Laboratory 10: Franck Hertz

In 1913 Bohr introduced his atomic theory in which the bound energy states of atomic electrons are only allowed to take on certain discrete values. The discrete lines seen in atomic spectra are evidence supporting this theory. Franck and Hertz, in their 1914 experiment, were the first to show definitively that the excited states above the ground state of an atom are quantized.

In that experiment they used a tube containing a dilute mercury vapor, shown schematically below.

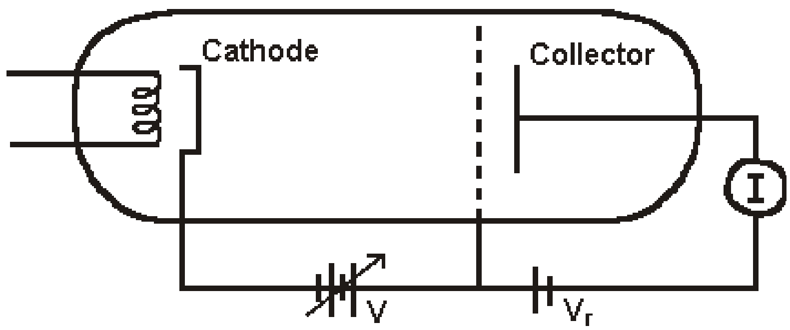

Figure 1: The Franck Hertz Tube, the space between the cathode and collector holds the substance being probed.

Electrons from a heated cathode experience a voltage V, which is variable. When V exceeds the work function of the heated cathode, W, electrons break free from the cathode and are accelerated towards an anode to a kinetic energy $KE = e(V - W)$ where e is the elementary charge. Increasing *V* beyond W increases the current at the collector. At some voltage $V_1 = V_{Hg} + W$ the current drops. As *V* is increased further the current again rises until a new voltage $V_2 = 2\,V_{Hg} + W$ is reached and the current drops again. One finds that $V_{Hg} = 4.9$ *Volts*.

These results are interpreted to mean that electrons with KE< *4.9 eV* were unable to excite the mercury atom to its first excited state. They might scatter elastically, but would still retain their energy and arrive at the collector. However, when an electron achieves a $KE \geq 4.9eV$ it may undergo an inelastic collision with a mercury atom, exciting the mercury atom into its first excited state and losing kinetic energy in the process. This would happen between the cathode and anode and the electron would be left with too little energy to overcome the repulsive voltage V_r between the anode and the collector. As *V* increases further this repulsion is overcome and current again increases. With larger *V* at $V_2 = 2V_1 + W$

it becomes possible for two inelastic collisions to take place, and so on.

Figure 2 shows a simplified description of the energy levels of a single mercury atom. The mercury atoms act as many independently atoms if they are in a dilute vapor. To obtain the mercury vapor we must heat the tube in an oven. Our target temperature is between 150 and 200 ^oC. This is because we must balance the need for a dilute vapor with the need to have a dense enough vapor to make an electron collision with a Mercury atom likely shortly after the electron's KE exceeds 4.9eV (in other words make the mean free path of an electron is considerably smaller than the dimensions of the tube). Thus, most electrons will suffer a collision before they gain enough energy to excite the atom into the second excited state directly.

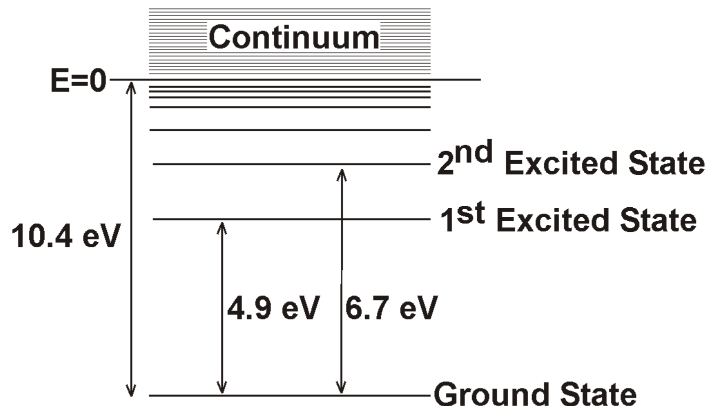

Figure 2: Energy Levels of Mercury

We must also limit electron emission such that a negligible number of electrons obtain enough energy to ionize the mercury atoms themselves. Ionized mercury is very conductive and would allow damagingly large currents to flow through the tube. Large currents can damage both the tube and the associated electronics. Electron emission is controlled by adjusting the potential between the cathode and a space charge grid just outside the collector. The collector currents used are on the order of 1-10nA. These are small currents which must be amplified to be measured.

During the experiment a mercury vapor pressure of 5 to 20 Torr must be maintained in the Franck-Hertz tube, corresponding to a tube temperature of from 150 to 200 ^oC. The mercury tube is encased in an oven, controlled by a thermostatic switch. Steady oven temperatures are only attained after the oven has been running for ~10min or so. Even then, the temperature will fluctuate as the thermostat cycles the heater control on and off. Do not be discouraged. Things will work if you are patient. Here are a few precautions to follow:

1. The Franck-Hertz tube contains metallic mercury. Every time the tube has been moved there is a risk of some mercury having settled between the electrodes, thus causing a short-circuit there. That is

why the tube is easily ruined by operating it without previous thorough heating.

2. With an overheated tube, the emission current will be small and maxima and minima are difficult or impossible to recognize.

3. If the tube is too cool, the emission current will be large. Maxima and minima, especially those of a higher order, are faint or absent. Should the vapor pressure in the insufficiently heated tube be too low, there will be a tendency for gas discharge to develop. In order to prevent these, the voltage on the cathode must be reduced so considerably, that the emission current becomes too small and likewise drops below 10^{-9} A. In this case, the tube must be heated up more.

4. In general, the experiment presents no difficulties when heating as specified before. Therefore, the voltages should not be altered unless one has made sure, after the experiment has failed, that no error has been made in the wiring, and that the set of symptoms observed agrees with one of those discussed above. The tube might easily be ruined by randomly increasing the oven temperature.

5. The Franck Hertz tube should, if possible, not be left to lie in the hot oven for hours on end, lest the vacuum be deteriorated by outgassing metal and glass parts.

6. The voltage between cathode and anode should not exceed 30 V, otherwise ionization by collision might develop.

Figure 3: Experimental setup

Procedure

1. Insert a thermometer (0-200 °C) into the top hole of the oven with the tip to be near the center of the tube or simply rely on the digital readout. Plug the oven into an appropriate AC power outlet, then turn the thermostat to 180 °C. Keep an eye on the thermometer. Do not let the temperature exceed 205 °C.

2. Connect the Franck-Hertz tube, control unit, and oscilloscope as shown in the figure. Note the German labeling: M = Collection Plate

   A = Anode

   H = Filament Heater

   K = Cathode

3. The use coaxial cables to run from the amplifier to the oscilloscope (do not use a digital scope and make sure the inputs are DC coupled and is in XY mode). After the tube has warmed up for a half an hour or so, switch on the control unit. Set the controls as follows:

   Filament voltage=6 to 7V

   Set the minimum accelerating voltage to zero

   Set the maximum accelerating voltage to zero.

   Start with the reverse bias at zero.

   Oscilloscope Channel 1 = about 1 volts/cm

   Oscilloscope Channel 2 = about 1 volts/cm

4. After the cathode has warmed up for at least 90 seconds (by turning on the filament voltage), slowly increase the maximum accelerating voltage with the control knob. The Franck-Hertz curve should appear on the oscilloscope screen. If necessary, improve the display by judiciously adjusting the "gain" control and the cathode temperature "filament heating". Adjust the

accelerating voltage such that no self-sustained discharge takes place in the tube. Otherwise, the curve is destroyed by collisional ionization.

Analysis

Note that on the oscilloscope trace the vertical deflection is proportional to the anode current I_c, and the input to the x-channel of the oscilloscope is equal to $V_a/10$. Use the oscilloscope to observe the trace in the X-Y mode. 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 (better precision can be had by consulting the NIST website for the energy levels of neutral mercury http://physics.nist.gov/PhysRefData/Handbook/Tables/mercurytable5.htm).

What is your estimate for the work function of the cathode?

Be sure to also measure the energy of the first excited state of Neon, which is substantially higher and allows you to see where the electrons have attained enough energy to inelastically scatter with the neon atoms.

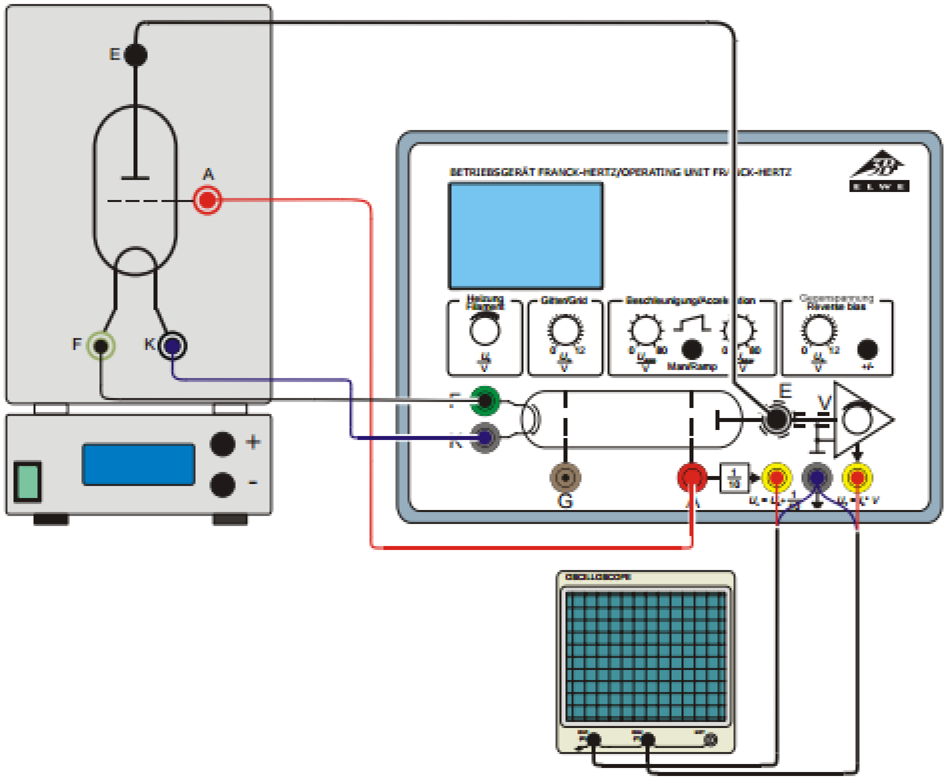

Fig. 1 Experiment set-up - Franck-Hertz tube filled with mercury

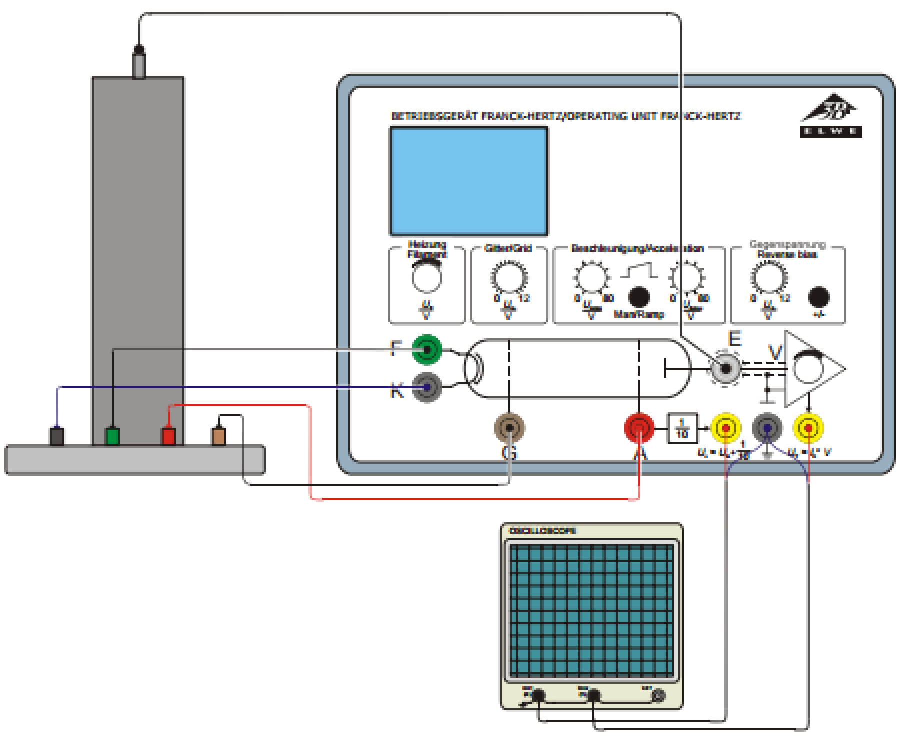

Fig. 2 Experiment set-up - Franck-Hertz tube filled with neon

Figure 2 From the 3B Scientific Manual