EXPERIMENT 14

The Franck-Hertz Experiment

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

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

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

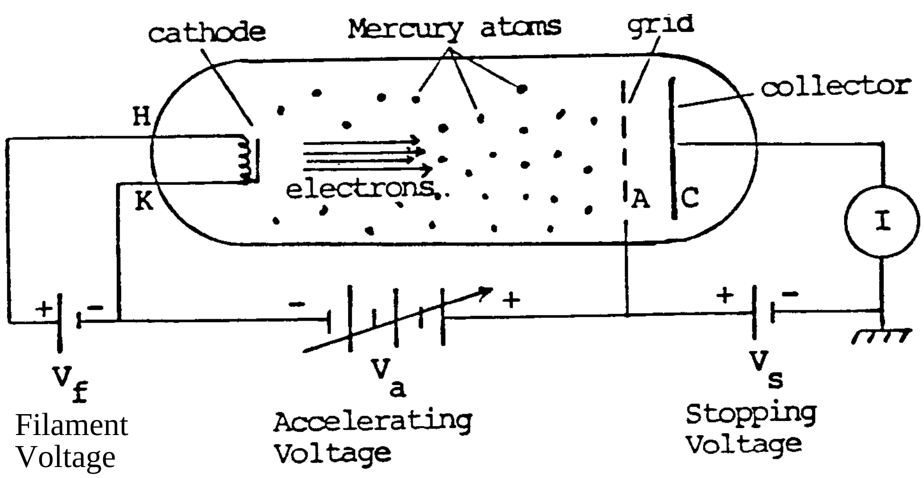

Figure 1

In this experiment, electrons are emitted thermionically from a heated cathode K (Figure 1). The electrons are accelerated through a mercury vapor towards the grid A using an adjustable potential V_a. A collector electrode C is mounted directly behind the grid to receive the electrons which 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.

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.

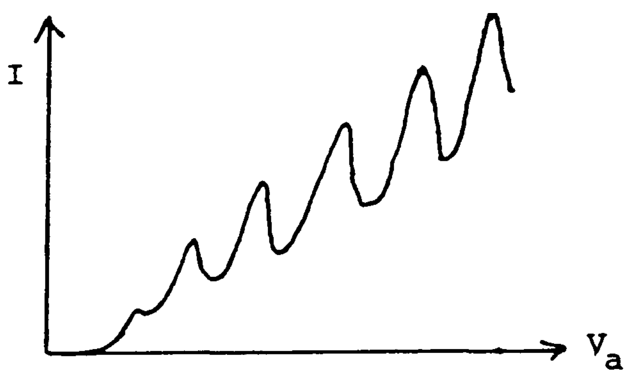

Figure 2

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.

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, cannot an electron 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.

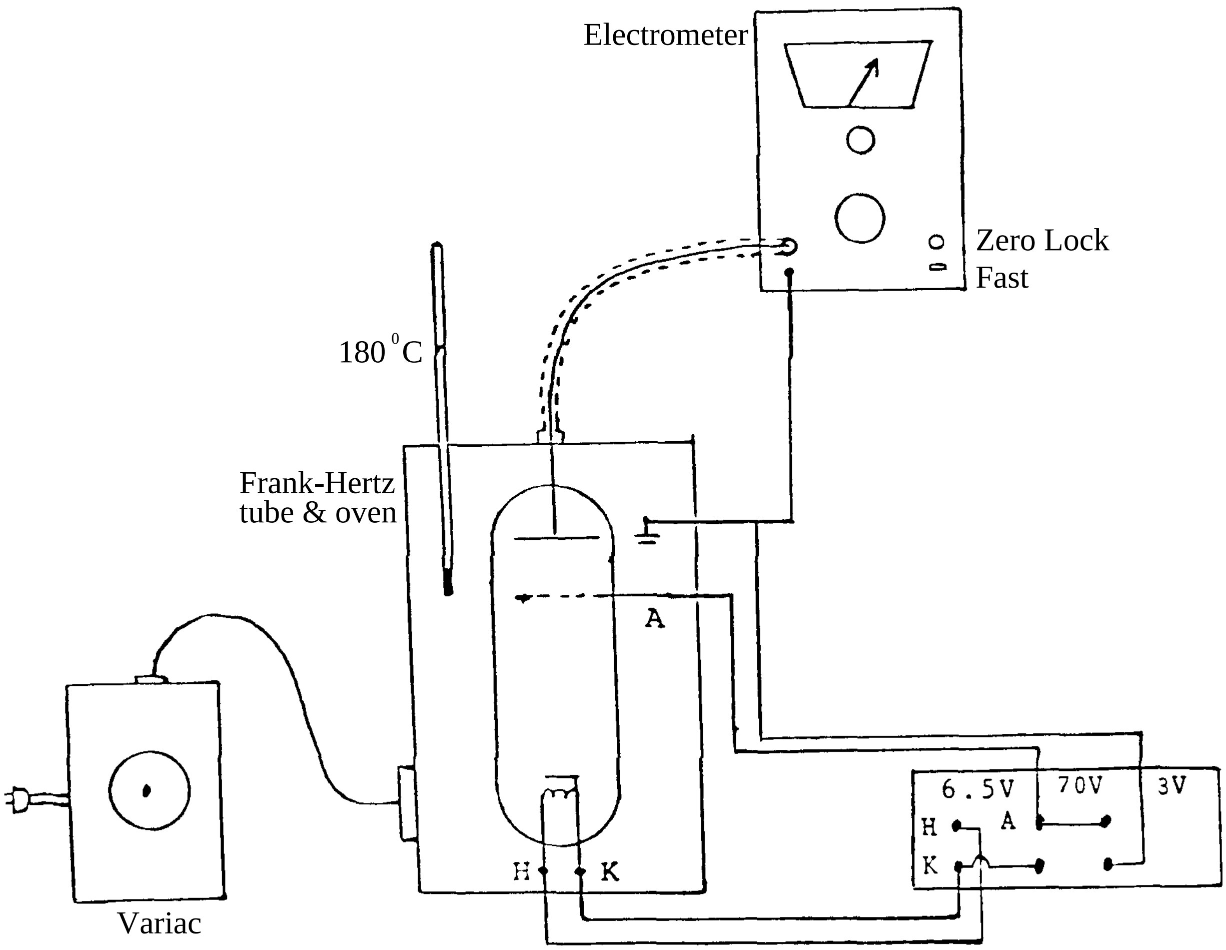

Figure 3

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 as to fill the tube with mercury atoms. Heat the oven to about 180°C by setting the thermostat control on the side of the metal oven to 180°C (or to 7.5 on some models) and the variac to 115 volts. The thermostat will regulate the oven temperature within ±5°C of this temperature. To obtain a more

stable regulation of temperature, the automatic thermostat is defeated by lowering the variac to 75-80 volts and raising the thermostat setting to over 200°C (e.g. about 210°C or 8.5). Several small adjustments to the variac will be necessary to hold the temperature steady at 180 ± 1°C.

2. Once the tube is heated to a stable operating temperature, set the stopping potential 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 ~ 0.5×10^{-10} amp. Continue increasing the voltage V_a until the last peak near 60 volts is reached. For safe operation of the tube, the current at this peak should be in the order of ~ 1×10^{-10} amp (or 3×10^{-10} 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 1×10^{-10} or 3×10^{-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.

3. The collection of data for this experiment can be made more expediently by using an X-Y plotter. However, only one apparatus is available. See your lab instructor for instructions on the use of the plotter.

   NOTE: When using the plotter in conjunction with the electrometer, choose a single scale for all the current values - preferably the 1×10^{-10} amp range.

   After making the preliminary test in step (2), the apparatus is now ready for obtaining a set of data. Return the accelerating voltage V_a to zero. Slowly increase V_a and plot a current-voltage graph for all the peaks up to near 60 volts. Pay close attention to the data you collect around each maximum, particularly the first and the last.

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 average the voltage differences between successive maxima from the current-voltage graph. Compare the accuracy of the two methods. Investigate the effects of changing the stopping voltage, filament current, and oven temperature.

Questions

1. 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?

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 to small to measure. 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 negative 50 volts. Use a filament voltage of 6 volts and a stopping potential of 1.5 volts. 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.