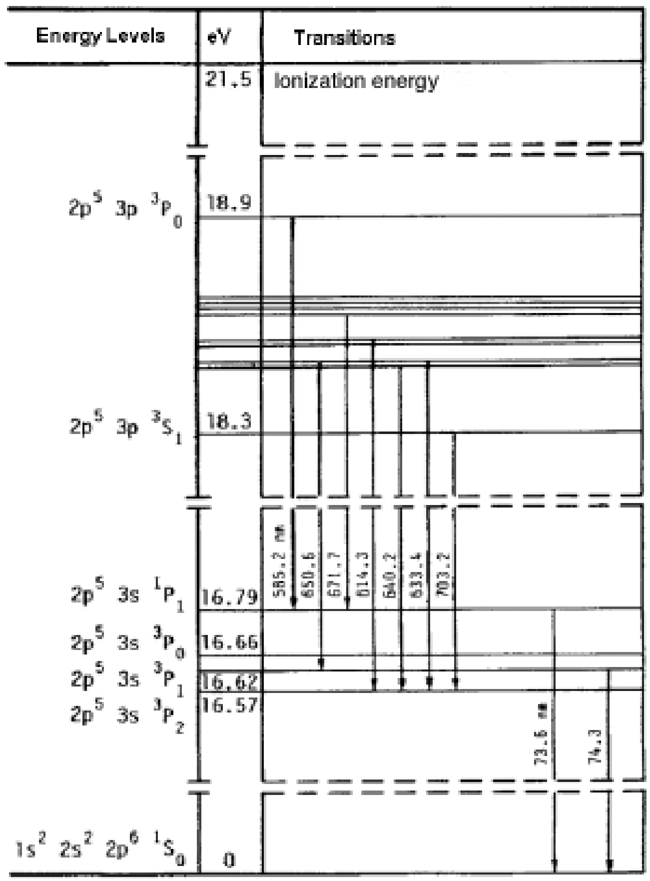

Figure 4: A partial energy diagram for neon.

4 Analysis

1. For exact evaluations of the current/voltage relationship, you must first subtract the iron/barium contact potential of the cathode (2.5 V) from your voltage differences. Now average these three voltage differences. What is the energy of an electron accelerated through this voltage? Is this voltage consistent with the energy diagram for neon given in Figure 4?

   Note that 10 $3p$ states fall within the energy range 18.3-18.9 eV, compared with four $3s$ states between 16.57 and 16.79 eV; furthermore, two of the four $3s$ states are metastable, since the probabilities of optical transitions to the ground state are very small due to the selection rule $J = \pm 1$. The transitions between these two groups of excited states lie in the visible region, and are responsible for the appearance of the glowing layers. The transitions to the ground state lie in the far ultraviolet, and therefore cannot be studied.

2. To verify from the spectrum that the gas filling it is neon vapor, observe the luminous discharge with a handheld spectroscope. Compare this spectrum to the spectrum of a known neon source.

5 Additional Requirements

You should ensure that your laboratory report addresses the following questions.

1. Why is it important to use a monatomic gas in the Franck-Hertz experiments?
2. Why is it necessary to apply a retarding voltage between accelerating grid and the collector?
3. According to basic classical mechanics, when an electron collides elastically with a neon atom, what will happen to the atom? To the electron? Should we expect the gas to heat up greatly? What sort of signal would you expect in this experiment if it behaved classically?
4. It is known that the ionization potential of neon atoms 21.6 eV. Why is it possible to apply a greater accelerating voltage (such that you can observe the second and third peaks) during your Franck-Hertz experiments without ionization of the gas?
5. What is the difference between a Franck-Hertz tube and an X-ray tube? Please, answer in terms of (a) physics, (b) operating parameters, and (c) design.