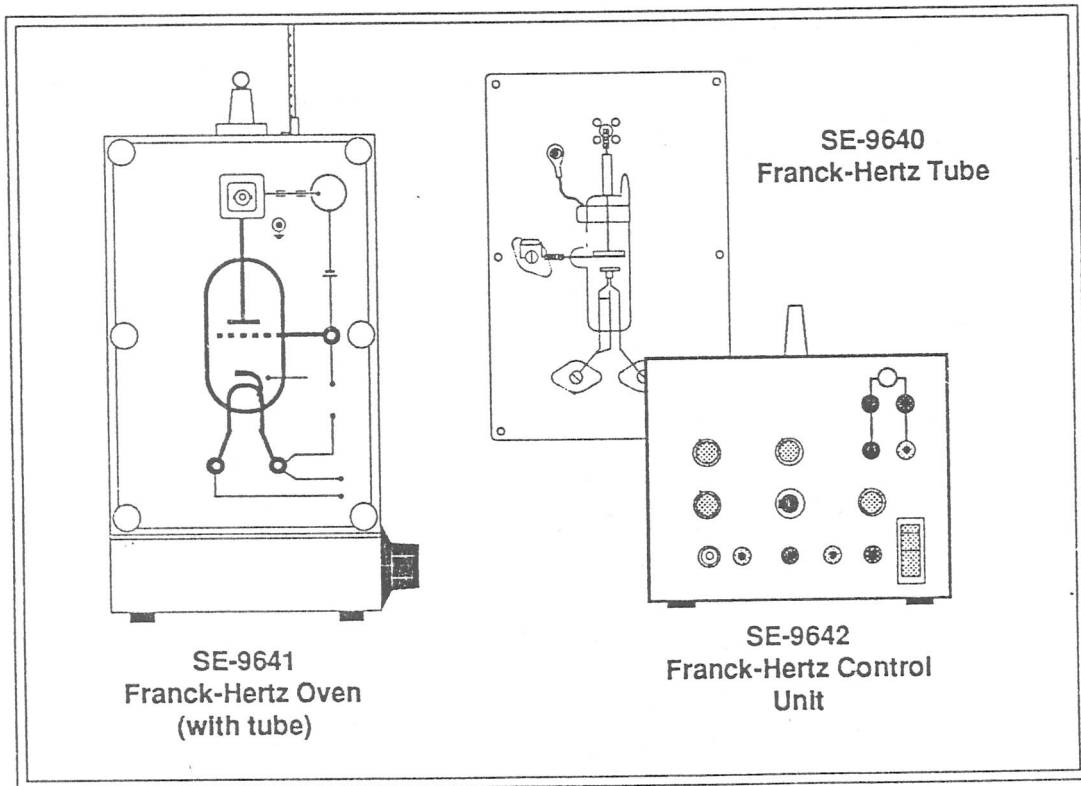


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**Instruction Manual
and Experiment Guide
for the PASCO scientific
Model SE-9640 Franck-Hertz Tube
Model SE-9641 Franck-Hertz Oven
Model SE-9642 Franck-Hertz Control Unit**

Franck-Hertz Experiment



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\$5.00



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NOTE: NO EQUIPMENT WILL BE ACCEPTED FOR RETURN WITHOUT AN AUTHORIZATION.

When returning equipment for repair, the units must be packed properly. Carriers will not accept responsibility for damage caused by improper packing. To be certain the unit

will not be damaged in shipment, observe the following rules:

1. The carton must be strong enough for the item shipped.
2. Make certain there is at least two inches of packing material between any point on the apparatus and the inside walls of the carton.
3. Make certain that the packing material can not shift in the box, or become compressed, thus letting the instrument come in contact with the edge of the box.

Introduction

In 1914, J. 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 ($V_p = V_a - \Delta V$; $\Delta V \approx 1.5$ V; 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 ΔV , 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 (ΔV), 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 ΔV , 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 4.9 eV 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 4.9 V, 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 4.9 V, 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 4.9 eV

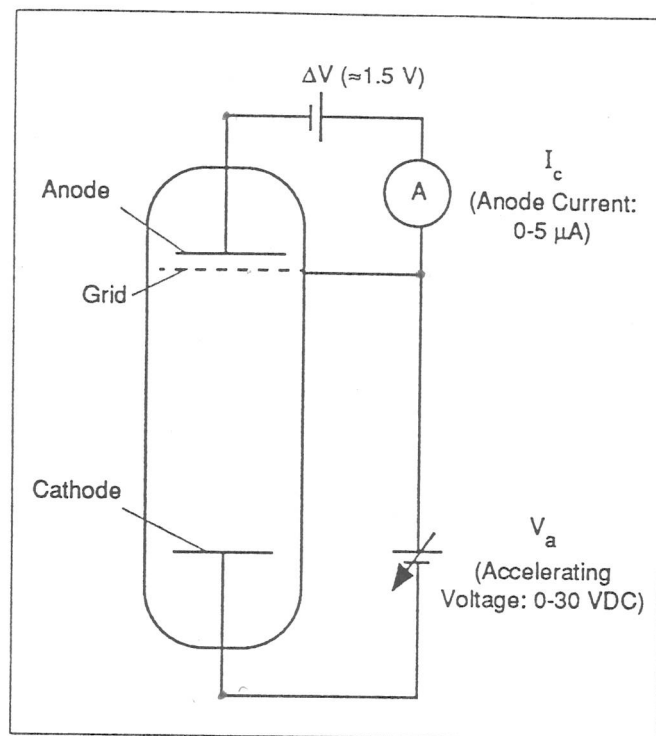


Figure 1 Simplified Diagram of Franck-Hertz Experiment

carried by the electrons. The electrons no longer have sufficient energy to overcome ΔV , and they fall back onto the grid. I_c is then a minimum.

As V_a is raised beyond 4.9 V, I_c increases again. However, when V_a reaches 9.8 V, 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.

Note: The above description is somewhat simplified. Due to contact potentials, the total energy gain of the electrons is not quite equal to eV_a . Therefore, V_a will be somewhat higher than 4.9 V when the first current minimum occurs. However, the contact potentials are a constant in the experiment, so at successive current minima V_a will always be a multiple of 4.9 V 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 (e.g., PASCO models SB-9591 or SE-9533), or
 - a voltmeter with 0-3 V and 0-100 VDC ranges, with a resolution of 0.1 mV (such as PASCO models SB-9599 or SE-9547).

The experiment can also be performed without the SE-9642 Franck-Hertz Control Unit. To perform the experiment without the control unit, you'll need the following:

- SE-9640 Franck-Hertz Tube (Hg)
- SE-9641 Franck-Hertz Oven
- Power supplies to provide the following tube voltages:
 - Heater Voltage, 0-6.3 VDC or AC (e.g., PASCO model SF-9585 High Voltage Power Supply).
 - Accelerating Voltage, 0-30 VDC (e.g., PASCO model SF-9585).
 - Opposing Voltage, 0-1.5 VDC (e.g., a battery or the PASCO model SF-9584 Low Voltage Power Supply or the PI-9595 Student Lab Power Supply).
- Thermometer (to 200 °C)
- Ammeter with sensitivity to 10pA
(a voltmeter with a 10 M Ω input impedance and 0.1 mV resolution can be used in place of the ammeter—see the section on *Setup and Operation*)
- Shielded cable with a BNC connector.

About 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 8 mm, which is large compared with the mean free path of the electrons at normal experimental temperatures ($\approx 180^\circ\text{C}$). This ensures a high collision probability between the electrons and the mercury gas molecules. The distance between the grid and the anode is small, to minimize electron/gas collisions beyond the grid. The tube contains a drop of highly purified mercury. A 10 k Ω 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 normal measurements the voltage drop across this safe resistor may be ignored, because the working anode current of the tube is smaller than 5 μA (voltage drop across the safety resistor less than 0.05 V). The tube is mounted to a

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

The SE-9641 Franck-Hertz Oven is a 400 watt, 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.

Caution: Even if you are familiar with the experiment, please read the section *Important Cautions and Tips* before using the equipment. A few simple rules can save you the cost of a blown tube.

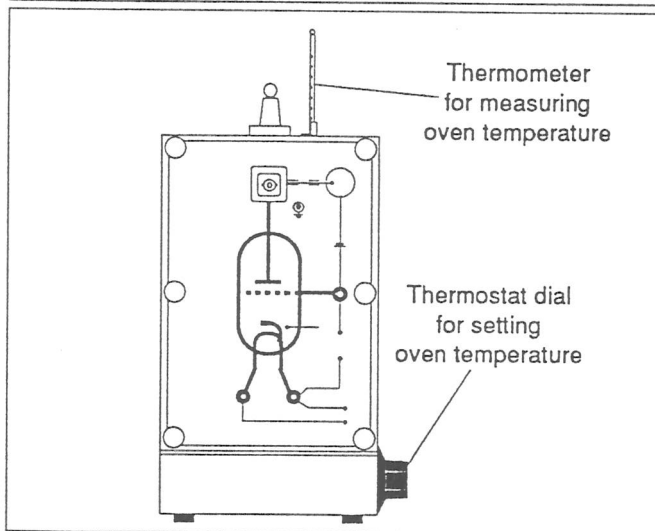
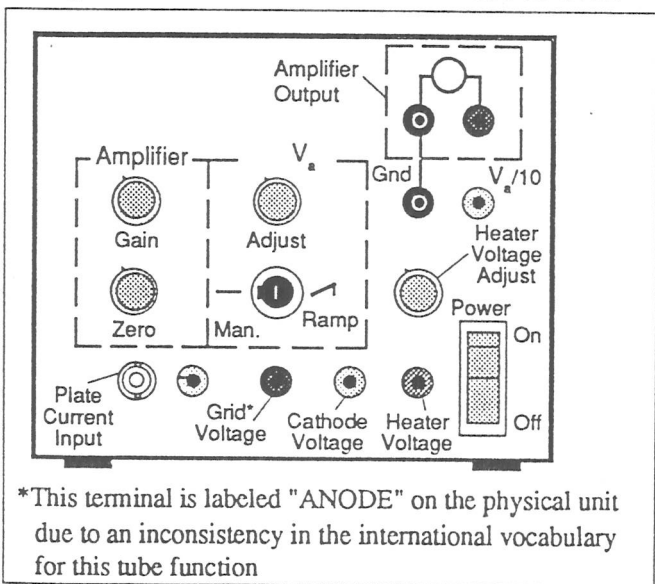


Figure 2 Franck-Hertz Tube Mounted in Oven



*This terminal is labeled "ANODE" on the physical unit due to an inconsistency in the international vocabulary for this tube function

Figure 3 Franck-Hertz Control Unit

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 0 V to about 30 V. Monitor the tube current to locate the potentials at which the current drops to a minimum.

Depending on whether you are using the Franck-Hertz Control Unit with an oscilloscope, or with a voltmeter, or if you are using separate power supplies instead of the control unit, the details of setting up the equipment and performing the experiment will vary. Information on each setup is given later in the manual.

Important—Please read before using the Franck-Hertz Apparatus:

Whether you are performing the experiment using the Control Unit, or using separate power supplies, the following guidelines will help protect your students 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.
7. 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:

8. Use a shielded cable to connect the anode of the tube to the amplifier input of the Control Unit.
9. 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.
10. 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 temperature should be between 150°C and 200°C, and the accelerating potential (between the cathode and the grid) should be no more than 30 V.

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 4.9 eV 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 three different setups:

- Using the Control Unit and an Oscilloscope
- Using the Control Unit and Voltmeters
- Without the Control Unit (using separate power supplies and an ammeter or voltmeter)

The procedure for each setup is described below. Data tables and information on how to analyze the experiment are provided at the end of the manual.

A Using the Control Unit and an Oscilloscope

- Remove the six thumbscrews that secure the front panel of the Franck-Hertz Oven. Replace the front panel with the Franck-Hertz Tube as shown in Figure 4.
- Insert a centigrade thermometer (0-200 degrees) into the hole in the top of the oven. Insert it so the tip of the thermometer is near the center of the tube.
- 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.**

- Connect the tube, control unit, and oscilloscope as shown in Figure 4. (The voltmeters that are shown in the figure are not needed when an oscilloscope is used.)
- Switch on the control unit, but only AFTER the tube has warmed up for 10-15 minutes. Set the controls as follows:

Heater:	midrange (about 5.5 V)
Amplifier:	Gain—midrange Zero—midrange
V_a :	Adjust—not applicable Switch—ramp (\nearrow)

- Wait about 90 seconds for the cathode to warm up, then adjust the gain controls on the oscilloscope to get a trace as shown in Figure 4. (The x-channel gain should be approximately 0.5 volts/cm; the y-channel gain should be approximately 0.5 volts/cm.)
- From the oscilloscope trace, measure the values of V_a for which the collector current (I_c) is a minimum.
Note: The input to the y-channel of the oscilloscope is proportional to I_c . The input to the x-channel of the oscilloscope is equal to $V_a/10$.
- See *Analyzing the Experiment* at the end of the manual for details about manipulating and analyzing your data.

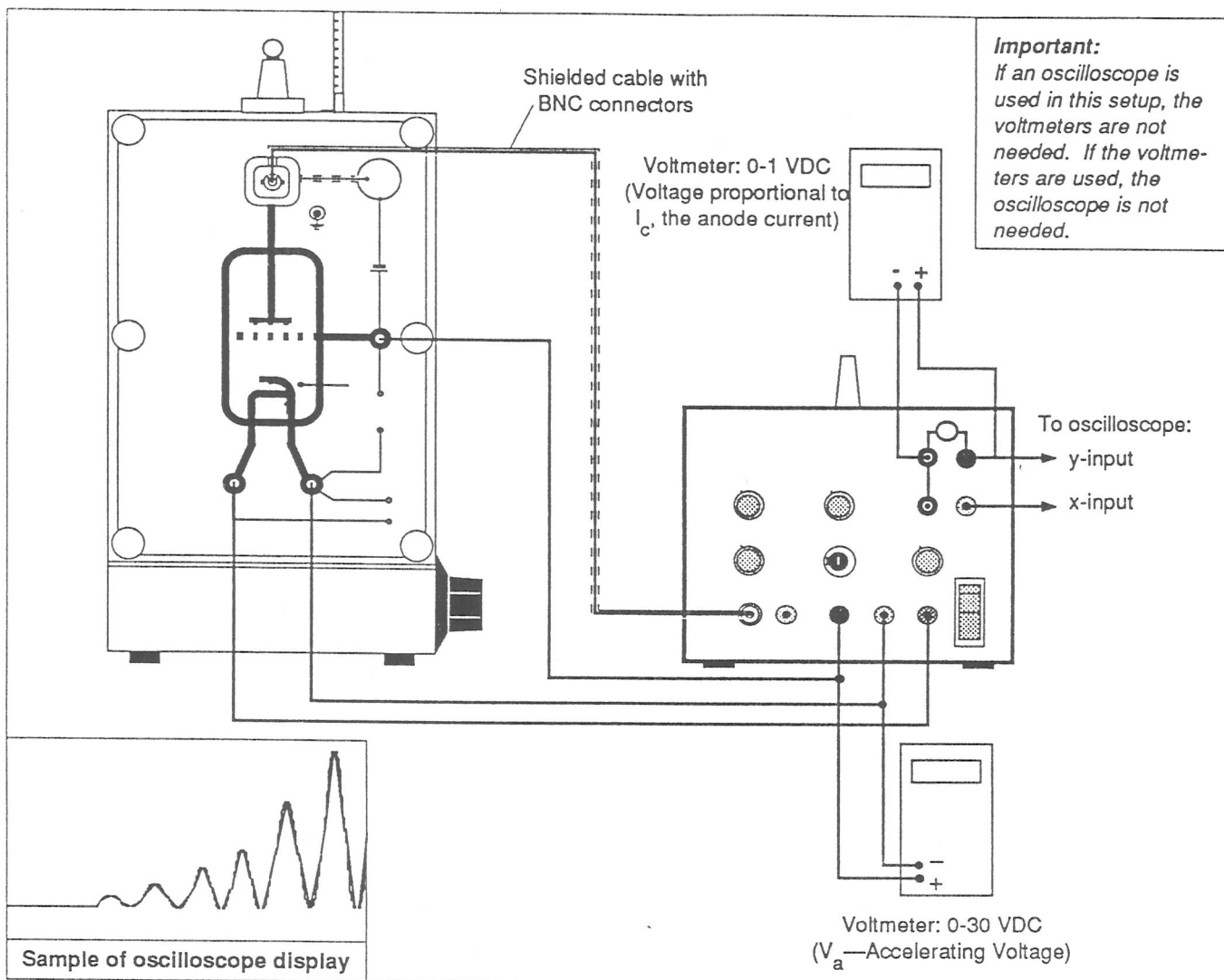


Figure 4 Franck-Hertz Experiment Using the Control Unit

B. Using the Control Unit and Voltmeters

1. Remove the six thumbscrews that secure the front panel of the Franck-Hertz Oven. Replace the front panel with the Franck-Hertz Tube as shown in Figure 4.
2. Insert a centigrade thermometer (0-200 degrees) 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 voltmeters as shown in Figure 4 (the oscilloscope connections that are shown in the figure are not necessary when using voltmeters).
5. Switch on the control unit, but only **AFTER** the tube has been allowed to warm up for 10-15 minutes. Initially, set the controls as follows:

Heater:	midrange (about 5.5 V)
Amplifier:	Gain – maximum gain (fully clockwise) Zero – midrange
V_a :	Switch – Man. (—) Adjust – zero (fully counterclockwise)

6. Allow at least 90 seconds for the cathode to heat up.
7. Adjust the Amplifier Zero so that the amplifier output is zero volts (if it won't go to zero, just adjust it as close to zero as possible).
8. Increase the accelerating voltage in increments of about 0.5 volts, by turning the V_a Adjust knob clockwise. At each value of V_a , record V_a and the corresponding value for the amplifier output.
Note: The amplifier output is not equal to I_c . It is a voltage that is proportional to I_c .
9. See *Analyzing the Experiment* at the end of the manual for details about manipulating and analyzing your data.

C. Without the Control Unit

1. Remove the six thumbscrews that secure the front panel of the Franck-Hertz Oven. Replace the front panel with the Franck-Hertz Tube as shown in Figure 4.
2. Insert a centigrade thermometer (0-200 degrees) 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, power supplies, and ammeter* as shown in Figure 5.

Important: All power supplies must be floating with respect to ground.

6. Set all the power supplies to zero volts. Then turn them on and set the heater voltage to 5.5 volts, the accelerating voltage to zero volts, and the opposing voltage to 1.5 volts. **DO NOT LET THE HEATER VOLTAGE EXCEED 7 VOLTS**, or the tube may be damaged.

17. Increase the accelerating voltage, V_a , in increments of about 0.5 volts. At each value of V_a , record V_a and the corresponding value for the anode current, I_c . Repeat your measurements, but this time try to locate the exact values of V_a for which current minima occur. Record these values of V_a and the corresponding values of I_c .
18. See *Analyzing the Experiment* at the end of the manual for details about manipulating and analyzing your data.

***Note:** If you don't have a sufficiently sensitive ammeter to accurately measure the anode current, you can use a voltmeter instead. The voltmeter must have 0.1 mV resolution and a 10 M Ω input impedance. Connect it just as the ammeter is connected in Figure 5. The voltage reading of the voltmeter will then be equal to the anode current, in units of 10^{-11} amperes.

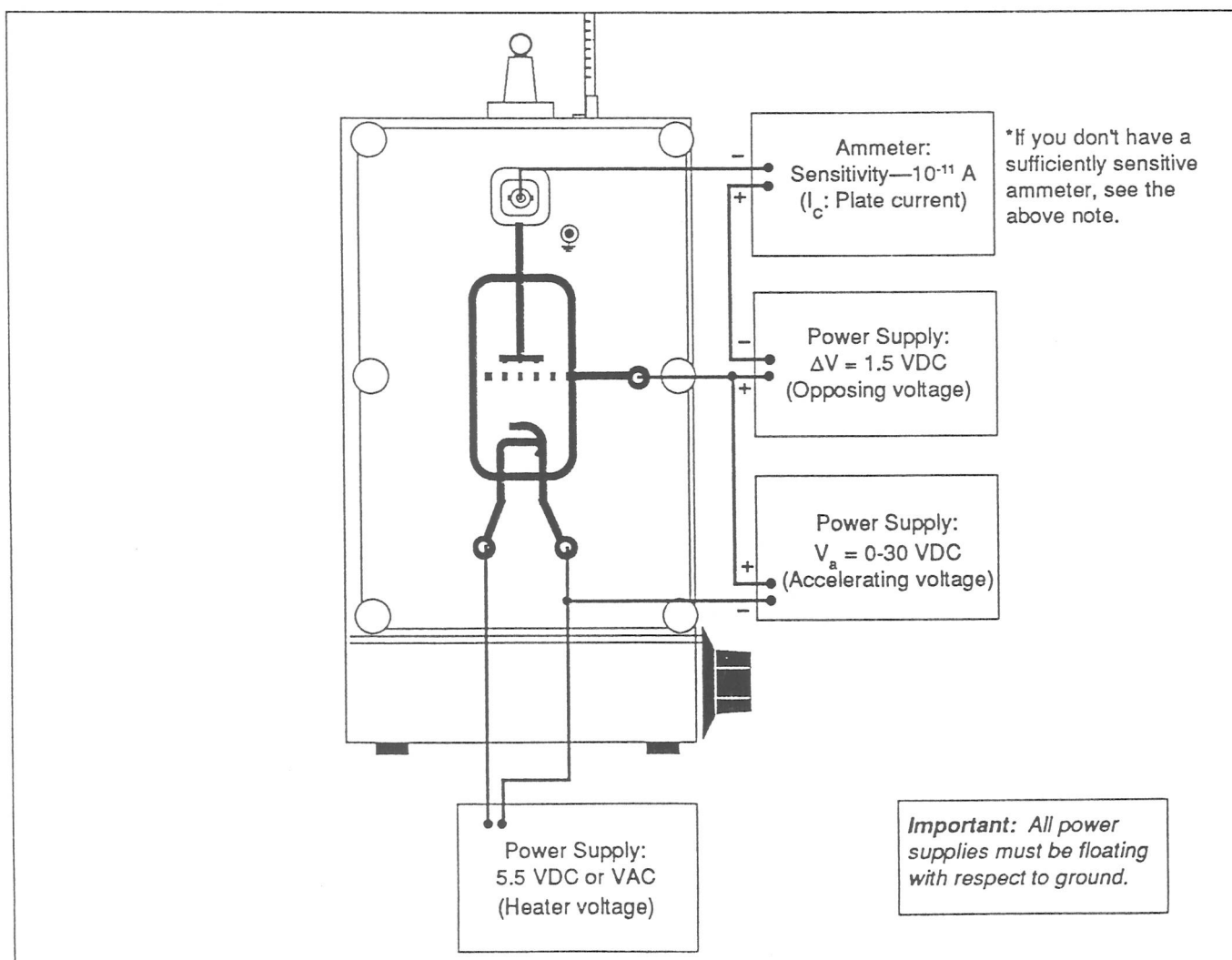


Figure 5 Franck-Hertz Experiment Without the Control Unit

Analyzing the Experiment

In performing the experiment (described in the previous section for the various setups), you will have collected values of V_a and corresponding values of I_c . To analyze this data:

1. Subtract 2.0 volts from each of your recorded values for V and record these value as $V_{a(\text{adjusted})}$ in your data table. $V_{a(\text{adjusted})}$ 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 functions of the two metals—in this case the electrons lose approximately 2.0 eV. This energy can be accounted for by subtracting 2.0 volts from the measured values of V_a .

2. If you did not use the oscilloscope to make your measurements, plot a graph of plate current versus $V_{a(\text{adjusted})}$, with $V_{a(\text{adjusted})}$ on the x-axis. Locate the plate current minima and record the corresponding values of $V_{a(\text{adjusted})}$ in Table 2.
3. 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 4.9 eV. The spectral frequency corresponding to this energy is:

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

4. The corresponding wavelength is:

$$\lambda = c/\nu = 253.7 \text{ nm.}$$

In their original experiments, Franck and Hertz verified the presence of this ultraviolet radiation with the aid of a quartz spectrometer.

Table 1 Acceleration Voltage and Anode Current

V_a	$V_{a(\text{adjusted})}$	I_c	V_a	$V_{a(\text{adjusted})}$	I_c	V_a	$V_{a(\text{adjusted})}$	I_c

Table 2 Resonance Data

Values for $V_{a(\text{adjusted})}$ at which I_c is a minimum	Voltage difference between adjacent minima