CENTRAL SCIENTIFIC COMPANY

OPERATING INSTRUCTIONS

Complete Franck-Hertz Experiment
No. 32047

1. Introduction

You can use the modular components of the Complete Franck-Hertz Experiment (32047) to duplicate the 1926 Nobel Prize winning experiment originally performed in 1913. The Franck-Hertz experiment verifies the concepts of quantum theory with an impressive proof. On your oscilloscope screen, well-defined periodic and equidistant maxima and minima show the quantum levels of mercury as the electrode current produced by the control unit excites the mercury resonance line at a 253.7nm wavelength.

2. Description

The Complete Franck-Hertz Experiment includes:

- a mercury Franck-Hertz tube
- an oven with a built-in temperature controller
- a control unit
- a shielded cable with BNC connectors

You will need to supply the following:

- an oscilloscope with an X-Y facility (such as our Dual-Trace 20MHz Oscilloscope, 32046)
- a thermometer with a 240°C range (such as our Mini Thermometer with Probe, 32824 or our Economy Thermocouple Digital Thermometer, 31274)

An alternative equipment setup using two voltmeters instead of an oscilloscope is presented in Section 3B, "Voltmeter Method."

2A. The mercury Franck-Hertz tube is a 3-electrode tube with an indirectly heated oxide-coated cathode, a grid-form anode and a collector electrode. The electrodes are arranged in a plane-parallel format. The 8mm distance between the anode and the cathode is large compared to the mean free path length of an electron in the mercury vapor atmosphere (190°C); this ensures a high collision probability.

During manufacturing, the mercury tube is provided with a highly activated contact getter and exhausted to high vacuum. The getter ensures a long tube life free of energy-consuming contamination gas.

The envelope wall between the anode and the collector electrode carries a vacuum-proof sealed-in protective ring made of sintered carborundum. This ring prevents leakage currents via the ion-conducting hot glass wall. The tube contains a drop of highly purified mercury.

2B. The oven consists of a steel-plated cabinet with the dimensions 24 x 16 x 14cm. The oven is heated with a tubular radiator mounted on its floor. Its power consumption is 400 watts. You use the bimetal switch, which can be adjusted with a control knob from the exterior, to set and stabilize the oven temperature.

Caution! Only connect the oven heater to a 110VAC supply. If you connect the oven to a DC supply, arcing will damage the bimetal contact when the circuit is active.

2C. 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. It’s very simple to set up the apparatus using the control unit. Just make four connections to the Franck-Hertz tube and hook up the measuring equipment.

The power supply component of the control unit delivers:

- the accelerating voltage $\mathbf{U_b}$ = DC voltage, continuously variable from 0 to 60V (switch $\mathbf{U_b}$ to “-” setting)
- the filament heating voltage for the tube $\mathbf{U_H}$ = AC voltage up to 8V. The filament current is adjustable from 270-350mA
- the opposing voltage $\mathbf{U_G}$ = DC voltage continuously variable from 0 to 1.5V

The control unit also has the following voltage controls, so you can display the Franck-Hertz curve on a cathode ray oscilloscope screen:

- A sawtooth waveform accelerating voltage $\mathbf{U_b}$ with a maximum amplitude adjustable from 0-70V pp (switch $\mathbf{U_b}$ to the setting).
- Voltage for the X-deflection on the oscilloscope = half-wave voltage obtained by half-wave rectification ($\mathbf{U_b/10}$).

The DC amplifier included in the control unit consists of two cascaded operational amplifiers (integrated circuits). You use the first amplifier as an electrometer amplifier. The current to be measured is applied to the non-inverting input. The input impedance is 680kΩ. The gain can be adjusted with a variable negative feedback resistance.

The second operational amplifier amplifies the signal further and inverts it. The output display voltage is proportional to the measured current. A 1-volt output voltage corresponds to a 0.7μA input current at the minimum sensitivity setting (i.e., the control knob turned to the far left), and to a 7nA input current at the maximum sensitivity setting (i.e., the control knob turned to the far right).

3. Setup and Operation

If you are using an oscilloscope, follow the instructions in Section 3A, "Oscilloscope Method." Section 3B, "Voltemeter Method," describes an alternative procedure using two voltmeters to measure the output, allowing students to collect and plot the data themselves.

Using the oscilloscope method prior to using the voltmeter method can be beneficial for students. It lets them view the Franck-Hertz curve on the oscilloscope screen, providing a means of comparison when they plot their own curves using the voltmeter data.

3A. Oscilloscope Method

Make all connections *with the power turned off*. Connect the control unit to the measuring oscilloscope as shown in Figure 1.

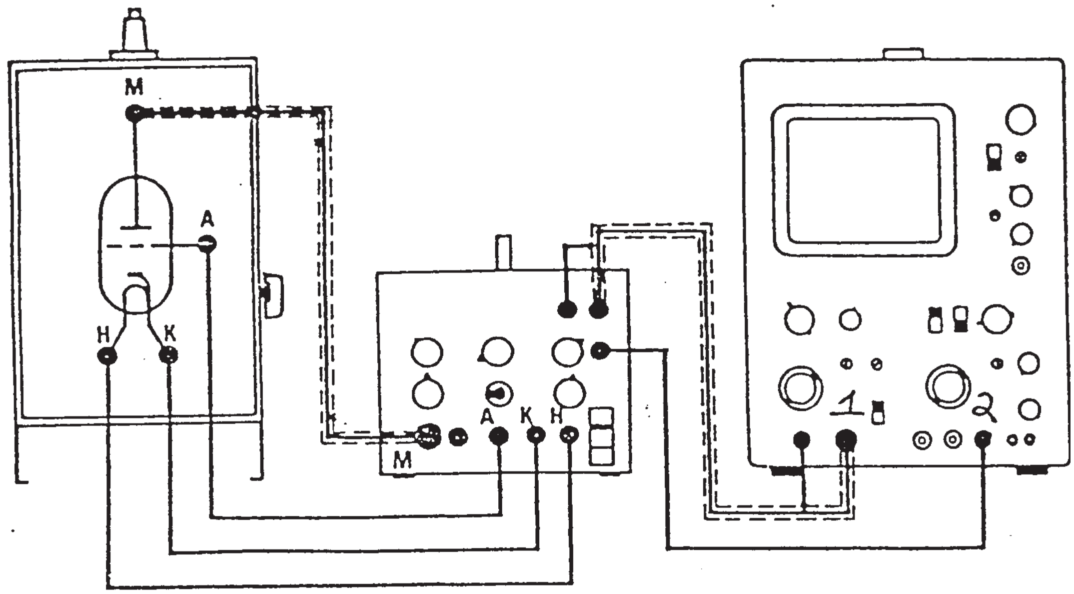

Figure 1 Connection of Control Unit and Oscilloscope

Connect the voltages as follows:

1. Connect the acceleration voltage $\mathbf{U_b}$ across the tubes, cathode **K** (**-**), and anode **A** (**+**) by connecting **K** on the control unit to **K** on the oven face. Similarly, connect **A** on the control unit to **A** on the oven face.

2. Connect the filament heating voltage $\mathbf{V_h}$ across **H** and **K** on the tube; that is, connect **H** on the control unit to **H** on the oven face.

3. Connect the opposing voltage $\mathbf{U_G}$ from **M** on the control unit to **M** on the oven. To reduce electronic noise, use the shielded cable with BNC connectors.

4. Connect the oscilloscope according to Figure 1. From (**V+**) to Channel 1 (Y-deflection). From $\mathbf{U_b/10}$ to Channel 2 (X-deflection). From ground (**V-**) to ground of Channel 1.

5. Set switch $\mathbf{U_b}$ to the setting.

To perform the Franck-Hertz Experiment, first connect the heating oven to a grounded AC line voltage using the supplied main cable. Set the bimetal contact switch to the desired temperature (e.g., 190°C). To read the temperature, insert a thermometer into the center of the oven. The oven initially “hunts” for the temperature set on the control knob by cycling on and off until it finds it. The oven will take about 10-15 minutes to stabilize at the set temperature.

Switch on the operating unit. Make sure that the black toggle switch $\mathbf{U_b}$ is set at the position. Set the red acceleration control knob $\mathbf{U_b}$ to 0 volts. Set the filament “adjust” knob about midway. Set the signal “gain” knob to the maximum sensitivity by turning it to the right as far as it will go. Adjust the “opposing voltage” knob so the meter reading is zero or less at the amplifier output (**V+**, **V-**)

The indirectly heated cathode requires a warm-up time of about 90 seconds after you switch on the operating unit. Slowly increase the accelerating voltage (starting from 0 volts) while reducing the “gain” setting to prevent the output from saturating the amplifier. Amplifier saturation is indicated by the waveform peaks becoming “clipped” on the oscilloscope display.

The Franck-Hertz curve should appear on the oscilloscope screen. To improve the display, carefully adjust the “gain” control and the cathode temperature “heater” control settings. Adjust the accelerating voltage so no self-sustained discharge occurs inside the tube. This discharge would be indicated by a rapid rise in the output voltage.

The measuring amplifier’s output is displayed on Channel 1 of the oscilloscope via the **FH** signal out (**V+**) and the ground (**V-**) terminals on the control unit. The indicated collector current shows equidistant minima as a function of the accelerating voltage. For information on the theory involved in this experiment, see Section 4 ("Notes on Operation").

3B. Voltmeter Method

This alternative method requires students to plot their own Franck-Hertz curves. You may disregard this section if you are using an oscilloscope to display the Franck-Hertz curve. Make all connections *with the power turned off*, as shown in Figure 2.

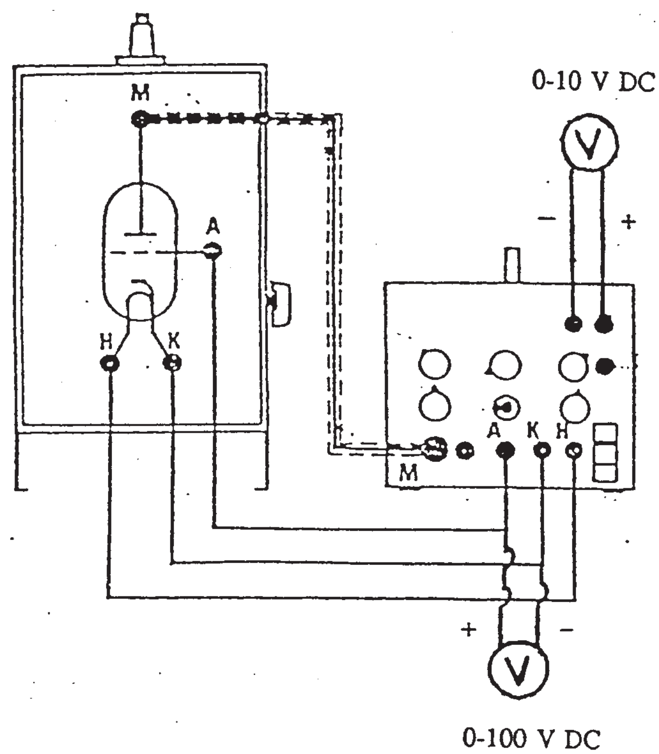

Figure 2 Voltmeter Connections

Connect the voltages as follows:

1. Connect the acceleration voltage **U_b** across the tubes, cathode **K** (**-**), and anode **A** (**+**) by connecting **K** on the control unit with **K** on the oven face. Similarly, connect **A** on the control unit to **A** on the oven face.

2. Connect the filament heating voltage **V_h** across **H** and **K** on the tube; that is connect **H** on the control unit to **H** on the oven face.

3. Connect the opposing voltage $\mathbf{U_G}$ from **M** on the control unit to **M** on the oven. To reduce electronic noise, use the shielded cable with BNC connectors.

4. Connect a voltmeter capable of measuring 10VDC across the amplifier output (**V+**, **V-**).

5. Connect a second voltmeter capable of measuring between 0 and 70VDC across the accelerating voltage $\mathbf{U_b}$ (**A**, **K**).

6. Set the black toggle switch $\mathbf{U_b}$ to the "-" position. This step makes the accelerating voltage $\mathbf{U_b}$ straight DC instead of ramped DC.

To perform the Franck-Hertz Experiment, first connect the heating oven to a grounded AC line voltage using the supplied main cable. Set the bimetal contact switch to the desired temperature (e.g., 190°C). To read the temperature, insert a thermometer into the center of the oven. The oven initially "hunts" for the temperature set on the control knob by cycling on and off until it finds it. The oven will take about 10-15 minutes to stabilize at the set temperature.

Switch on the operating unit. Verify that the toggle switch $\mathbf{U_b}$ is set on the "**-**" position. Set the red acceleration control knob $\mathbf{U_b}$ to 0 volts. Set the filament "adjust" knob about midway. Set the signal "gain" knob to the maximum sensitivity by turning it to the far right. Adjust the "opposing voltage" knob so the meter reading is zero or less at the amplifier output.

The indirectly heated cathode requires a warm-up time of about 90 seconds after you switch on the operating unit.

Collect data by recording the accelerating voltage $\mathbf{U_b}$ and the amplifier output **V** as you increase the accelerating voltage from 0 to 70V in 1 volt increments. To produce the Franck-Hertz curve, plot the data points. For more information on the theory involved in this experiment, see Section 4 ("Notes on Operation").

4. Notes on Operation

The emission current in the tube and the collector electrode current are affected by the cathode's temperature. If the current is too small, it can be increased by increasing the cathode heater voltage (e.g., to 8V).

A 10kΩ resistor in the tube's anode circuit prevents tube overloading. Thus, the tube is not endangered even if a discharge by collision ionization occurs inside it due to excessively high applied voltages. To verify from the spectrum that the gas filling it is mercury vapor, you can observe the luminous discharge with a spectroscope through the glass side panel.

The Franck-Hertz tube is mounted on the rear side of the front panel so the entire tube, including the connecting wires, is heated to a constant temperature. This is absolutely essential because the vapor pressure of the mercury is always determined by the temperature of the tube's coldest point.

The front panel carries the ceramic-insulated connecting sockets for the tube. The collector electrode is connected to a BNC-type jack, which is connected to the shielded lead of the operating unit (measuring amplifier). The tube's designation is marked in bold lines on the front panel, and the connections are marked by thinner lines. You can observe the tube and the heater spirals through the oven's two windows. The oven's cover plate has a hole for inserting the thermometer, which is held in place with a clamp spring.

A permanent 10kΩ current-limiting resistor is located between the connecting socket for the accelerating voltage and the tube's anode. This safety resistor protects the tube in case a continuous discharge occurs inside it when an excessively high voltage is applied. For normal measurements, the voltage drop across the safety resistor can be ignored because the tube's working anode current is less than 5μA (i.e., the voltage drop across the safety resistor is less than 0.05V).

The front panel with the tube can be taken off after releasing the six milled screws. Thus, you can use the oven for other purposes such as the sodium fluorescence experiment.

5. Theory

The Franck-Hertz Experiment makes it possible to observe the energy transitions produced by collisions between electrons and mercury atoms. The tube contains a small amount of mercury, some of which vaporizes when you heat the tube in the oven. At 180°C, the mercury vapor pressure is about 20 millibar. The oxide-coated, heated cathode emits electrons.

The kinetic energy of these electrons increases with an increasing accelerating voltage ($\mathbf{U_b}$). Consequently, the electrons fly through the grid-form anode and then against an opposing voltage of 1.5V to the collector electrode. A typical 10^{-10}A current flows from the collector electrode to the anode. The measuring amplifier amplifies this current.

Initially, the collisions between electrons and mercury atoms occur elastically, without significant energy transfer to the mercury atoms. However, when the accelerating voltage is increased significantly, the electrons' kinetic energy is large enough to excite the mercury atoms directly in front of the grid-form anode. The electrons lose their kinetic energy and can no longer reach the collector electrode against the braking voltage (-1.5V). 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 mercury atom. This energy transfer recurs periodically with an increasing accelerating voltage.

On the Franck-Hertz curve, 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 voltage. The minima are spaced at intervals of 4.9V, showing that the excitation energy of the mercury atoms is 4.9eV.

The spectral frequency corresponding to this energy is:

$$V = F(E,H)$$

where:

$$F(E,H) = F(4.9\text{eV}, 4.133 \times 10^{-15}\text{eVs}) = 1.18 \times 10^{15}\text{Hz}$$

and the corresponding wavelength is:

$$l = F(c,v) = 253.7\text{nm}$$

Franck and Hertz verified the presence of this ultraviolet radiation with the aid of a quartz spectrograph. A contact potential of about 2V exists in the tube between the cathode and the anode. Thus, the first current minimum lies at about 7V.

Figures 3 and 4 show the collector current as a function of the accelerating voltage. The form of the curve depends strongly on the oven temperature. At low temperatures (around 160° to 185°C), the first minima are developed more fully, but the curve rises rapidly so only the first few peaks are seen (see Figure 4). The tube produces a continuous discharge at about 30V. At higher oven temperatures (185° to 200°C), more minima are obtained, but at a lower current range. Eventually, the first minimum becomes less defined and may even be undetectable.

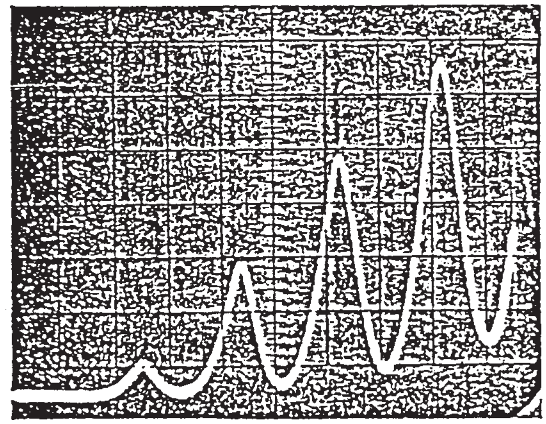

Figure 3 The collector current as a function of the accelerating voltage.

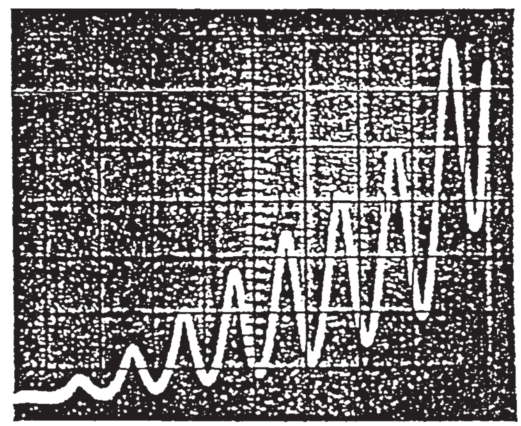

Figure 4 The collector current as a function of the accelerating voltage. Depicted is a low temparture where the curve rises rapidly so only the first few peaks are seen.

6. Maintenance

The Complete Franck-Hertz Experiment requires no special maintenance. If you should experience any problems with the apparatus or need more information about operating it, please contact Central Scientific Company, giving details of the problem. To ensure better service, please do not return any item to Central Scientific Company until we have sent you authorization.

7. Accessories

Description	Cat. No.
Dual-Trace 20MHz Oscilloscope	32046
Standard Single-Range DC Voltmeter, 0-100V .	82420-05
OR	
Standard Single-Range DC Voltmeter, 0-10V ...	82420-03
Mini Thermometer with Probe	32824
OR	
Economy Thermocouple Digital Thermometer ..	31274

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