

# THE FRANCK-HERTZ EXPERIMENT

**OBJECT:** To measure the excitation potential of mercury using the Franck-Hertz method.

**EQUIPMENT LIST:** Mercury vapor triode, oven and control unit (Neva-Klinger Scientific), rheostat, multimeter, digital storage oscilloscope, Variac.

**THEORY:1. Excitation by electron impact of quantized, bound atomic states.** In 1913 Niels Bohr proposed the Bohr model of the atom which assumes that atoms can exist only in certain bound energy states. This idea was given a powerful boost in 1914 when James Franck and Gustav Hertz performed an experiment that demonstrated the existence of quantized energy levels in mercury. The experiment involved sending a beam of electrons through mercury vapor and observing the loss of kinetic energy when an electron strikes a mercury atom and excites it from its lowest energy state to a higher one.

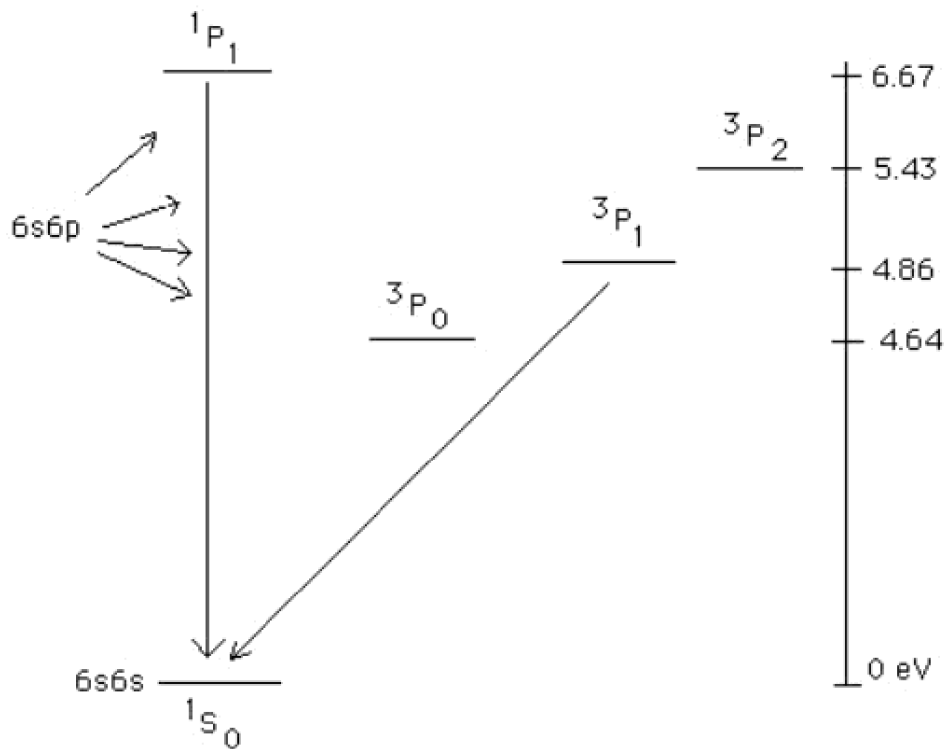


Figure 1: Energy Levels of Atomic Mercury

Mercury vapor atoms will normally be in their lowest or ground state, with the two valence electrons occupying a state designated by  $(6s)^2$  (two electrons in  $n = 6$ ,  $l = 0$  single particle states). The two electrons do not move independently so that three quantities -- the total spin angular momentum  $S$ , the total orbital angular momentum  $L$ ,

and the total angular momentum  $\mathbf{J}$  -- are constants of the motion designated by quantum numbers  $S$ ,  $L$ , and  $J$ , respectively. Thus the electron states are labeled with the spectroscopic notation  $^{2S+1}L_J$ . The value of  $L$  is denoted by  $S$  for  $L = 0$ ,  $P$  for  $L = 1$ , etc. The ground state in mercury is then  $^1S_0$ .

As shown in Fig. 1, the next levels above the ground state are a "triplet" of levels --  $^3P_0$ ,  $^3P_1$ , and  $^3P_2$  -- corresponding to single electron states ( $6s6p$ ) where the electron spins are parallel. There is a higher singlet  $^1P_1$  state with spins antiparallel. In a collision with an energetic electron the atom could be raised into any of these excited states.

However, in the Franck-Hertz experiment we mainly observe excitation into the  $^3P_1$  state for the following reason: Once the atom is in an excited state it can return to the ground state by emission of a photon. This is normally a very rapid process typically taking  $10^{-8}$  s. However, photon de-excitation transitions must satisfy conservation of total angular momentum. The emitted photon carries an angular momentum of  $J=1$  which it carries away from the atom. Thus the total angular momentum quantum number of the atom must change by  $\Delta J = \pm 1$  (according angular momentum addition rules -- see Zeeman experiment writeup for details). Thus de-excitation can occur from the  $^3P_1$  and  $^1P_1$  states, but not from the  $^3P_0$ , and  $^3P_2$  states, which are metastable -- de-excitation from a metastable state can only occur by slower processes which typically take on the order of  $10^{-3}$  s. In the Franck-Hertz experiment the electron beam may excite a mercury atom into the  $^3P_0$  or  $^3P_2$  state, but then it is stuck there (for a millisecond) and unable to absorb more energy. On the other hand, if the  $^3P_1$  state is excited, it quickly de-excites (in 0.01 microseconds) and the atom is again available to absorb energy from the electron beam. The  $^1P_1$  state is not usually observed since the  $^3P_1$  state is so effective at taking energy from the electron beam once the electrons reach  $\sim 4.86$  eV that they are not able to acquire the 6.67 eV needed to excite the  $^1P_1$  state.

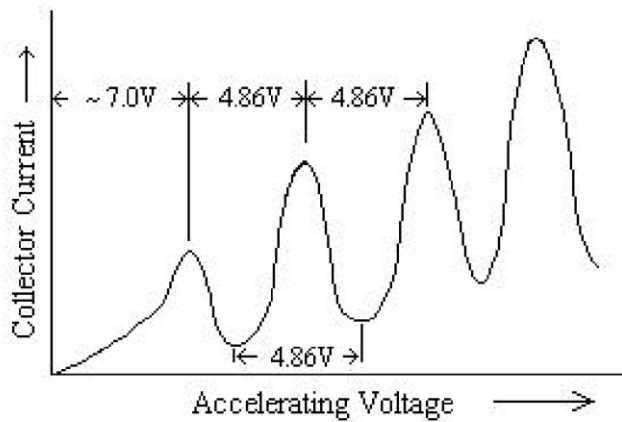


Figure 2

In this experiment electrons emitted by a hot cathode are accelerated through the mercury

vapor to a collector electrode. When the accelerating voltage is increased to 4.86 V, the collector current will drop due to the onset of energy loss of the electrons caused by collisions with Hg atoms that raise the atoms from their  $1P_0$  ground state to their  $^3P_1$  excited state. If the voltage is further increased the current will again increase until  $2 \times 4.86 = 9.72$  V where it will drop again, as shown in the sketch on the previous page. This is due to electrons which having lost most of their kinetic energy in the first collision again being accelerated to 4.86 eV kinetic energy so that in a second they can again excite the  $^3P_1$  state. This process will be repeated for  $3 \times 4.86$  V,  $4 \times 4.86$  V, etc. As we will discuss below there are several effects that will shift this pattern of repeated valleys (or peaks, depending how you look at the graph) to higher voltages. In principle, the spacing between the peaks/valleys should remain equal to 4.86 eV. However, you may find that this does not quite agree with your experiment. You should then try to find a reasonable physical explanation for the discrepancy. Excitation of states of lower and higher energy than 4.86 eV, if seen at all, will appear as "shoulders" on the dominant current drop.

**2. Mean free path of electrons.** The phenomena involved in this experiment are influenced strongly by how far, on the average, an electron goes before colliding with a vapor atom, and producing excitation. The average distance which an electron travels between collisions, **of any type**, is called the **electron mean free path**  $\bar{l}$ . This can be estimated from :

$$\bar{l} = \frac{4}{\sqrt{2}} \frac{1}{n(\pi R_0^2)} \quad (1)$$

$R_0$  is the radius of a Hg molecule and  $n$  is the number density of the gas, i.e. the number of molecules per unit volume. (See Halliday and Resnick for a derivation.) Note from Eq. (1) that  $\bar{l} (\pi R_0^2) n \approx 1$ . This means that  $\bar{l}$  is the average distance an electron will travel before coming within  $R_0$  of a mercury atom. In mercury the atomic radius is about  $0.15 \text{ nm} = 1.5 \times 10^{-8} \text{ cm}$ .

In this experiment the Franck-Hertz tube, which contains a drop of mercury, is placed in a heated oven. The mercury drops evaporates until the vapor is saturated, i.e. the rate of evaporation equals the rate of condensation. By changing the temperature  $T$  of the oven, you will be able to change the vapor pressure and hence the density. To estimate the mean free path, we will need to calculate  $n(T)$ . Mercury is monatomic. From the definition of gram-atomic weight  $A$ , the number of molecules per cubic centimeter is

$$n = (\text{mass/cm}^3)/(\text{mass/atom}) = \rho \div (A/NA) = \rho NA/A \quad (2)$$

where  $\rho$  is the mass density of the vapor and  $NA = \text{Avogadro's number}$ .

The Handbook of Chemistry and Physics or International Critical Tables give the pressure of saturated mercury vapor at various temperatures. If it is assumed that the vapor behaves approximately as an ideal gas at these low temperatures, then the density can be calculated by using the general gas law

$$PV = (m/A)RT, \quad (3)$$

where  $\underline{R}$  is the general gas constant,  $m$  is the mass of gas in the volume  $V$  and  $m/A$  is the number of moles. Then using  $\rho = m/V$  in Eqs. (2) and (3) we find

$$n = \frac{N_A}{R} \frac{P}{T} \quad (4)$$

In using this equation, be sure that you use a value for  $\underline{R}$  expressed in the same system of units you use for  $\underline{P}$  and  $T$ . Then you can estimate the mean free path at any oven temperature by using Eq. (4) and Eq. (1) along with the tabulated saturated vapor pressure  $P(T)$ . This table is given in the binder of readings available in the lab and can also be accessed from the supplementary reading column on the course website.

In order to see several peaks and valleys for taking data to determine the excitation potential, it is necessary, on the one hand, to have the electron mean free path shorter than the distance from the cathode to the anode (grid). But on the other hand it must be larger than the distance between anode and collector. During the experiment vary the oven temperature to optimize your data. For your report you will need to prepare a theoretical plot of  $\bar{l} (T)$ .

Note below the distinction between mean free path (related to total cross-section, including that for elastic scattering) and mean distance for collisional excitation (related to inelastic cross-section for scattering to a particular excited state), the latter being relevant to this experiment.

### 3. Excitation collisional distance

Eq. 1 above implies that the mean free path for electron collision of any kind is independent of electron energy. This is an approximation only, and in fact the cross section for elastic collisions does vary with energy. However, since elastic collisions involve essentially zero loss of electron energy (and little average change in electron direction), we have little interest in this process for the present measurement.

The collision distance we are interested in is for "inelastic" collisions. These transfer 4.86 eV of electron kinetic energy to the Hg atom which is excited to the  $^3P_1$  state and leave the electron with little or no kinetic energy. Such a collision has zero probability (inelastic cross section) for electron energies below 4.86 eV (elastic collisions may occur), and becomes likely beginning at a distance over which the electron can acquire 4.86eV from the accelerating field. (The hot cathode thermally emits electrons with a kinetic energy spectrum dependent on the cathode temperature, related in turn to the cathode current and the oven temperature.) For a cathode-anode distance of 8 mm and accelerating potential  $V_a = V_{K-A}$ , this distance is

$$L_c \sim 8 \text{ mm} \times 4.86/V_a \quad (5)$$

Thus, the collision distance of interest is a function of the accelerating potential. We will see that  $\underline{V}_a$  needs to be corrected slightly for the contact potential of different electrode

metals, an effect of the Fermi-Dirac quantum statistics of electrons discussed below. ( A similar effect occurs in the photoelectric effect.)

Attaining an electron kinetic energy of 4.86 eV represents a threshold for the excitation of interest ( $^3P_1$  second excited state). The excitation may occur at higher electron energy, but not lower. The energy at which the excitation probability is maximized is not necessarily 4.86 eV so that the characteristic distance would be modified by the actual maximum excitation value in the right hand side of equation (5). This will introduce an offset (intercept) in the experimental plot of  $I_{\text{collector}}$  vs  $V_{\text{anode}}$  of current minima, in addition to that arising from the cathode-anode contact potential difference discussed below. However, the spacing of successive excitation minima in the collector current should still be 4.86 Volts.

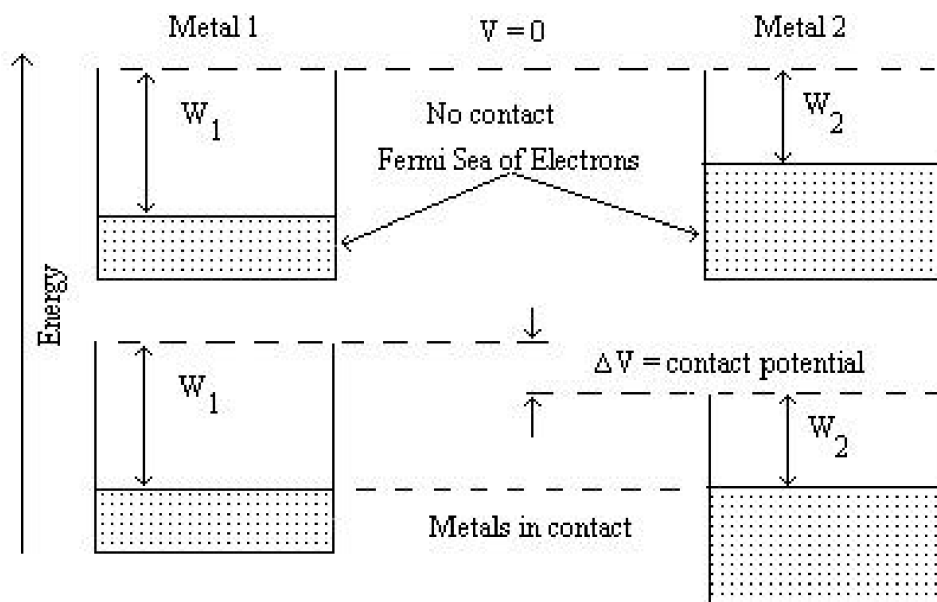


Figure 3: The Fermi energy and work function for two metals.

**4. Contact potential.** One of the central concepts in the physics of electrons in metals is the work function,  $W$ . The work function is equal to the minimum photon energy required to extract an electron from a substance. Figure 3 (top panel) illustrates the concept of the work function. In a metal, the valence electrons are not bound to the metallic ions but can wander freely throughout. Since no two electrons can have the same quantum numbers in the same position (because they are fermions) once an electron occupies an available state the next electron has to find another available state which may have higher energy. In each energy interval the number of electrons that can be accommodated per unit volume is called the “density of states”. One can think of the electrons in a metal in terms of filling a box of marbles. As the marbles are thrown into the box their height above the bottom (energy) increases. The last marbles to go in have the highest energy and they are also the most mobile (because the ones in the bottom have now available open spots to move into and so they are stuck). Same with electrons: the electrons can be thought of as filling a “Fermi

sea” of states. The highest energy (top of the sea) is called the Fermi energy. Only electrons at the Fermi energy contribute to the electronic properties of a material (because the rest are stuck). The work function is defined as the minimum energy to remove an electron from the top of this sea to a point far from the metal.

If the two metals shown in the diagram are placed in contact electrons flow from one to the other until energies of the top of the two Fermi seas (called the Fermi levels) are equalized.

**Question:** if the capacitance between the two metals is 10 pF, how many electrons must be transferred between them to equalize the Fermi seas?.

A potential difference  $\Delta V$  then develops between the two metals which is called the contact potential, as shown in the diagram. From the diagram we see  $\Delta V = W_1 - W_2$ . For the Franck-Hertz tube the manufacturer indicates that the contact potential is about 2 V, which you will be able to verify with your measurements. Note that to have a contact potential, the two metals do not have to be in intimate physical contact; it is sufficient for there to be a way for electrons to travel from one metal to the other. In the Franck-Hertz tube the electrons travel through the vacuum from the cathode to the anode; the two metals do not “touch”.

The electrons that travel through the Franck-Hertz tube are released by **thermionic emission** from the very hot cathode as follows: The surface of the Fermi sea that we have shown in the diagram is appropriate for a temperature of absolute zero. At higher temperatures thermal agitation raises some of the electrons above the Fermi level. At room temperature the average thermal energy is  $kT \sim 0.025$  eV, which is not enough for electrons to overcome the work function and escape. But when the cathode is raised to a high temperature ( $\sim 1500$  K) a few electrons have enough energy to escape, i.e. to be thermionically emitted. Ideally for the Franck-Hertz experiment we would like these electrons to have zero kinetic energy so that this initial kinetic energy will not interfere with our measurement of the change in kinetic energy due to inelastic collisions. However, experimental measurements show that for cathode temperatures in the 1500 K to 2500 K range thermionic electrons have a distribution of kinetic energies peaking at 0.2 to 0.3 eV. This will affect the location of the first peak in the current, but not the spacing of subsequent peaks.

**EQUIPMENT:** The essential components are a mercury thyratron tube, a variable power supply for the cathode heater, anode and collector voltage supplies with necessary meters, a sensitive dc amplifier for observing the small collector currents, and an oven with thermometer and controls to heat the thyratron to an appropriate temperature to produce the desired vapor pressure. You will use a digital oscilloscope for data collection.

**1. The oven.** The oven consists of a small steel cabinet with a heating element to uniformly heat the tube (and all connections leading to it). A 300 Watt heating element is mounted on the bottom of the housing. An adjustable thermostat in the oven regulates the temperature of the oven. Since the thermostat functions imperfectly (1-3 degrees drift), it is preferable to bypass it by setting it to maximum temperature and instead limiting the power delivered to the oven with a Variac (a variable auto transformer that steps down the 110 V AC line voltage). This approach gives adequate stability. To achieve a temperature

of about 185°, you can flip the switch to 140 V and turn the dial to 65% and wait for about 10 minutes. A hole in the top of the cabinet is provided for a thermometer.

**2. Thyatron tube.** A thyatron is a vacuum tube in which a drop of mercury was added before sealing. There are a couple of sample tubes next to the setup that you can inspect. Can you identify the various electrodes; where is the mercury? Such tubes, therefore, contain saturated mercury vapor (vapor in equilibrium with the liquid) at a pressure corresponding to the temperature of the bulb. The Franck-Hertz tube, a triode, has three plane-parallel electrodes which provide a uniform electric field to accelerate the electrons. The electrodes are the cathode (K), anode (A) and collector (M). The cathode is indirectly heated with a heater electrode (H and K) using a nominal voltage of 6.3 volts AC. (Note that the rheostat used to vary the cathode heater current should be connected to H, not to K which is grounded.) The anode is a perforated screen 8 mm beyond the cathode that is held at a positive potential  $V_a$  relative to the cathode in order to accelerate the electrons thermionically emitted by the heated cathode. The screen allows most of the electrons to pass through the anode. The collector lies a small distance (~2 mm) beyond the anode and is negatively charged relative to the anode with a voltage  $V_{ret}$ , which acts to retard (slow) the electrons that pass through the anode. These electrons (charge  $e$ ) can make it to the collector, if as they pass through the anode their kinetic energy is greater than  $eV_{ret}$ . Otherwise, they slow, stop, and reverse direction to return to the anode.

**3. Operation of the Franck-Hertz tube to observe inelastic scattering through changes in the collector current.** There are two lengths of interest -- the cathode anode separation (8 mm) and the mean free path  $\bar{l}(T)$  -- and two voltages -- the accelerating voltage  $V_a$  between the anode and cathode and the retarding voltage  $V_{ret}$  between the anode and collector. It is important to understand how they affect the experiment. The value of  $l$  and hence the temperature of the oven is not critical as long as  $\bar{l} \ll 8$  mm since you want to be sure the electrons make collisions with mercury atoms in the space between the cathode and anode. In order for this condition to hold, you will take data in the temperature range 180o-195o C. [On the other hand, you do not want collisions between the anode and collector, so the tube is built with these electrodes closely spaced, ~ 2 mm.]

As shown in Figure 2, the collector current will show a series of equally spaced peaks as the accelerating voltage  $V_a$  is increased. For a given  $V_a$  the number of times  $n_{col}$  that an electron can make an inelastic collision with a mercury atom and excite it to its 3P1 state (and losing 4.86 eV of kinetic energy in the process) while in the space between the cathode and anode is determined by the ratio

$$n_{col} \leq V_a / 4.86, \quad (6)$$

where  $n_{col}$  is the largest integer smaller than the ratio. As shown in the sketch, this relation has to be slightly corrected for two reasons. First, before an electron can make its first inelastic collision, it must overcome the cathode to anode contact potential of about 2 eV. Second, there is a small shift (toward lower  $V_a$ ) due to the small (~ 0.2 to 0.3 eV) initial kinetic energy of thermionically emitted electrons. Note that the contact potential and the initial kinetic energy only affect the value of  $V_a$  needed for the first inelastic collision; successive peaks will be separated by 4.86 eV.

Also note that although the onset in inelastic scattering is governed by Eq. (6), the drop in current is not sharp. This is because the excitation cross section is small at the threshold of excitation (kinetic energy = 4.86 eV) and the drop in current due to inelastic scattering doesn't reach a maximum until the kinetic energy is larger, say 5.1 eV. Note however, that the spacing of successive minima in the collector current should still be 4.86 volts: If peak excitation of the 4.86 eV state occurs at 5.10 eV, then an electron inelastically scattered with 5.10 eV will still have 0.24 eV of kinetic energy after collision. After accelerating through another 4.86 V, the electron will again have 5.10 eV of kinetic energy.

As one scans the accelerating voltage up to the maximum  $V_a$  allowed by the power supply, fewer peaks may be observed than predicted by Eq. (6), if (due to low oven temperature) the mean free path for inelastic scattering exceeds the distance required for the electron to attain 4.86 eV. The number of peaks observed will vary with oven temperature; experimentally you will want to vary the temperature to optimize the pattern of peaks.

The final relation we need to discuss is the role that the retarding voltage  $V_{ret}$  plays in the experiment, which is to generate the valleys. The current in the tube is proportional to the product of the electron density and the mean electron speed. If the tube had only two electrodes, you would not observe deep drops in current; these are produced by  $V_{ret}$ . When  $V_a$  is such that electrons undergo inelastic scattering just before passing through the anode, then they do not have enough kinetic energy to overcome the retarding effect of  $V_{ret} \sim 1.5$  V. The retarding voltage will then turn them around and prevent them from reaching the collector, producing the sharp drop in current (as a function of  $V_a$ ). We thus see that the locations of the peaks and valleys are independent of the value of  $V_{ret}$ , although the depth and shape of the valleys will depend on  $V_{ret}$ .

**4. Digital Storage Oscilloscope.** You will use a Tektronix Digital Storage Oscilloscope TDS2000C Series to collect the data. Prior to turning on the equipment read the operating manual for the scope to familiarize yourself with all its functions. The manual is in the reference material bin. Data recording is done by saving the data file to the PC. Alternatively you can save data directly from the scope using the dedicated 500Mb memory stick, attached to the computer. Note that no larger memory sticks are compatible with this scope.

### **PROCEDURE:**

**1.** The Franck-Hertz control unit and triode are shown schematically on page 11. Wire the apparatus by connecting terminals **M** to **M**, **A** to **A**, etc. with a rheostat and AC ammeter in series with the **H** (heater) input to allow heater current variation. [Note: When connecting banana plug outputs to BNC cables, be sure to observe proper grounds on the connectors; the little tab on the plastic banana plug labeled "gnd" indicates that that side of the banana plug is connected to the coaxial cable shielding, therefore to the ground of the coax BNC connector.]

**2.** Connect the F-H signal out terminal to the channel 1 input of the digital scope and the  $V_a/10$  output to channel 2. If the scope is set to X-Y display, you will observe, once the system is turned on, the plot shown in Fig. 2 (rotated by  $90^\circ$ ). Invert the inputs to "straighten out" the display. But to take data you will use the dual trace mode and observe both the F-H signal and  $V_a/10$  as a function of time.

**3.** Turn everything on, including the cathode heater, and allow the system to warm up and



come to equilibrium for about twenty minutes. **Do not touch the hot oven!** Note the notation on the control unit:  $V_{ret}$  is labeled “reverse bias” and can be varied between 1 and 10 V.  $V_a$  is labeled “ $V_a$ ” and can be varied from 0 to 70 V, but note that the output to the scope is  $V_a/10$  and hence varies from 0 to 7 V. While the oven is heating observe the range over which the current changes as the rheostat is adjusted and observe the current setting where you can first see the heater glowing red. [If the resistance of the rheostat is set too large, the filament may never heat up enough to thermionically produce a detectable collector current.]

4. The value of the mean free path, which is a crucial parameter in this experiment, depends on the oven temperature. Using your calculation of  $\bar{l}(T)$  and the dimensions of the experimental cell, estimate the optimal temperature of the oven (it will be in the range  $120^\circ\text{C}$  -  $200^\circ\text{C}$ ). When the oven temperature has stabilized near your desired temperature, set the scope to X-Y display (with the  $V_a/10$  signal into the X axis and the F-H signal into the Y axis) and adjust the various voltages to obtain a display such as shown in Fig. 2. (Be sure the  $V_a$  selector switch is set on sawtooth.) Take time to understand how each of the variables affects the display. Note that when the heater current is changed, it takes several minutes for the pattern to stabilize. Save the data sets to include in your report.

5. Switching the scope to dual display observe that the time dependence of  $V_a/10$  signal is not a linear ramp. Rather, you see the signal is a half wave rectified sine wave. So the F-H signal on the oscilloscope (channel 1), when observed in dual display with a time sweep for the x-axis, is not linear in  $V_a$ ; the peaks are not equally spaced. To record data manually, move the t1 cursor on the scope to the center of the peak (or valley) you want to measure. Then move the v2 cursor to the point where the t1 cursor intersects the  $V_a/10$  signal. The v2 reading is  $V_a/10$  for that peak or valley. The value of t1 is irrelevant.

6. As you have seen in (4) it is more convenient to observe the results in the X-Y because the distortions associated with not having a linear  $V_a$  ramp are not seen. Unfortunately there is no option for saving data from the X-Y mode. To report your results you will have to use the raw data  $FH(t)$  and  $V_a/10(t)$  from each channel and combine it into a plot of  $FH$  vs  $V_a$ .

7. The Franck-Hertz experiment claims to show that the energy levels of Hg are quantized, which implies that the spacing of the peaks (or valleys) do not depend on other variables like the retarding voltage, the filament current (temperature) or the oven temperature. However this may not always be the case. To verify this claim measure the spectrum for:

a. Several oven temperatures in the range ( $150^\circ\text{C}$  ~  $195^\circ\text{C}$ ). The different temperatures are intended to test whether higher excited states affect the average spacing of the peaks.

b. Three values of the filament current. The different filament currents are intended to test whether the kinetic energy distribution of the thermionically emitted electrons affects the location of the peaks.

c. Three values of the retarding voltage. The different filament currents are intended to test whether the kinetic energy distribution of the thermionically emitted electrons affects the location of the peaks.

8. Chose the optimal settings for the temperature and  $V_{\text{ret}}$  to observe as many peaks as possible. Measure the values of  $V_a$  for as many successive valleys and peaks as possible. Show this data in your report.

9. Extra credit. Under certain conditions alternating bright and dark horizontal stripes will appear between the cathode and anode. Try to find these conditions by going to higher temperatures and looking at the tube in the dark - use the black cloth to darken the surroundings. How does the spacing of the bands depend on temperature and the voltage. Take a picture for your report.

**ANALYSIS:** Assign an index number ( $n = 1, 2, \text{etc.}$ ) to each of the peaks and the following valley. You may not have been able to see the first few peaks, but by using Eq. (6) you can deduce the correct value for  $n$ . Make a plot of  $V_a$  versus  $n$  for the peaks and valleys with error bars for each data set. The plot should give you two straight lines. For the peaks the equation for the line is:

$$V_{ap}(n) = V_c - V_{th} + nV_{(13P-01S)} \quad (7)$$

while for the valleys:

$$V_{av}(n) = V_c - V_{th} + V_{\text{max}} + nV_{(13P-01S)} \quad (8)$$

Here  $V_c$  is the contact potential,  $V_{th}$  is the kinetic energy the electrons have after thermionic emission. Looking at the color of the filament and assuming blackbody radiation, estimate the temperature of the filament and the value of  $V_{th}$ .  $V_{\text{max}}$  is the energy above threshold where the  $^3P_1$  excitation rate reaches a maximum – this influences the voltage difference between the  $n$ 'th peak and its corresponding valley. Fit the data to these formulas to extract the values and error bars for of average separation of the valleys and of the peaks. Interpret the results of your fit in terms of these parameters. From the difference in the two intercepts calculate the value of  $V_{\text{max}}$  and observe its dependence on temperature. Find the contact potential and compare to expected value. Estimate the fitting errors for each parameter.

Summarize your results for the average separation including error bars in two tables one for the valleys and one for the peaks. For each temperature show the values obtained for the three current values and for the three retarding voltages. What can you conclude from this data?

### REPORT guidelines:

The structure of the report should follow the format of a scientific paper. Include the following: Title, authors, abstract, theory, apparatus, data, analysis, discussion and references. See for example articles published in [Physical review letters](#). We also keep several issues in the lab.

1. Summarize the theory of the Franck Hertz effect and discuss how it is tested in your experiment. How does the temperature affect your result? Estimate the temperature range where the effect can be observed in the tube. Discuss what you expect to happen when the temperature is too low and what happens when the temperature is too high? Estimate the number of valleys that can be observed for a given range of accelerating voltage values and how it depends on the cathode-anode distance.

2. In the apparatus section describe the function of each component in the Franck Hertz tube and its role in testing the theory. Use your own schematic diagrams if necessary. Do not copy figures or procedures from the writeup.
3. Display the data and analysis in neat compact figures including captions and legends for each figure. Make sure to include error bars on both axis when relevant. All the relevant parameters (instrumental settings, field value etc) should be stated in the caption or legend.
4. Analysis of the data should be presented in close proximity to the relevant figure. Discuss the interpretation of the peaks and that of the valleys in your data and their relation to the theory.
5. Discuss your results, including remarks about whether they support the simple theory, possible reasons for deviation from the simple theory, resolution, accuracy, sources of errors, etc. Discuss the origin of the blue light seen in the tube at high temperatures.

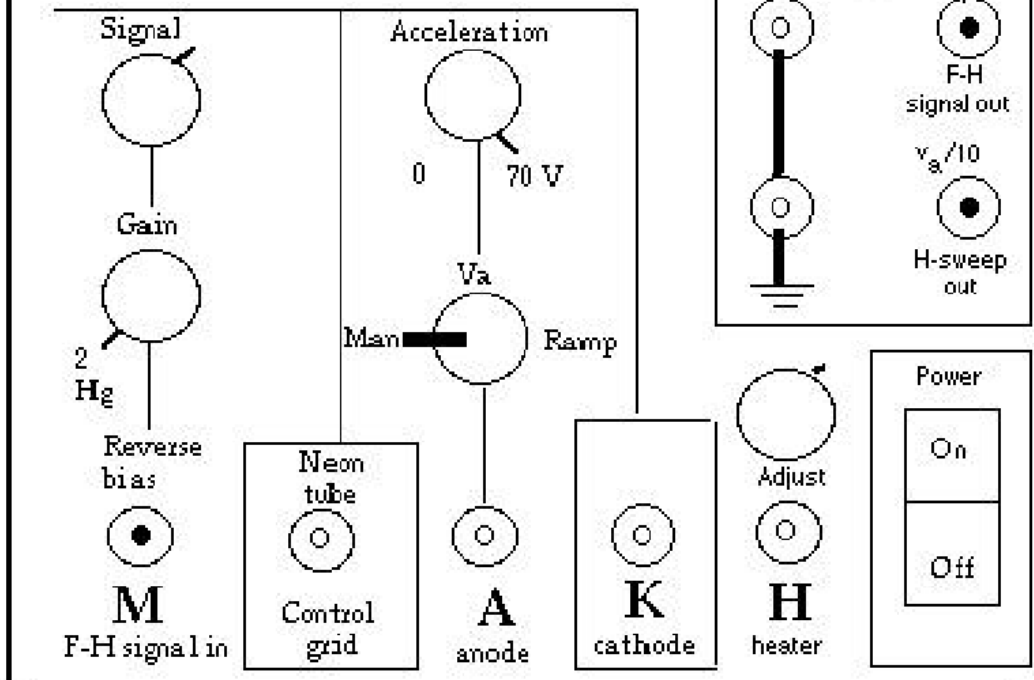
In your report include the following:

- Show a semilog plot of the mean free path versus temperature in Kelvin from room temperature to 660K.
- For each data set plot the valley voltage versus valley number including error bars. In the same figure plot the peak voltage versus peak number. Include a linear fit of the data. Interpret the slopes and intercepts and give values for all the parameters used in Eqs. (7) and (8). What conclusions can you draw? Discuss the errors and the sources of error. In the main report show only one or two such figures. You may include the rest in an appendix.
- Summarize the data in two tables as detailed in the analysis section. Do your data show any evidence that the initial kinetic energy of the thermionically emitted electrons varies with cathode temperature?
- Discuss the shape of the current versus accelerating voltage curves. What determines the rounding of the peaks and valleys and how do you expect it to depend on mean free path and cathode temperature.
- Discuss the effect of the retarding voltage on your curves.
- Suppose the excitation probabilities of all three triplet excited states were about the same. How would the shape of the observed collector current curves change for "high" Hg vapor pressure ["high" = probability that an inelastic scattering occurs in a voltage interval much less than that between the threshold energy (the peak) and the energy for maximum excitation cross section (the valley).]
- Discuss and give examples of the effect of varying the experimental parameters on: (a) the number of visible peaks, (b) the contrast between peaks and valleys (c) the first visible peak. (d) spacing between peaks.
- Extra credit. Show the picture of the dark and bright bands and discuss their relation to the Franck Hertz effect and the lines that you see, their spacing, their color etc.

## READING:

1. Melissinos: Experiments in Modern Physics
2. R. Eisberg and R. Resnick: Quantum Physics of Atoms, Molecules, Solids, Nuclei and Particles, pp 107-110 (F-H effect in Hg), pp 407-409 (contact potential, thermionic)
3. D.W. Preston and E.R. Dietz: The Art of Experimental Physics, Experiment 6
4. Neva: Franck-Hertz Experiment, KA6040/41; 6750-984 (manual)

# Fransck-Hertz Control Unit



## Neva Franck-Hertz Oven and Triode

