

# Physics 201: Experiment #1 Franck-Hertz Experiment

Carl Adams

Winter 2004

## Purpose

To demonstrate that electrons colliding with gaseous mercury atoms lose energy in discrete amounts. **Nobel Prize Winner 1925!**

## References

Tipler, *Modern Physics*, pp. 155-157, Beiser, *Concepts of Modern Physics*, pp. 144-145

## Optional Prelab

1. What is the velocity of an electron that has an energy of 20 eV? Suppose that the electron has a head-on elastic collision with an Hg atom that is at rest. How much has the kinetic energy of the electron changed?
2. What is the wavelength of a photon that has an energy of 4.9 eV? Where is it in the EM spectrum?
3. Assuming ideal gas law, what is the density of Hg atoms in a vapour that has a pressure of 1 kPa and a temperature of 180 °C. Look up the atomic radius of Hg. How far do you think an electron could travel through this gas before hitting an Hg atom? (think a bit, draw a picture, make some assumptions)

## Apparatus

Computer with IEEE interface and Labview, Labview program “Franck-Hertz”, two Hewlett-Packard 34401A Multimeters, Franck-Hertz Operating Unit, combined Franck-Hertz tube and oven, digital storage oscilloscope, connecting wires

## Theory/Operation

The electron-mercury collision experiment of Franck and Hertz, for which they received the Nobel prize in 1925, is one of the key experiments that helped establish modern atomic theory. It shows that atoms can absorb energy only in quantum portions, confirming Bohr’s postulates. It also demonstrated this fact in a purely *non-optical* experiment. Consult the diagram on the front of the oven, the schematic in Fig. 1, and also look at the tube itself through the windows in the oven. The tube is heated in the oven, vapourizing some of the mercury atoms in the tube. (You should be able to see a small drop of mercury at the

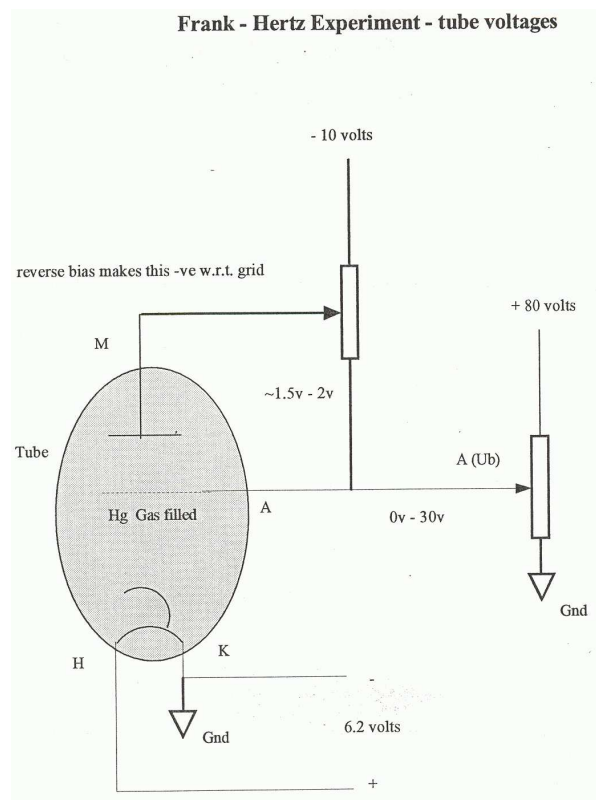


Figure 1: Franck-Hertz schematic

bottom of the tube.) 150 to 200 °C is a typical tube temperature. The cathode is heated using the operating unit (to a much higher temperature than the oven) and some electrons also “vapourize” so that they are emitted from the cathode. Their kinetic energy is quite small so if nothing else happened they would form a cloud near the hot cathode. However the operating unit provides an accelerating voltage towards the anode (generally between 0 and 40 V). The electrons move towards the anode, colliding with mercury atoms while in transit. Although many collisions are elastic, others are inelastic, causing the electrons to lose energy. This energy is transferred as an electronic excitation in the mercury atoms (which we hypothesize is a discrete quantum value). The anode is perforated so electrons can easily pass through and just beyond it is the counter electrode where current is collected, providing an output signal. The counter electrode is held at some small potential ( $\sim 1.5$  V) lower than the perforated anode (it is *reverse biased*) so electrons will need a bit more energy to make it to the counter electrode and be counted as a current. This prevents electrons which have lost most of their energy from being counted (eliminates a background of low energy electrons, turn it off and see what the signal looks like). Energies of electrons are given in eV or *electron-Volts*. An electron which passes through a one Volt potential will have a kinetic energy of 1 eV.

The whole thing acts as a scattering experiment or as an I-V curve that is very non-Ohmic (it is very similar to a *gas-filled thermionic diode* of pre-solid state electronics days). You set the total available electron energy with the accelerating voltage and then you measure how many get through. As you increase the accelerating voltage the current will increase until

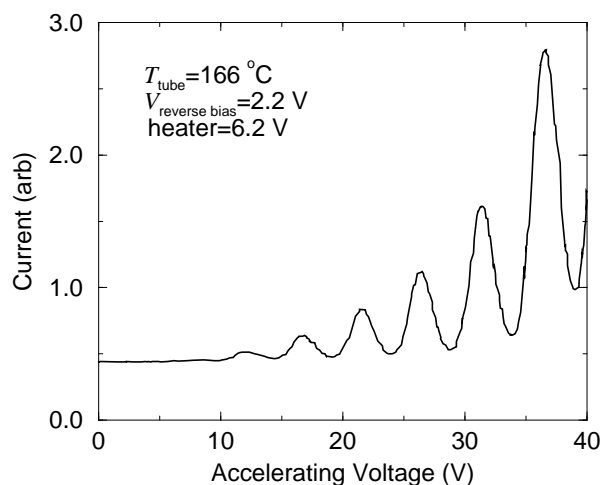


Figure 2: A sample of data taken with the computer.

the Hg atoms begin to strongly absorb energy, then the current drops off since the scattered electrons cannot overcome the reverse bias to reach counter electrode. If the accelerating voltage is increased beyond this point, the slowed electrons accelerate again until they have enough energy to once again inelastically collide with the Hg atoms. The total possible current goes up with voltage so you have a current versus voltage profile that looks like Fig. 2 with a series of dips and peaks.

## Procedure

Ordinarily, the result of the Franck-Hertz experiment is displayed as a plot of counter electrode current versus accelerating voltage, but this leaves the experimenter with no permanent record of the results for later examination and study. For this reason we have written a Labview program (on the Desktop) to take data from the two multimeters. You still need to slowly increase the accelerating voltage by twisting the knob on the “Operating Unit”. *A computer plot of this data should accompany your results!* Before using the computer however it is worthwhile to take some time to study the Franck-Hertz I-V curve with an oscilloscope.

1. The apparatus is already set up. Make a schematic diagram in your lab book showing the parts of the Franck-Hertz tube and the applied voltages. During the experiment, a mercury vapor pressure of 0.6 to 2.6 kPa must be maintained in the tube. Therefore the entire tube must be kept at a temperature of about 150 to 200 °C. Turn on the oven using the thermostat knob on the side and wait approximately 10 minutes for the temperature to reach 180 °C.
2. You can use this time to familiarize yourself with the Labview program and the experimental setup. Turn on the multimeters. They should both be set to read DC voltage. Identify which one reads the accelerating voltage. For some reason the operating unit doesn't output the accelerating voltage but in fact one tenth of the voltage! (maybe to prevent shocks? or the need to use a high voltage setting on the multimeter?) The

Labview program multiplies by 10 to give you the real voltage. The other multimeter will give an indication of the electron current as measured at the counter-electrode but its magnitude is arbitrary since it is controlled by the amplitude knob. (I believe the real current values are in the neighbourhood of picoamps. That's still 10 million electrons per second. We could look for a picoammeter to attempt an absolute measurement.) In the Labview program check to see if the device numbers for the multimeters correspond and give your data a file name that you can recognize. If you leave the file name unchanged any new data will just be appended to the old data.

3. Turn on the "Operating Unit" making sure that "Reverse Bias" (M block), "Acceleration" (A block), and "Heater" (H block) are turned to minimum values. Turn the reverse bias to 2 V. Turn amplitude (for the amplifier of the picoammeter which is inside the operating unit) to roughly two thirds. Turn the heater to 7 V (that's right, above the "MAX" mark). Make a note of the voltages that you see. (This is like a background current.)
4. Once you are up to 180 °C make a note of the oven temperature from the glass thermometer. You will probably feel the heat coming off of the oven. Mercury smells a bit like roasting turkey with electrical solder just in case you notice a strange odour. . .
5. Slowly turn up the acceleration voltage making sure the switch is set to "MAN". You should see a corresponding increase of the voltage on the "Volts" multimeter. Not much will happen to the current except that there should be some slight increase as you move up towards 12.5 V and then a drop, then another stronger rise at 17.5 V. Continue to increase slowly up to 41 V or so and note the peaks and valleys in current as they occur.
6. Trying to see what is going on is much easier using an oscilloscope and the *Ramp* feature on the operating unit. Transfer the cables from the multimeters to the scope or else make connections in parallel. Set the scope to run in "XY" mode. (This is the mode you would have used for looking at Lissajous figures in AC circuits and is also useful for displaying IV characteristics of diodes and transistors. Access through the "DISPLAY" menu, then use the buttons at the side of the screen). Change the mode of operation to *Ramp* on the operating unit. Adjust the scales and positions until you see the IV curve on the screen. (neat, eh?) If you don't see something that looks like Fig. 2 see the next step in the *Procedure* for some advice. Adjust the accelerating voltage downward (you are still at 41 V?). You will probably see the curve clean up quite a bit. Turn back up slowly and you will see a bit of chaos at the high voltages. Take a look at the tube itself and you will probably see a bluish glow of gas discharge coming from the cathode. Turning the tube temperature up a bit will probably help extend your range. Try to push it up to 40 V. Now adjust the reverse bias: the peaks don't shift but the heights change. You may find better contrast at slightly lower reverse bias, near 2 V. Turn the cathode heater down a bit and notice what happens. Make a note of your final, best settings and temperature. If the temperature gets too high your peaks might wash out somewhat . I also noticed that there seems to be a fair bit of noise. Make a sketch of what you see.

7. A common problem is that if the temperature is too low there will be a gas discharge. (The gas in the tube becomes ionized, neutralizes the negative *space charge* near the cathode, current flows easily, and the glow is like a neon light. You use a gas discharge tube for measuring the Balmer series of lines in hydrogen.) It will look like a bluish glow in the tube and you will lose your Franck-Hertz signal. Too much electron current or accelerating voltage can cause the same problem. If you are still waiting for the oven to heat up you can just do a trial run with Labview if you keep the (real) accelerating voltage below 10 V

Another common problem is not enough electron current by having a filament/cathode that is too cold from not enough Heater power. A very slight increase is probably all that is necessary and try to keep the Heater set to as low a setting as possible.

8. The next part of the procedure is to use the computer to make a record of the data. You will manually ramp the accelerating voltage and let the computer record the XY points. Later you can produce a plot of the data using a computer plotting program. The data will hopefully look something like what you see in Fig. 2. Have a close look at the Franck-Hertz tube when you are at 30-40 V and you should see a series of blue stripes where the Hg gas is being ionized. (There should be a picture of this as part of the Labview front panel.)

## Data Analysis

First make sure that you have lots of points going through the peaks. This may take a bit of practice at slowly turning up the voltage. You have hopefully optimized the various voltage settings for maximum contrast and minimum noise. So ... what do you think of the data? Does it look like the Hg atoms collide elastically or inelastically with the electrons? What is the best way of establishing that the peaks (or valleys) are a uniform distance apart and determining that distance? A typical plot establishing the value of quantum level appears in Fig. 3.

## Error Analysis and Other Questions

1. Why are the valleys wide? The quantum level is narrow, right (one part in  $10^9$ )? Give the ratio of full width half-maximum of a valley to the energy of the quantum level as a percentage width. The reason for the large width is the range of energies that the electrons have as they come from the heated cathode. How might you improve on the electron energy resolution?
2. How much of an uncertainty is there in the peak position? Is it related to the number of points in the peak and the width of the peak? Answer: YES, it is probably something like the error in the average of a number of points each with a random gaussian error of  $\sigma$ .
3. Give an error estimate of the active Hg energy level based on your results. Keep it in mind when you do similar spectroscopic measurements.

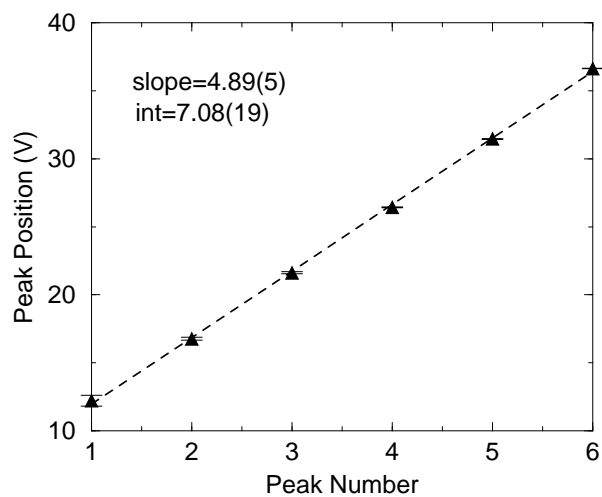


Figure 3: A plot of peak position versus peak number establishing the value of quantum excitation energy in Hg.

4. Is this the only quantum level in Hg? Why don't we see other levels? What would happen to our results if other levels were prominent?