Modern Physics Lab

Franck-Hertz experiment **9/02**

Quantum physics, even in the simple Bohr model, predicts that the total energy of an electron in an atom is quantized. Every atom, therefore, has certain distinct energy states. These states are often probed using optical spectroscopies. The Franck-Hertz experiment uses the interaction of free electrons with a gas of atoms rather than light to probe the energy levels of an atom.

Free electrons can excite an atom by collision. In this collision process, the energy of the electron is lost to the atom, raising the atom into an excited state. If the electron does not have sufficient energy to excite the atom, the interaction during the collision will be minimal.

In this experiment electrons will be generated by thermionic emission from a heated filament. The electrons will be given a certain (variable) energy and accelerated across a volume filled with a dilute gas (often Hg). The current of electrons striking a collector plate on the opposite side of the volume is measured. Generally, as the accelerating voltage is increased, the current will increase, as more electrons get across the volume. At certain energies, however, a sudden drop in the current is detected. At these energies the electrons are reacting with the atoms and losing their kinetic energy in an excitation process. These energies are indicative of the separation between energy levels of the atom and thus the quantization of atomic energy levels.

The current drops may indicate energy separations between various excited states and the ground state, or between excited states, or could indicate multiple collisions of the electron with several atoms with each collision producing an additional energy loss for the electron. The energy levels of the atoms can also be determined optically by looking at the emission spectrum of the atom. (This experiment is available later in the semester). The results of this optical experiment are in good agreement to the Franck-Hertz experiment.

A simplified energy spectrum for Hg is presented in Figure 1. The actual energy of the ground state can not be measured with the Franck-Hertz experiment, but the separation between energy levels can be.

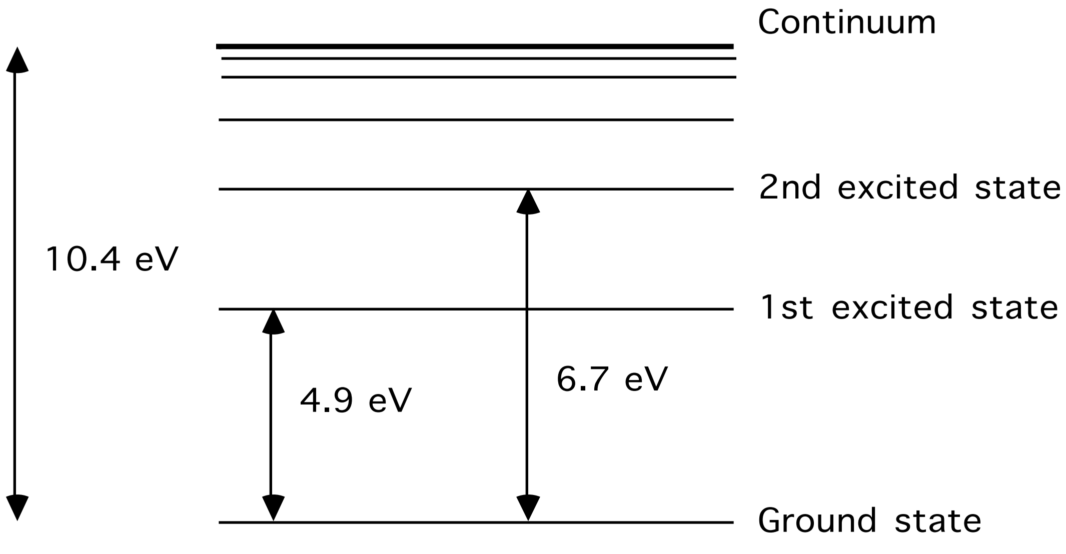

Figure 1. Simplified energy level diagram for Hg.

Experiment:

CAUTION: Do not apply any voltages to a cold tube. If gas discharge occurs (indicated by a sudden increase in current, immediately set both grid voltages to zero. Parts of the experiment (oven, tube) get HOT - do not touch without protective gloves.

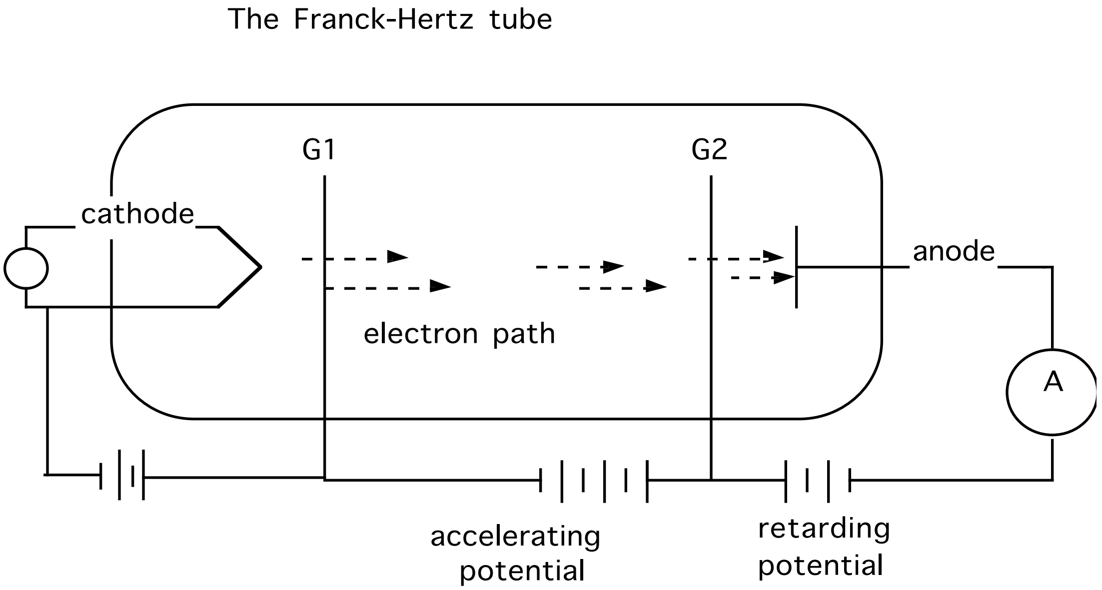

Figure 2. The Franck-Hertz tube

The Lebold-Heraeus tube used in this experiment, shown in Figure 2, is filled with mercury. The tube is placed in a small oven to heat the mercury and produce a mercury vapor at a temperature of about 200°C. The vapor pressure of Hg at this temperature is approximately 25 mbar. Inside of the sealed Franck-Hertz tube is an electron gun. The electron gun consists of a cathode heated by a filament, and 2 grids, designated G1 and G2. As the cathode is heated, electrons are released, but in the absence of an accelerating potential they have nowhere to go. The electrons may congregate around the cathode and form a negatively charged electron cloud which inhibits the release of more electrons. This condition can be rectified by applying a small potential between the cathode and the first grid(G1). This potential is just large enough to pull the electrons away from the cathode into the region between G1 and G2.

Electrons that are away from the cathode can be accelerated by a potential applied between G1 and G2. It is this potential that we measure to determine the energy of the electron beam using the equation

$$eV_e = (1/2)mv^2$$

where V_e is the accelerating potential.

The electron beam is finally collected at the anode and produces a current which we can also measure using an ammeter. Between the anode and G2, however, we apply a slight retarding voltage so that less energetic electrons will not reach the anode.

In the Franck-Hertz tube the electron beam must pass through a vapor of mercury atoms. In doing so many electrons will suffer collisions with the monatomic mercury. These electrons will, for the most part, collide elastically with the mercury atoms and will therefore lose no energy in collision. If, however, the electron beam attains certain energy levels, it will collide inelastically with the mercury and in doing so will give up its kinetic energy to a valence electron of the mercury. The energy required for this transaction is the excitation energy of mercury from its ground state to its 1st excited state. As the electron beam is energized to the level of this excitation energy, many electrons in that beam will lose their energy through inelastic collisions. They will no longer have enough energy to overcome the retarding potential and reach the anode. As fewer electrons contribute to the current we see a drop in the anode current for electrons of specific energies. We can determine the energy of the electrons at this point by

$$e(V_{G2} - V_r) = E.$$

where V_{G2} = voltage at grid 2
V_r = retarding voltage

The energy at the point of maximum current drop would correspond to the first excitation energy of mercury except that we are ignoring work functions and the potential which pulls the electrons away from the filament.

As the voltage at G2 is increased past the excitation energy, the anode current will increase steadily because, even if inelastic collisions occur, the electron still has enough energy to overcome the retarding potential and reach the anode. Once the potential is equal to an integer multiple of the excitation energy, the current will again drop as the electrons suffer multiple collisions with the mercury atoms, each time giving up energy equal to the first excitation energy of mercury until they have insufficient energy to reach the anode. It is very difficult to detect higher energy levels of mercury. The additional dips which you see are multiples of the first excitation state. Measuring the difference in energy of these minima will give you a good estimate of the first excitation energy of mercury.

Procedure:

Set up: The Franck-Hertz experiment is equipped with an oven to heat the tube and vaporize the mercury. The heater current is supplied and controlled by a 0-110 V ac variac in a separate box. A thermocouple is positioned in the oven to monitor the temperature. The millivolt readout of the thermocouple can be converted to temperature using the attached table.

The electronics of the tube require the following:

3 power supplies
1 - 4.6 volt (approximately) between the cathode and G1; this pulls the electrons from the cathode
1 - 0 - 30 volt between G1 and G2; this is the accelerating potential
1- 1.6 volt (approximately) between the anode and G2; this is the retarding potential

4 DMM's
1 - to monitor the variac voltage at the oven
1 - to monitor the accelerating voltage (G2)
1 - to measure the anode current
1 - to monitor the thermocouple output
In addition , we use a Keithley 427 current amplifier to boost the anode current to levels usable by a digital multimeter, and the Franck- Hertz box which contains the 0-110 volt ac supply as well as the 6.3 volt ac filament supply.

If you look closely at the oven (square gray box with a hole through which the FH tube fits), you will see 3 banana plugs connected to leads coming from it. Two of the leads are plugged into the 110v supply jacks and the green one is connected to the jack marked (Gnd). The plug with the bare copper braid is also plugged into ground. The experimental configuration is presented in Figure 3.

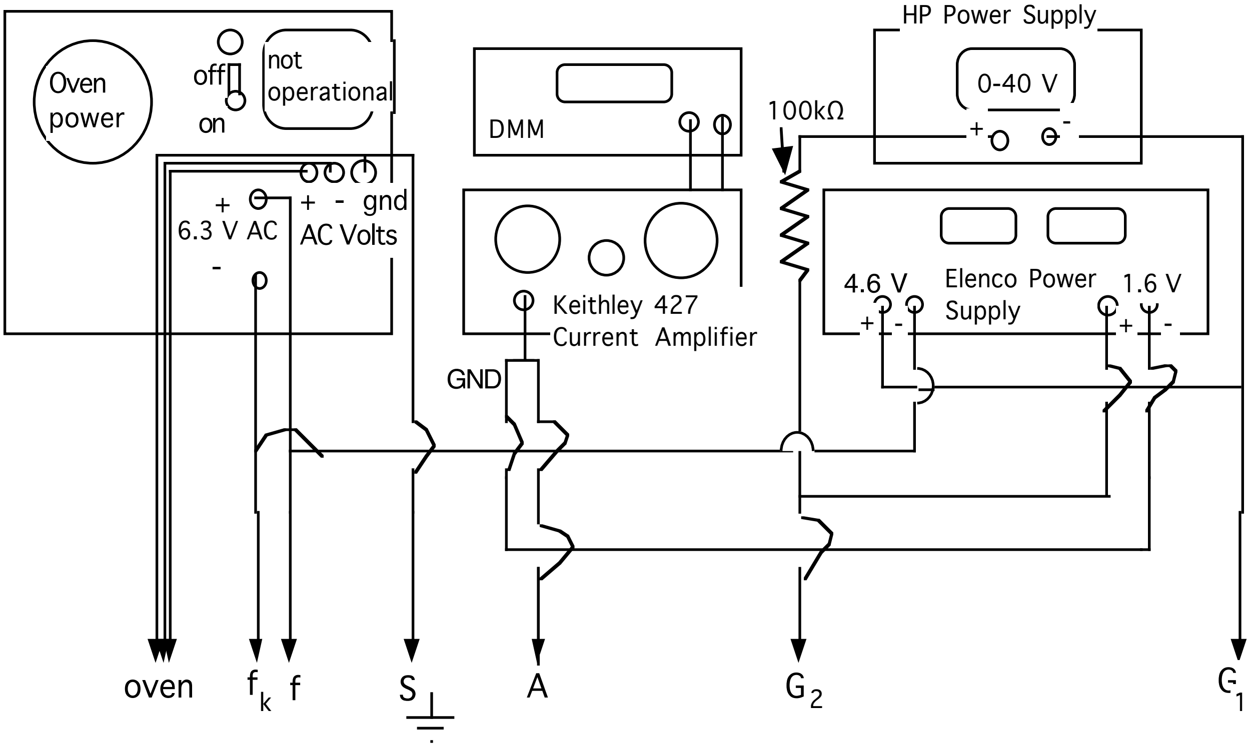

Figure 3. Experimental configuration for Franck-Hertz experiment.

<u>The experiment:</u>

First, place the tube in the oven. Make sure the thermocouple leads are in contact with some part of the tube. Disconnect the 6.3 volt supply by removing either wire "f" or "f_k". You may have to tilt the oven back slightly by propping up the front of the oven about 0.25 inch in order get the mercury to roll down into the tube where it will be heated.

Preheat the oven by turning the switch on the Franck -Hertz box and adjusting the variac to 110V for about ten minutes. As the temperature approaches 200°C turn the variac down to approx. 45 - 55V. Try not to overshoot 200˚C too far or you will have to wait a while for the oven to cool down. You may have to watch the temperature monitor and adjust the oven voltage up or down in order to keep the temperature steady at something near 180-210°C. Note that there is several minutes delay between the time you adjust the voltage and the time the temperature changes as a result of your adjustment.

The electronic connections of the Franck -Hertz tube emanate from the bottom of the tube itself. There are six banana plugs, all tagged. Connect these as shown in the diagram, but apply no voltages until the tube is up to temperature to reduce the risk of shorting the grids with liquid mercury. Note that the 6.3 v ac filament supply is unswitched, therefore if the box is on to heat the tube you should leave the filament connectors unplugged until the tube is hot. When the tube has reached 200° C, plug in the filament leads and let the filament heat for a minute or so. Then adjust G1 to 4.6 V, and retarding voltage to 1.6 V. At this point, as you slowly increase G2, you should see a steady rise in the anode current. If the current rises quickly, the gas is discharging and is too cold. If the current increases very little the tube may be too hot. Adjust the oven temperature accordingly up or down a few volts at a time and wait 5-15 minutes for the temperature to stabilize. You may also need to vary the potential on G1 between 2 and 10 volts. For the present configuration, around 5 volts is usually best. If everything is just right your current should rise steadily until it approaches the excitation energy of mercury, whereupon it will decrease. Record the output current in fairly small steps (around .2 V) as you vary G_2 from 0-25 volts to measure multiple peaks. An x-y plotter or computer may also be available to record the output directly. If you have time, you may want to compare the spectra at different values of G_1 (0 - 10 volts), retarding voltage (0 - 10 volts) or temperature (150 - 250˚C) to see how they influence your results.

Why are your curves shaped the way they are? How does your result compare with the known first excited level of mercury ?

Some pertinent information:

1. The current should drop at around 5V intervals of G2
2. If the current amplifier is set at 10^7 volts/amp, your DMM should be set on millivolt scale and you should see .5 to 10 millivolt rise as you adjust G_2 between 0 and 25 volts.
3. The experiment is not well shielded and very small currents are being measured. You may find that motion of your body will cause noise in the readings.

At the end of the experiment, unplug the filament voltage lead (f or f_k) and then turn off all of the tube voltages. Then shut off the oven. It will take some time for the oven to cool.

References:

1. R. Eisberg and R. Resnick, *Quantum Physics of Atoms, Molecules, Solids, Nuclei, and Particles,* (John Wiley and Sons, New York, 1974). - theory of Franck-Hertz experiment

2. S. T. Thornton and A. Rex, *Modern Physics for Scientists and Engineers,* (Saunders College Publishing, Fort Worth, 1993). -theory of Franck-Hertz experiment

3. J. W. Rohlf, *Modern Physics from α to Z˚,* (John Wiley and Sons, Inc., New York, 1994). - theory of Franck-Hertz experiment

4. A. C. Melissinos, *Experiments in Modern Physics,* (Academic Press, Orlando, 1966). - description of theory and experimental procedure.

Type K Thermocouple Reference Tables from NIST: http://srdata.nist.gov/its90/main/

Type K is Nickel-Chromium vs. Nickel-Aluminum
Type K usually has a positive yellow wire and a negative red wire.

These tables assume that we are referencing our thermocouple to 0 volts at 0˚C. We are actually referencing our thermocouple to room temperature (about 25˚C). As a result, **you need to add 1.0 mV to the reading on your meter before going to this table to determine the temperature**. Temperatures in Degrees C

Deg C	0	1	2	3	4	5	6	7	8	9	10
100	4.096	4.138	4.179	4.220	4.262	4.303	4.344	4.385	4.427	4.468	4.509
110	4.509	4.55	4.591	4.633	4.674	4.715	4.756	4.797	4.838	4.879	4.920
120	4.920	4.961	5.002	5.043	5.084	5.124	5.165	5.206	5.247	5.288	5.328
130	5.328	5.369	5.410	5.450	5.491	5.532	5.572	5.613	5.653	5.694	5.735
140	5.735	5.775	5.815	5.856	5.896	5.937	5.977	6.017	6.058	6.098	6.138
150	6.138	6.179	6.219	6.259	6.299	6.339	6.38	6.420	6.460	6.500	6.540
160	6.540	6.580	6.620	6.660	6.701	6.741	6.781	6.821	6.861	6.901	6.941
170	6.941	6.981	7.021	7.060	7.100	7.140	7.180	7.220	7.260	7.300	7.340
180	7.340	7.380	7.420	7.460	7.500	7.540	7.579	7.619	7.659	7.699	7.739
190	7.739	7.779	7.819	7.859	7.899	7.939	7.979	8.019	8.059	8.099	8.138
200	8.138	8.178	8.218	8.258	8.298	8.338	8.378	8.418	8.458	8.499	8.539
210	8.539	8.579	8.619	8.659	8.699	8.739	8.779	8.819	8.86	8.9	8.94
220	8.940	8.980	9.020	9.061	9.101	9.141	9.181	9.222	9.262	9.302	9.343
230	9.343	9.383	9.423	9.464	9.504	9.545	9.585	9.626	9.666	9.707	9.747
240	9.747	9.788	9.828	9.869	9.909	9.95	9.991	10.031	10.072	10.113	10.153
250	10.153	10.194	10.235	10.276	10.316	10.357	10.398	10.439	10.48	10.52	10.561
260	10.561	10.602	10.643	10.684	10.725	10.766	10.807	10.848	10.889	10.93	10.971
270	10.971	11.012	11.053	11.094	11.135	11.176	11.217	11.259	11.3	11.341	11.382
280	11.382	11.423	11.465	11.506	11.547	11.588	11.63	11.671	11.712	11.753	11.795
290	11.795	11.836	11.877	11.919	11.96	12.001	12.043	12.084	12.126	12.167	12.209
300	12.209	12.25	12.291	12.333	12.374	12.416	12.457	12.499	12.54	12.582	12.624

thermocouple voltages in mV