

# Experiment 16: The Franck-Hertz Experiment

## From Physics Lab

The Franck-Hertz experiment is one of the best demonstrations to show the existence of discrete energy states in an atom as suggested by Niels Bohr. In this experiment, you measure the energy required to raise a mercury atom from its ground state to its first excited state.

### Theory

One postulate in the Bohr theory of the atom is that the transition of an atom from one stationary state  $E_1$  to another  $E_2$  requires the emission (or absorption) of a discrete amount of energy. The change in energy is given by

$$E_1 - E_2 = hf \quad (1)$$

where  $h$  is Planck's Constant and  $f$  is the frequency of the radiation emitted (or absorbed).

In this experiment, electrons are emitted thermionically from a heated cathode (see Figure 1). The filament in this tube heats the cathode indirectly, and thermionic emission is from the surface of the cathode (not from the filament itself, so the filament voltage does not affect the initial potential of the thermionic electrons at the cathode.) The electrons are accelerated through a mercury vapor towards the grid  $A$  using an adjustable potential difference  $V_a$ . A collector electrode  $C$  is mounted directly behind the grid to receive the electrons that pass through the wire mesh of the grid. A small opposing voltage  $V_s$  is applied between the grid and collector. Only electrons whose energy when reaching the grid is greater than the opposing voltage  $V_s$  may pass through the grid and reach the collector. The collector current  $I$  is measured using an electrometer.

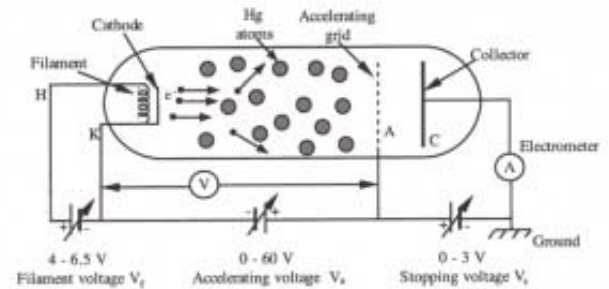
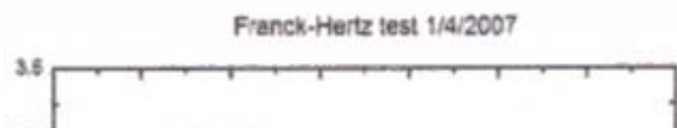


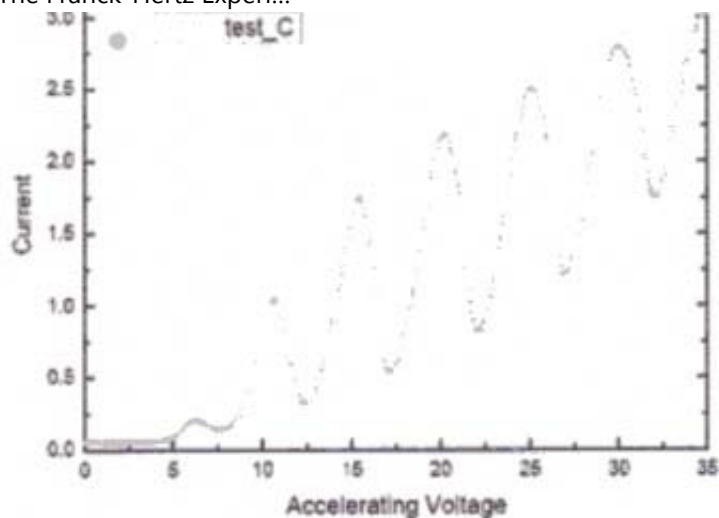
Figure 1 Experimental setup for the Franck-Hertz experiment.

As the electrons are accelerated towards the grid  $A$  they collide with the mercury atoms in their path. If the kinetic energy of an electron is less than the lowest excitation level for the mercury atom when they collide, the collision is elastic and no energy is lost to the more massive mercury atoms. If the collision is inelastic, a discrete amount of energy,  $hf$ , will be transferred from the electron to the mercury atom by raising the atom to its first excited state. Almost immediately after the inelastic collision (about  $10^{-8}$  sec.), the excited atom will return to its ground state. The number of inelastic collisions an electron undergoes with the mercury atoms while accelerating from the cathode to the anode depends on how many times the electron can gain enough kinetic energy to raise a mercury atom to its first excited state. Therefore, as the voltage between the cathode and anode is raised, one would expect the number of inelastic collisions between an electron and the mercury atoms to increase.

As the voltage  $V_a$  between the cathode and grid is slowly increased from zero, a current will flow. This current will increase until the accelerated electrons gain enough energy to



raise a mercury atom to its first excited state. After undergoing an inelastic collision with the mercury atoms, not all of the electrons have sufficient energy to reach the collector. This results in a sharp decrease in collector current. Increasing the voltage further accelerates the electrons after their inelastic collision with the mercury atoms. More electrons regain sufficient energy to overcome the stopping potential and reach the collector. The current increases to a new maximum followed by a minimum. As the voltage is increased over the range from 0 to 65 volts, twelve such maxima occur.

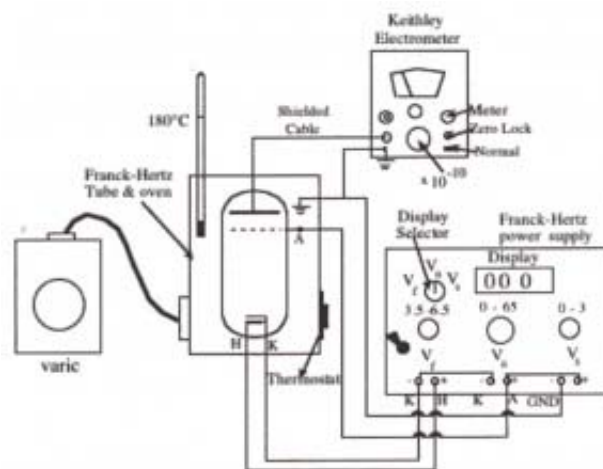


**Figure 2** Collector current versus accelerating voltage in the Franck-Hertz experiment.

At this point you may ask yourself why do the mercury atoms only get raised to their first excited state. Why, when  $V_a$  is large, can an electron not gain sufficient energy to ionize a mercury atom? The answer is that such a transition is possible but undesirable. The chance of ionization occurring depends on the mercury vapor pressure (temperature), the current, and the accelerating potential  $V_a$ . The higher the pressure, the lower the mean free path of the electrons. Therefore, an electron seldom gains much more than the first excitation level's worth of kinetic energy between collisions. However, when ionization occurs, this adds one extra electron to the tube current. This extra electron increases the chance that ionization will occur, especially for larger values of  $V_a$ . If too many mercury atoms are ionized, the current in the tube becomes uncontrollably large; this will damage the tube. To avoid excessive ionization, the current is limited by adjusting the filament voltage.

### Procedure

1. Wire the apparatus as shown in figure (3) and check that all the power supply voltages are completely turned down. Insert the thermometer to the 76 mm immersion mark. The Franck-Hertz tube contains a bubble of mercury which can be vaporized so that it will fill the tube with mercury atoms. Heat the oven to about 180C by setting the thermostat control on the side of the metal oven to 180C (or to 7.5 on some models) and the variac to 115 volts. The thermostat will regulate the oven temperature within  $\pm 5C$  of this temperature. To obtain a more stable regulation of temperature, the automatic thermostat can be defeated by lowering the variac to 75-80 volts and raising the thermostat setting to over 200C (e.g. about 210C or 8.5). Several small adjustments to the variac will be necessary to hold the temperature steady at  $180 \pm 1C$ .



**Figure 3** Basic wiring diagram.

1. Once the tube is heated to a stable operating temperature, set the stopping potential difference  $V_s$  to 1.5

volts, and adjust the filament voltage  $V_f$  to 5.5 volts. Slowly increase the accelerating voltage  $V_a$  to about 35 volts and observe the current  $I$  on the Keithley electrometer. Since the tube is prone to ionization if the current is too large, carefully re-adjust the filament voltage so that the current peak closest to 35 volts is no more than  $\sim 0.5 \times 10^{-10} \text{ amp}$ . Continue increasing the voltage  $V_a$  until the last peak near 60 volts is reached. Pay close attention to the data you collect around each maximum; the accelerating voltages corresponding to each peak are the most significant numbers for your data analysis. For safe operation of the tube, the current at this peak should be in the order of  $\sim 1 \times 10^{-10} \text{ amp}$  (or  $3 \times 10^{-10} \text{ amp}$  maximum!). Finally, a very slight adjustment can be made to the filament voltage so that the current peak occurs at a convenient value on either the  $1 \times 10^{-10}$  or  $3 \times 10^{-10}$  amp range of the electrometer.

**CAUTION:** If a sudden large increase in current is observed due to ionization, immediately shut off the power on the module.

- The acquisition of data for this experiment can be made more expedient by using computerized data collection to enable a systematic investigation of the effects of varying one or more of the parameters of stopping voltage, filament current, and oven temperature. Wire the apparatus as shown in Figure 4/4b. Slowly increase  $V_a$  and collect current-voltage curves up to near 60 volts. The curves can later be plotted together on the same graph to make comparisons easier. You will have to ramp the voltage by hand with the knob. Turn it very slowly (especially around the peaks) so the changes are within the long time constant of the electrometer response. You can tell if you are going too fast if the peak positions as the voltage is ramping up do not match the peak positions as the voltage is ramping down, when the computer is collecting data in “etch-a-sketch mode”.

**Note:** You will have to scale the results from the computerized data collection. Ensure that you record values of voltages at both ends of the range of peak voltages as read off the display to compare to the voltages recorded by the computer.

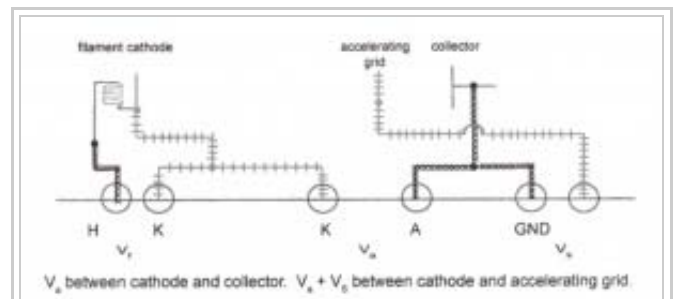
To avoid grounding problems when connecting the DAQ ADC to the power supply, it is best to cable up the tube such that everything is referenced to common ground (at the counter-electrode/electrometer input).

### Analysis

Determine the energy required to raise a mercury atom to its first excited state. This can be done using two methods. The first method is to determine the voltage difference between the first and last maxima from the current-voltage graph. Then divide this value by the total number of intervals. The second method is to plot a graph of the accelerating voltage for each peak versus peak number, and determine the slope via a linear least-squares fit. Compare the accuracy of the two methods.

### Questions

- What is the wavelength associated with the photons emitted by mercury atoms undergoing the transition from the first excited state back to the ground state?



**Fig. 4** Wiring connections between the Franck-Hertz power supply and tube, in the configuration used for computerized data acquisition. (Note: the twisted pair wires from the DAQ are not shown here.) We want the computer to simultaneously measure the accelerating voltage, and the current reading of the electrometer. There are two complications to reading the voltage. 1) The range of the analog inputs to the DAQ (“Data Acquisition”) card is  $\pm 10\text{V}$ . so we must use a

2. Why is it necessary to have the 1.5 volt stopping voltage? What would be the effect if it was eliminated?
3. The peaks may be shifted by some fraction of a volt due to the difference between the contact potentials of the anode and cathode of the tube. In addition, the first peak is often too small to measure at 180 C (it becomes more prominent at lower tube temperature.) What value do your results suggest for the contact potential?
4. Draw a potential diagram (voltage or energy vs position) for the region between the cathode and the collector in the Franck-Hertz tube. Assume the collector is grounded and the cathode is at -50 V, a stopping voltage of 1.5 V, and a filament voltage of 6 V. Try to account for the contact potential between the cathode and the collector. Draw, on the same diagram, the kinetic energy and the total energy - potential plus kinetic - for a typical electron as it passes through the tube. Refer to figure 1 for the physical layout.

voltage divider. This is done with large, fixed resistors, in order not to load to accelerating voltage supply too much (it is limited to very low currents).  
 2) The DAQ card introduces another ground reference, in addition to that of the electrometer. The input of the electrometer is a “virtual ground”; hence the ground reference of the tube is at the collector electrode. In the setup of Fig. 3 the accelerating voltage supply is floating and this is not a problem. Here, however, we tie one side of the accelerating voltage to ground via the computer, necessitating a measurement of the potential drop between the cathode and the collector. The stopping voltage must be recorded separately and added to the measurement to derive the potential difference between the cathode and the collector.

**Appendix**

Franck-Hertz Experiment Software

Computer-assisted data collection for the Franck-Hertz experiment can be performed using a “virtual instrument” (vi) in LabView. The program we use was written by David Fortin, and has the following “front panel”:

**Running the experiment:** Simply click on the run button, after setting up the parameters as described below.

Parameters

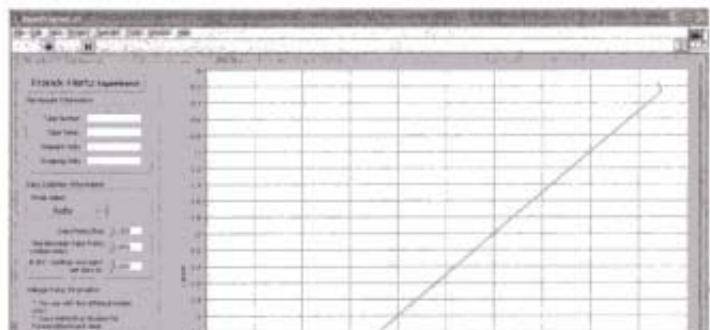
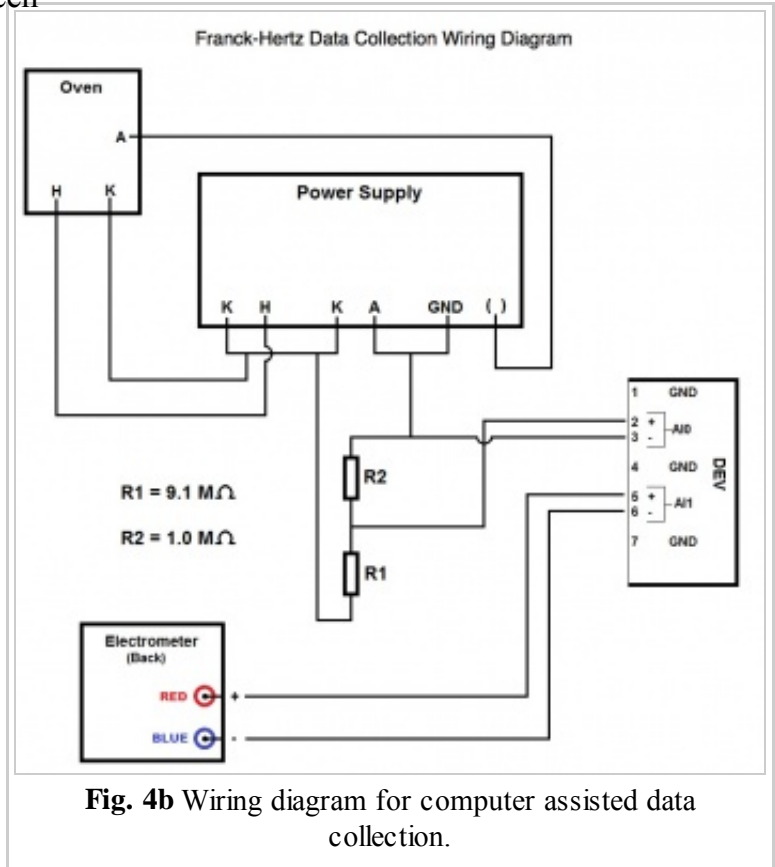
File Header Information:

Fill out the file header information.

Data Collection Information:

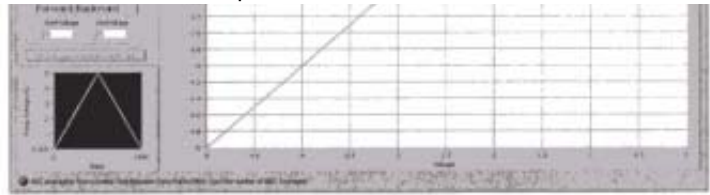
Mode Select:

You can use the ring control to set the





stepping between Manual, Automatic and Logging.



**Manual Mode** – A button will appear next to the ring control that allows you to single step each data point.

**Automatic mode** - The program steps automatically at 1/3 second intervals.

**Logging Mode** - The program steps at the Time Between Data Points input

You can also set the # of Data Points you want to take for the run and the number of averages you want to take per data point.

**Voltage Ramp Information:**

Voltage Ramp is used for the Auto and Manual modes only. You can choose Forward/Backward or just Forward. Forward/Backward ramps up from the StartVoltage to the EndVoltage. The number of points collected comes from the settings in Data Points/Run chosen in Data Collection Information. Once it reaches EndVoltage, it ramps down the same number of steps to the StartVoltage. Forward ramps up but not down.

Click on the run button to start the acquisition.

Once acquisition is complete click on the Stop Acquisition & Save button. A dialog will pop up prompting you to save your data. The data will be saved as a multi-column file which you can read into Origin or Excel for graphing and analysis.

**Display:**

**Ramp Display** - The ramp display shows what the output voltage ramp looks like based on your selection.

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