

# Exp5 Franck-Hertz

## Introduction

In 1914, F. Franck and G. Hertz performed a landmark experiment, providing important empirical support for Max Planck's quantum theory and for the model of the atom suggested by Niels Bohr. Through the study of collisions between electrons and gas molecules, Franck and Hertz demonstrated that energy is indeed quantized in atomic interactions. For this work, they shared the 1925 Nobel Prize in physics. Because of the importance of their experiment, and because of its conceptual simplicity, it has become an important experiment in the undergraduate laboratory.

A simplified diagram of the Franck-Hertz experiment is shown in Figure 1. In an oven-heated vacuum tube containing mercury gas, electrons are emitted by a heated cathode, and are then accelerated toward a grid that is at a potential  $V_a$  relative to the cathode. Just beyond the grid is an anode, which is at a slightly lower potential than that of the grid ( $V_p = V_a - \Delta V$ ;  $\Delta V = 1.5V$ ; where  $V_p$  is the anode potential, and  $V_a$  is the grid potential.).

If the accelerated electrons have sufficient energy when they reach the grid, some of them will pass through and will reach the anode. They will be measured as current  $I_c$  by the ammeter. If the electrons don't have sufficient energy when they reach the grid, they will be slowed by  $\Delta V$ , and will fall back onto the grid. Whether the electrons have sufficient energy to reach the anode depends on three factors; the

accelerating potential ( $V_a$ ), the opposing potential ( $\Delta V$ ), and the nature of the collisions between the electrons and the gas molecules in the tube. As long as the electron/molecule collisions are elastic, the collector current depends only on  $V_a$  and  $\Delta V$  because the electrons lose no energy to the gas. However, Franck and Hertz discovered that  $I_c$  went through a series of maxima and minima as the accelerating potential was varied. This implies that the gas molecules absorb energy from the electrons only at specific electron energies (resonant energies).

For example, the first excited state of mercury is  $4.9eV$  above the ground state. This is the minimum amount of energy that the mercury atoms can absorb in collisions with the accelerated electrons. When  $V_a$  is less than  $4.9eV$ , the electron/molecule collisions are therefore elastic, so the electrons lose no energy to the gas and arrive at the grid with kinetic energy equal to  $eV_a$ . If  $V_a > \Delta V$ , the electrons have sufficient energy to overcome the opposing voltage, and many of them will pass through the grid and reach the anode, to be measured as current. However, if  $V_a$  equals  $4.9V$ , the electrons gain enough kinetic energy to collide inelastically with the mercury atoms just as they reach the grid. In these collisions, the mercury atoms absorb the full  $4.9eV$  carried by the electrons. The electrons no longer have sufficient energy to overcome  $\Delta V$ , and they fall back onto the grid.  $I_c$  is then a minimum. As  $V_a$  is raised beyond  $4.9V$ ,  $I_c$  increases

again. However, when  $V_g$  reaches 9.8V, the electrons can lose all their energy to the gas molecules in two collisions. One collision is likely to occur midway between the cathode and the grid, the other will occur just as the electrons reach the grid. Again, the electrons lose all their kinetic energy in the inelastic collisions, so they fall back onto the grid, and  $I_c$  again falls to a minimum. Because of multiple inelastic collisions between the accelerated electrons and the mercury atoms, current minima are found whenever  $V_a$  is a multiple of 4.9 V.

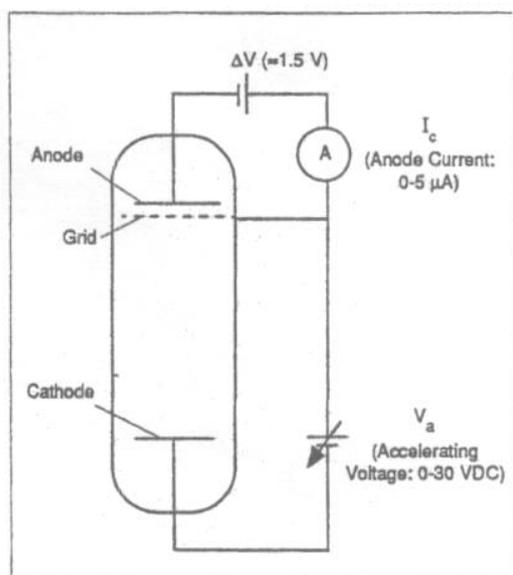


Figure 1 Simplified Diagram of Franck-Hertz Experiment

Note: The above description is somewhat simplified. Due to contact potentials, the total energy gain of the electrons is not quite equal to. Therefore, will be somewhat higher than 4.9 eV when the first current minimum occurs. However, the contact potentials are a constant in the experiment, so at successive current minima will always be a multiple of 4.9V higher than it was when the first current minimum occurred.

## The Franck-Hertz Apparatus

### Required Equipment

In order to perform the Franck-Hertz experiment, you'll need the following equipment:

- SE-9640 Franck-Hertz Tube (Hg)
- SE-9641 Franck-Hertz Oven
- SE-9642 Franck-Hertz Control Unit
- Thermometer (to 200°C)
- One of the following
  - an oscilloscope or
  - a voltmeter with 0-3 V and 0-100 VDC ranges, with a resolution of 0.1mV

### Above the Franck-Hertz Apparatus

The SE-9640 Franck-Hertz Tube (Hg) is a three-electrode tube with an indirectly heated oxide-coated cathode, a grid and an anode. The distance between the grid and the cathode is 8mm, which is large compared with the mean free path of the electrons at normal experimental temperatures (=180°C). This ensures a high collision probability between the electrons and the mercury gas molecules. The distance between the grid and anode is small, to minimized electron/gas collisions beyond the grid. The tube contains a drop of highly purified mercury. A 10KΩ current limiting resistor is permanently incorporated between the connecting socket for the accelerating voltage and the grid of the tube. This resistor protects the tube in case a main discharge strikes in it when excessively high voltage is applied. For Norman measurements the voltage drop across this safe resistor may be ignored, because the working anode current of the tube is smaller than 5μA (voltage drop across the safety resistor less than 0.05V). The tube is mounted to a plate which

mounts, in turn, onto one wall of the SE-9641 Franck-Hertz Oven (see Figures 2).

The SE-9641 Franck-Hertz Oven is a 400watt, thermostatically controlled heater used to vaporize the mercury in the Franck-Hertz tube.

The SE-9642 Franck-Hertz Control Unit provides all the necessary voltages for powering the mercury vapor tube. It also includes a highly sensitive DC amplifier for measuring the collector current. The front panel control designations are shown in Figure 3. Instructions for using it are provided later in the manual.

### **Important Cautions and Tips**

The basic procedure for the Franck-Hertz experiment is straightforward:

1. Heat up the tube to approximately 170°C.
2. Apply the heater voltage to the cathode (wait 90 seconds for the cathode to heat).
3. Apply an opposing voltage (approximately 1.5 volts) between the grid and the anode.
4. Slowly raise the accelerating voltage (between the cathode and the grid) from 0V to about 30V. Monitor the tube current to locate the potentials at which the current drops to a minimum.

### **Important Please read before using the Franck-hertz Apparatus:**

When you are performing the experiment using the Control Unit, or using separate power supplies, the following guidelines will help protect you and the equipment. They will also help you get good results.

#### **To Avoid Burns:**

1. The outside of the Franck-Hertz Oven gets very hot. Do not touch the oven when it is operating, except by the handle.

#### **To Protect the Oven:**

2. Be sure the power to the oven is ac and is equal to the rated voltage for the oven. A dc power supply, or excessive ac power, will produce arcing that will damage the bimetal contacts of the thermostat.

#### **To protect the Tube:**

3. Always operate the tube between 150°C and 200°C. Never heat the tube beyond 205°C.
4. Always use a thermometer to monitor the oven temperature. The thermostat dial gives the temperature in °C, but the reading is only approximate.
5. Turn on the oven and allow the tube to warm up for 10-15 minutes (to approximately 170°C) **BEFORE** applying any voltages to the tube.

Explanation: When the tube cools after each use, mercury can settle between the electrodes, producing a short circuit. This mercury should be vaporized by heating before voltages are applied.

6. When possible, do not leave the tube in a hot oven for hours on end, as the vacuum seal of the tube can be damaged by outgassing metal and glass parts

If the tube is left in a hot oven for a lengthy period of time, heat the cathode for approximately two minutes, and then apply an accelerating potential of approximately 5 volts to the grid before turning off the oven. This will prolong the life of the cathode.

#### **To Ensure Accurate Results:**

7. Use a shielded cable to connect the anode of the tube to the amplifier input of the control Unit.
8. After heating the tube in the oven, apply the

heater voltage to the cathode, and allow the cathode to warm up for at least 90 seconds before applying the accelerating voltage and making measurements.

#### 9. Minimizing Ionization

Ionization of the mercury gas within the tube can obscure the results of the experiment, and, if severe, can even damage the tube. To minimize ionization, the tube temperatures should be between 150°C and 200°C, and the accelerating potential (between the cathode and the grid) should be no more than 30V.

Even if ionization is not severe enough to damage the tube, the positive Mercury ions will create a space charge that will affect the acceleration of the electrons between the cathode and the grid. This can mask the resonance absorption that you are trying to investigate.

Ionization is evidenced by a bluish-green glow between the cathode and the grid. In fact, if ionization occurs, the side of the grid facing the cathode will have a blue-green coating, and the cathode will have a bright blue spot on its center. If this happens, lower the accelerating potential and check the tube temperature before proceeding.

Causes and Dangers of Ionization: If the tube temperature is too low, the mercury vapor pressure will be low, and the mean free path of the electrons in the tube will be excessive. In this case, the accelerated electrons may accumulate more than 4.9eV of kinetic energy before colliding with Mercury atoms. This can lead to ionization of the mercury gas, which can increase the pressure inside the tube, and damage the

vacuum seal.

If the tube temperature is too high, ionization can occur due to interactions between the Mercury ions themselves. Again, pressure will be excessive and the tube can be damaged.

If the accelerating voltage is too high, the electrons can still gain excessive energy before striking Mercury atoms, even if the temperature is correct, and the same problem can occur.

### **How the Tube Should Look During the Experiment**

When the tube is properly heated and the accelerating voltage is within the proper range, there will be a deep blue cloud between the cathode and the grid (as opposed to the blue-green glow caused by ionization). You should see dark bands forming near the grid and moving towards the cathode as the accelerating voltage is increased. These bands are the regions in the tube where the electrons are colliding inelastically with the gas, raising the mercury atoms to their first level of excitation. The blue light is caused by the emission of a photon as the atoms return to the ground state

$$(E_{\text{photon}} = 4.9\text{eV}; \lambda_{\text{photon}} = 254\text{nm}).$$

### **The Experiment: Setup, Operation, and Analysis**

The Franck-Hertz experiment can be performed using lots of different setups, and we put one of them below:

### **Using the Control Unit and with the**

### assistant of computer

1. Set the front panel with the Franck-hertz Tube as shown in Figure 4 but all the voltmeters are replaced by digital voltmeters and connect them to the computer.
2. Insert a centigrade thermometer (0-200°C) into the hole in the top of the oven. Insert it so the tip of the thermometer is near the center of the tube.
3. Check the label and plug the oven into an appropriate AC power outlet, then turn the thermostat dial to 180°C. Let the oven heat up for 10-15 minutes. Keep an eye on the thermometer. Do not let the oven temperature exceed 205°C.
4. Connect the tube, control unit, and digital voltmeters as shown in Figure 4.
5. Switch on the control unit, but only **AFTER** the tube has warmed up for 10-15 minutes.

Initially, set the controls as follows:

Heater:	Midrange (about 5.5V)
Amplitude:	Gain – Middle gain
Reverse bias:	about 1.5V
V <sub>a</sub> :	Zero – midrange
	Switch – Main (--)
	Adjust – zero (fully counterclockwise)

6. Allow at least 90 seconds for the cathode to heat up.
7. Increase the accelerating voltage in increments of about 0.5 volts, by turning the V<sub>a</sub> adjust knob clockwise. At each value of V<sub>a</sub> and the corresponding value for the amplifier output V<sub>F</sub> should be recorded by computer.

Note: the amplifier output V <sub>F</sub> is a voltage proportional to I <sub>c</sub> .
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8. Change the temperature from 160 °C to 180

°C by degrees of 10 °C, and follow steps form 1. to 7.

### Analyzing and data fig of this Experiment

In performing the experiment, you will have collected values of V<sub>a</sub> and corresponding values of V<sub>F</sub> to analyze this data:

1. Subtract 2.0 volts from each of your recorded values for V and record these values as V<sub>a</sub> in your data table. V<sub>a</sub> is proportional to the energy supplied to the electrons by the field between the cathode and the grid.

Explanation: The electrons emitted by the cathode lose a certain amount of energy in escaping and gain some energy when they are absorbed into the plate. The net energy lost or gained in this transition is just the difference between the work function of the two metals.

In this case the electrons lose approximately 2.0eV. this energy can be accounted for by subtracting 2.0 volts from the measured values of V<sub>a</sub>.

2. You should find that the current minima are spaced at intervals of 4.9 volts, showing that the excitation energy of the mercury atom is 4.9eV. The spectral frequency corresponding to this energy is:

$$\nu = \frac{E}{h} = \frac{4.9eV}{4.133 \times 10^{-15} eV} = 1.18 \times 10^{15} Hz$$

3. The corresponding wavelength is:

$$\lambda = \frac{c}{\nu} = 253.7nm.$$

4. Collect data from different temperatures and plot the figure of V<sub>F</sub> v.s. V<sub>a</sub> (as Fig 5.).

Compare the presentations and discuss why.

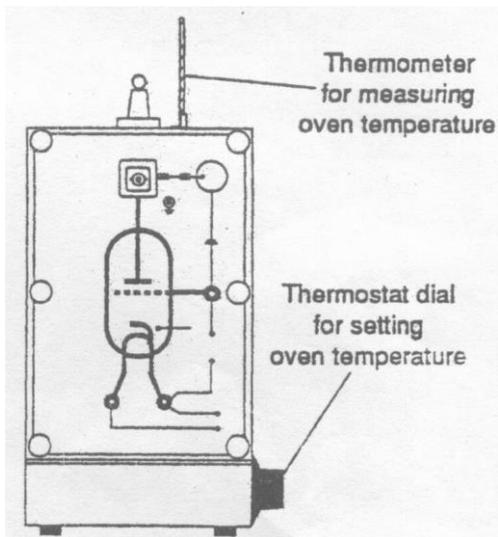


Figure 2. Franck-Hertz tube



Figure 3. Franck-Hertz Control Unit

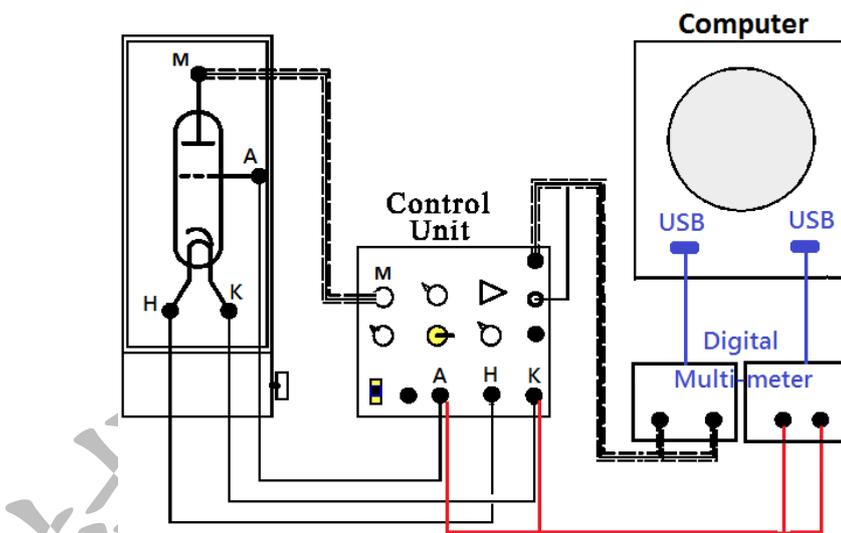


Figure 4. Franck-Hertz Experiment Using Computer

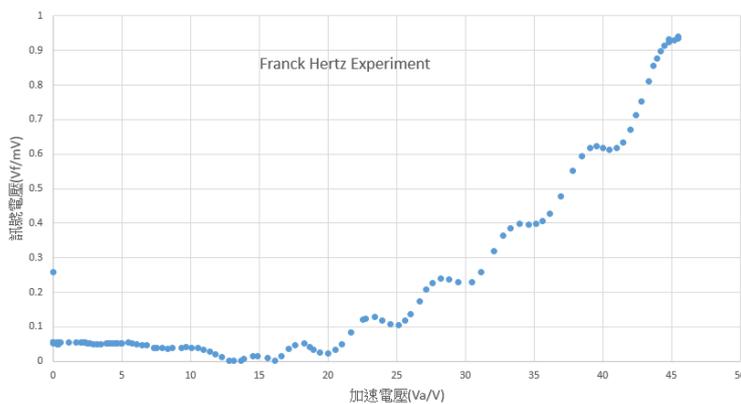


Figure 5. Result sample for Franck-Hertz Experiment