PHYS 4211 **Last edit: May 3, 2011**
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FRANCK-HERTZ EXPERIMENT

GOAL

- You will repeat a portion of the 1914 Nobel-Prize winning experiment that demonstrates the quantization of energy transfer in inelastic electron-atom collisions.
- You will measure the first excitation energy of mercury.

Overview

We know from quantum mechanics that bound electrons in an atomic system occupy discrete energy states. In order to excite the atom – promote an electron from one energy level to one of higher energy – a definite amount of energy must be imparted to the electron, implying that energy levels in an atom are discrete or quantized. These ideas were also present in the then recent (1913) Bohr theory of the atom, but with somewhat fragile theoretical and experimental justification. The Franck-Hertz experiment was originally performed in order to determine

- whether atoms can be excited by low-energy electron bombardment;
- if the energy transferred from the bombarding electrons to atoms was discrete or not;
- if energy transferals assume discrete values, do these values correspond to the values derived from spectroscopic measurements.

This particular PHYS 4211 experiment concentrates on the second issue and as a by-product of this experiment you will measure the first excited energy level of mercury.

Hg in its ground state has the electronic configuration $[Xe]4f^{14}5d^{10}6s^2$, meaning all its available subshells are filled. (See your modern physics text for an explanation of atomic shells.) This makes Hg act a bit like a nobel gas element and thus forms weak bonds and easily melting solids.

FH tube

Figure 1 shows the essential features of the device used to detect the quantization of energy transfer to gaseous atoms from electrons. A pair of closely spaced, coaxial of electrodes is positioned a few centimeters away from a wire electrode, all inside an evacuated glass tube that contains a small amount of "spectroscopically pure" mercury. Provision is made to heat the tube to produce mercury vapor inside it. It is useful to know that the vapor pressure P of mercury between 298 K and 400 K is given to a good approximation by $\log_{10}(p/\text{Pa}) = 10.12 - 3190/(T/\text{K})$, to an accuracy of about 5%. (This is just an approximation to the Clausius-Clapeyron equation that gives the pressure of a vapor in equilibrium with a liquid at a temperature T. See your favorite statistical mechanics text.) From the ideal gas law, $p = nk_BT$, you can then estimate the number density n of Hg atoms in the gaseous phase inside the tube at a temperature T.

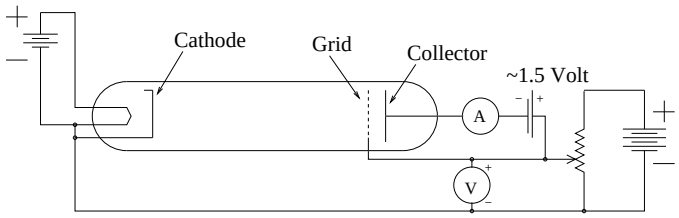

Figure 1: Diagram of Franck-Hertz tube.

An electric current is run through the isolated metal electrode to produce free electrons through *thermionic emission*. Essentially, you just heat the electrode, much like you heat the nichrome wire in your toaster, and the electrons stream out of the metal. The current density J of emitted electrons is given by Richardson's formula, $J = C_0T^2\exp(-\phi/kT)$. Here C_0 is a material dependent constant and ϕ is the *work function* of the metal, the minimum energy required to free an electron from the binding potential inside the metal. The work function is typically measured in the energy units of electron-Volts. For reference, $kT \sim 1/40\,\text{eV}$ at $T = 300\,\text{K}$ and and the exponential factor in J completely dominates the T^2 factor. The emitted electrons have a range of kinetic energies and are emitted in all directions.

The electrode marked "grid" is placed at a positive and adjustable potential with respect to the hot electrode that produces our electrons. The "collector" electrode is placed at a slight fixed negative potential (~ 1.5 Volts)

with respect to the grid. Electrons emitted from the hot cathode are accelerated by the electric field between it and the grid. They then collide either elastically or inelastically with the atoms in the mercury vapor.

Collisions and mean free path

From your modern physics text, you may recall that the mean free path λ for collision is given by $n\lambda\sigma = 1$, where σ is the collisional cross-section and n is the number density of targets. Combining this result with the above pressure versus temperature relationship, you can estimate the mean free path for inelastic collisions as a function of temperature T. Figure 2, taken from Hanne's article, shows Hg-electron inelastic cross-sections relevant for us. Compare your estimate for λ with the distance between cathode and grid in the FH tube. Do you see why the cathode-grid distance is what it is? What can you say about the grid-collector distance? Can you estimate how less likely it is for an inelastic collision to occur between the grid and collector than between the cathode and the grid? **Include these comments in your lab report!**

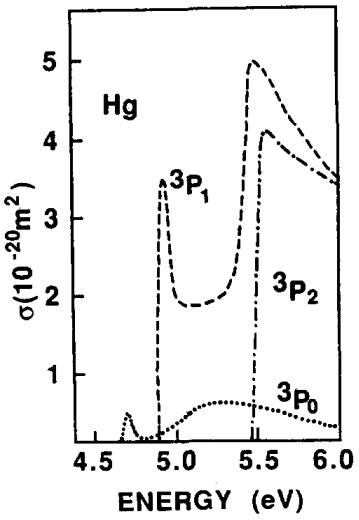

Figure 2: Some important Hg-electron inelastic cross sections. Taken from Hanne.

Energy levels in Hg

Read the Hanne article in the bibliography section for a detailed discussion of what Hg energy levels are relevant for this experiment and a

discussion of the size of various inelastic cross sections. Here, we just give a cursory summary. The ground state of mercury is $^1S_0$, in spectroscopic notation, which means that the 2 valence electrons form a state with no spin or orbital angular momentum. The next highest atomic energy level corresponds to putting the valence electrons into a 6s6p state. However, combining spin and orbital angular momentum properly, and taking into account the *spin-orbit effect* you can read about in your modern physics text, the mercury valence electrons can occupy any one of a *triplet* of states, each of which has a slightly different energy: $6^3P_0, 6^3P_1$ and 6^3P_2. Figure 3, taken from Hanne, summarizes the situation.

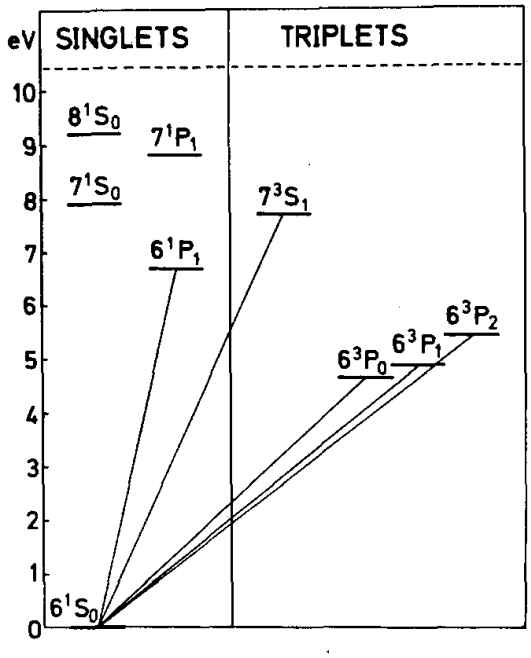

Figure 3: Low lying energy levels in neutral Hg. Taken from Hanne.

Collector current

Electrons accelerated to an energy equal to or larger than one of the excitation energy levels of mercury, and that suffer an inelastic collision, can transfer their kinetic energy to a mercury atom by exciting it (without ionizing it). Afterwords, the electron has either zero kinetic energy or at least

a much reduced value. It is then possible for the electron to be collected by the grid if it does not subsequently acquire sufficient kinetic energy through further acceleration by the ambient electric field to overcome the repulsive potential between the grid and anode. (Read the Melissinos reference for a nice figure that shows, among several things, the shape of the electric potential inside the tube. You should draw for yourself the direction of the electric field in the various parts of the tube.)

The electron current captured by the collector is monitored as a function of the accelerating voltage between the heated cathode and the grid. A distinct minimum in this current should be observed if an appreciable number of bombarding electrons suffer an inelastic collision with the mercury atoms in the vapor *and* if these collisions transfer the same amount of energy to the mercury atoms.

This experiment is more subtle than it looks. It is possible to observe the modulations in the collected electron current even if there is not a retarding potential between grid and anode but an *accelerating* potential. This effect, due to the combination of *elastic* collisions and the variation of the electron mean free path with energy, is explained in McMahon's article listed in the bibliography.

A technical description of the equipment can be found in the attached PASCO Instruction Manual. Notice that the Control Unit described in the PASCO manual differs slightly from the one used in our laboratory. There is no "Zero Gain Adjustment" knob but instead there is a "Reverse Bias" knob.

The PASCO manual also contains a brief theoretical introduction. More detailed explanations of the experiment can be found in the literature listed below. *I strongly recommend that you read reference 4.* There are copies in the library (what's that?) and I have placed my own copy in the lab.

Be careful setting the temperature of the oven. We have had students break the tube because they overheated it and produced too much mercury vapor pressure. A temperature of 190 C produces a vapor pressure $p \simeq 15$ Torr, plenty for the experiment.

You will perform Franck-Hertz experiment by first using voltmeters (Experiment B in the PASCO manual), and then by using an oscilloscope (Experiment A in the PASCO manual). The experimental procedures, somewhat different from those in the PASCO manual, are given below. **You should read both sets of instructions.**

Literature

1. J. Franck and G. Hertz, *Verhand. Deut. Physik Ges.*, **16** (1914) 457.

2. G. P. Harnwell and J.J. Livingood, "Experimental Atomic Physics," McGraw-Hill, New York, 1933.

3. G.F. Hanne, "What really happens in the Franck-Hertz experiment with mercury," Am. J. Phys. **56**, 696 (1988).

4. D.R.A. McMahon, "Elastic electron-atom collisions in the Franck-Hertz experiment," Am. J. Phys. **51** 1086 (1983).

5. T.A. Littlefield and N. Thorley, "Atomic and Nuclear Physics," Van Nostrand, 1968.

6. A.C. Melissinos, "Experiments in Modern Physics," Academic Press, New York, 1966, Chapter 1, section 3.

7. Stephen T. Thornton and Andrew Rex, "Modern Physics for Scientists and Engineers," Saunders College Pub., 1993.

8. M. R. Wehr et al., "Physics of the Atom," 3rd ed., Addison-Wesley, 1978.

Lab Report Contents

1. Abstract;

2. Concise description of relevant theory and procedure;

3. Schematic of apparatus with appropriate identification;

4. Raw data;

5. Explanation of results, **including answers to lab questions** and curve of V_c v. V_a;

6. Concise conclusion (i.e, what does it all mean?).

INSTRUCTIONS

I. Experiment using voltmeters

Connect the Control Unit with the Franck-Hertz tube enclosed in the oven. (See Figure 4 in the PASCO manual). Use one of the more precise voltmeters lying around the lab to measure a voltage V_c proportional to the anode current. You can use the autoranging Fluke 73 DVM to measure the acceleration voltage, V_a.

Adjust the height of the thermometer so that its base is about even with the middle of the Franck-Hertz tube. Turn the thermostat dial to slightly less than 180°. Plug the oven into a power outlet. and allow the oven to heat up for 10-15 minutes. Watch the thermometer. **Do not let the oven temperature exceed** 195°**.** Excess heat will damage the tube by increasing the pressure in the tube from mercury vapor and by stressing some of the vacuum seals on the tube.

The acceleration voltage V_a switch should be set to its minimum value (counter clockwise all the way). The V_a switch on the control unit should be set to MAN. Cathode Heater voltage should be set at the midrange (about 5.5V). Set the Reverse Bias voltage to the "Hg" position and measure this voltage by measuring the voltage difference between the grid and the collector with a voltmeter. Now set the Signal Gain to the maximum (fully clockwise). Finally, switch the control unit on.

Slowly increase the acceleration voltage V_a to the maximum value possible $30 - 35$ V. If you try to increase the voltage even further (the V_a knob goes up to 70 V) the measured V_a will actually drop. Look at the tube through the side window in the oven when this happens. What do you see when you pass the maximum attainable acceleration voltage? Can you explain why the measured voltage actually drops when you pass this point? **Do not increase voltage much beyond the maximum. Do not keep the tube on such voltages for extended periods of time.**

Set V_a somewhat below below the maximum, say, $V_a = 25\,\mathrm{V}$ or so. If the V_c reading exceeds about 11 V, the amplifier is almost certainly saturated. You may decrease the Signal Gain to avoid the saturation. Record V_c versus V_a by decreasing V_a in steps of 0.5V, or so. Make a plot of V_c versus V_a. You should see at least two maxima and minima. Briefly explain the origin of the minima. Why don't the minima extend all the way to zero? Why aren't the "dips" narrow valleys? Repeat your measurements but this time start at low voltage and end at higher voltage. Determine the excitation energy of Hg from your plots. Should you be concentrating on the positions of the peaks or the dips? Finally, take a picture or two of the experimental setup with your camera phone if you have one handy.

II. Experiment using an oscilloscope

The temperature in the oven is not completely constant but varies with time over a certain range. You will often hear a clicking sound when the heating control switch opens or closes. Temperature changes in the oven have a large effect on the anode current, and therefore, V_c. (Just think of what is happening to the density of gaseous Hg atoms.) Thus, the temperature variation may constitute a serious problem when measuring the excitation energy of Hg by the previous method. These difficulties are minimized by using an oscilloscope instead of the voltmeters.

Set the V_a switch to RAMP. Connect the $V_a/10$ output to the input of the oscilloscope. Observe the V_a pulse generated by the Control Unit on the screen. Include a sketch of the pulse shape in your report (indicate time and voltage units). You can control the amplitude of this pulse by using the acceleration knob (contrary to the control unit described in the PASCO manual). Adjust this knob to get the maximum of the pulse at about 30 V (i.e., about 3 V on the scope screen).

Disconnect the $V_a/10$ output from the normal input of the oscilloscope and connect it to the X–INPUT of the scope. The pulse you have observed will now be displayed on the horizontal axis (instead of time). Connect the V_c output from the Control Unit to the normal input of the oscilloscope. The V_c signal will be displayed on the vertical axis. The X–Y switch should be on. You should see Franck-Hertz minima and maxima directly on the screen. Since the temperature variations are very slow compared to one V_a pulse, they do not upset the measurements.

Increase the V_a amplitude (with the acceleration knob) to observe as many peaks as possible. You will need to adjust the signal gain as well. Do not increase V_a amplitude beyond the point where you see a flat saturation of the V_c response. With the time dependent V_a voltage you will be able to explore much wider V_a range (up to about 50 V or so) than in the previous experiment. Why?

If you can, take a picture of the oscilloscope trace. Otherwise, sketch the waveform you see on the scope screen. The picture or sketch should be included in your lab report. You may also want to annotate it so that it is understandable by the reader.

You need to be able to calibrate the horizontal axis of the oscilloscope plot since the normal time sweep feature is disabled in X–Y mode. You will also need to measure the voltage difference between voltage minima of the wave form. First, measure the total width of the wave form along the X–coordinate using the screen units, D_x. Measure distance between the maxima (or minima) in screen units, D_m. Without changing any controls on the Control Unit, Observe the V_a pulse on the oscilloscope again, in order to

measure the maximal generated value of V_a (V_{max}). Calculate the excitation level of Hg by: $V_{max}D_m/D_x$. Why does this procedure make sense?

Determine the excitation energy of Hg from your plot. Include an error in your answer and some explanation of how it is estimated.