Franck-Hertz Effect in Mercury

Object

To measure two phenomena encountered in collisions between electrons and atoms: inelastic scattering resulting in quantized excitation of the target atom, and ionization, resulting in the removal of an electron from the atom. In addition, the experiments provide an opportunity to explore the phenomena of thermionic emission of electrons and space charge limited current in a vacuum tube.

References

1. 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 emission)

2. D.W. Preston and E.R. Dietz: The Art of Experimental Physics, Experiment 6, pp 197-208

3. A. Beiser, Concepts of Modern Physics, pp 153-155

4. Neva: Franck-Hertz Experiment, KA6040/41; 6750-984 (manual)

5. Hoag & Korff: Electron and Nuclear Physics, Sec. 7-4 through 7-6 (a general description of the methods.

6. Harnwell and Livingood: Experimental Atomic Physics, pages 314-320, (a more detailed description of the method)

7. Melissinos: Experiments in Modern Physics, pages 8-17, (a detailed description of the method)

8. Hagen: Atomic Physics, p107

Inventory

Electrometer (Keithley 60 #0017), digital multimeter (Keithley 160 #0019), DC power Supply 0-300 V (Klinger Scientific), mercury vapor triode and oven (Neva-Klinger Scientific), rheostat ($\approx$ 80 ohms, $\approx$ 20 amperes), X-Y recorder (Hewlett-Packard 7035B), Elenco multimeter (M-L200 #492L)

I. Theory

1. Excitation by electron impact of quantized, bound atomic states

An atom can exist in certain bound energy states (the principle of quantization).

(Unbound states can have any energy.) The Hg atom normally will be in the lowest or ground state, with a valence electron occupancy designated by $(6s)^2$ (two electrons in n=6, l = 0 single particle states). This has a spectroscopic designation of $^1S_0$, or $(^{2S+1}L_J)$, where **S**, **L** and **J** are system orbital, spin and total vector angular momenta, respectively.

The next level above this is the "triplet" $^3P_0$ level (6s6p), with the lowest member (first excited state) at 4.667 electron volts (eV). Photon de-excitation transitions from this to the ground state are not allowed, by the requirement of vector angular momentum conservation (the total angular momentum of both of these states is zero, i.e. the transition is **J** = 0 --> **J** = 0 , whereas the final state photon has non-zero angular momentum.). However, electron impact on a Hg atom in its ground state can excite the first excited $^3P_0$ state, with corresponding loss of electron energy (inelastic collision). The cross section (e.g., probability) of this electron impact excitation is less than that for the next state. We will not normally observe the first excited state energy loss in our experiment, although its presence may contribute to broadening of the observed peaks.

The second energy level above the ground state is the "triplet" $^3P_1$ (6s6p) member at 4.86 eV; the third in this "triplet multiplet" is the $^3P_2$ at 5.43 eV above the ground state. Next is a "singlet" $^1P_1$ at 6.67 eV, also formed from the (6s6p) configuration, with anti-parallel intrinsic spins. (See Preston & Dietz, Fig. 11.3; also Hoag and Korff, table, p 322.) Transitions to these also occur readily from the ground state. The reverse of such transitions are usually radiative (photon emitting). For instance, the atom returning from the $^3P_1$ second excited state to the $^1S_0$ state) results in the emission of light of wavelength 253.651 nanometers. This might be observed thru a quartz tube with a grazing-incidence grating spectrometer, when electron energies are ≥ 4.86 eV. (It would be difficult to observe in air near normal incidence.) (The Hg atom, in its first excited state at 4.667 eV, cannot de-excite by radiation; as discussed above, angular momentum could not be conserved. The $^3P_0$ state is metastable, drifting around until it de-excites by collision, or by allowed two-photon emission.)

The onsets of electron energy loss by inelastic electron collisions with Hg atoms in the ground state will be observed as a drop in current to the collector electrode (see later discussion).   Excitation cross-section will rise above threshold; therefore the maximum current reduction may occur at an electron kinetic energy slightly greater that 4.9 eV. We thus expect this current drop to represent mainly electron kinetic energy reduction near the anode, due to collisional excitation of the second excited $^3P_1$ state at 4.9 eV . Excitation of the next higher $^3P_2$ at 5.43 eV may be suppressed by prior electron energy reduction to zero in collision with the lower energy 4.9 eV state (see discussion question # 7), which becomes energetically accessible earlier. We can assume that excitation of the lower energy, first excited $^3P_0$ state at 4.667 eV is unobserved, due to small excitation cross section for electrons in the 5 eV region. (See schematic curve shape in

Hagen, showing "shoulders" on a dominant peak, due to excitation of states lower and higher than that at 4.9 eV.)

The separation of any two levels can be expressed in either of two ways:

a. By the difference in the wave numbers ($k = 1/\lambda$) of the levels and

b. By the energy, expressed in electron volts, necessary to raise the atom from the lower to the higher level. The separation of the $^3P_1$ and the $^1S_0$ levels can therefore be given in wave numbers

$$\nu* = 39,409.6 \text{ cm}^{-1} \quad \text{or, in electron volts, as}$$

Eq. 1) $\qquad V = 1.240 \times 10^{-4} \, \nu* \quad$ (approximately 4. 886 eV).

The first ionization potential is that energy (usually expressed in electron volts) which is just sufficient to remove the outermost electron from the atom, i.e. it is the energy required to singly ionize the atom. This can be determined spectroscopically from "series limits", i.e. from the limiting wavelength of a series of lines in the spectrum of the element, such lines decreasing regularly in wavelength to a limiting value. Thus determined, the Hg series limit, as compared with the ground state, corresponds to a wave number change of 84,178.5 cm^{-1}, or to an energy above the ground state of 10.436 eV.

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 $L_{collision}$. This can be estimated (see Loeb, Kinetic Theory of Gases, Sec. 24) by an equation from kinetic theory :

Eq. 2 $\qquad L_c = \dfrac{1}{\pi r^2 n}$

where r is the radius of the molecules and n is the number of molecules per cm^3.

(This is close to the expression of Preston & Dietz, p 201. Properly, the total scattering cross section σ_t should be used instead of (πr^2). The elastic cross section (no center-of-mass kinetic energy loss, and no "spin-flip") is electron wavelength (energy) dependent. For an interesting example of a systematic relation of elastic cross section to $\left\{ \dfrac{\text{wavelength}}{\text{atomic size}} \right\}$. See Eisberg and Resnick, also Hoag and Korff Fig. 7.1 and 7.3, on the Ramsauer effect.)

For sufficiently low Hg density, Eq. 2 is simply the reciprocal of the projected

area of the molecules in one cubic centimeter. In the present experiment you will be concerned with saturated mercury vapor. Mercury is monatomic; the atoms have a diameter of about 1.5×10^{-8} cm. From the definition of gram-atomic weight A, it is obvious that the number of molecules per cubic centimeter is

Eq. 3 $n = (\text{weight/cm}^3)/(\text{weight/atom}) = \rho \div (A/N_A) = \rho\, N_A/A$

where ρ is the density of the vapor and N_A = 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 = nRT (T in Kelvin). Taking 1 cm^3 as the volume, this reduces to

Eq. 4 $P \times 1 = \dfrac{r}{A}\ RT$, or $\rho = \dfrac{PA}{RT}$

where R is the general gas constant. Inserting Eq. 4 into Eq. 3 gives

Eq. 5 $n = \dfrac{N_A}{R}\ \dfrac{P}{T}$.

In using this equation, be sure that you use a value for R expressed in the same units you use for P and T.

When taking data to determine the ionization potential, it is necessary to have the mean path for collisional excitation of the same magnitude or longer than the distance d from the cathode to the grid, but smaller than the distance between cathode and anode. On the other hand, when taking data to determine the excitation potential, it is necessary to have this mean path short compared with this same distance, in order to see several peaks and valleys. (See Melissinos, or Eisberg & Resnick.) 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 the excitation experiment.

3. Excitation collisional distance

Eq. 2 above implies that the mean free path electron collision of any kind is independent of electron energy. As mentioned above, this is an orienting approximation only, and the cross section (and thus L_e) is a wave phenomenon, which may be expected to vary with electron de Broglie wavelength. (See Hoag and Korff, Fig. 7-3.) However, there is no energy scale factor for elastic collisions, which involve essentially zero loss of electron energy and little average change in electron direction). Since there is very little energy loss, we have little interest in $\sigma_{elastic}$ or L_e. Most important, there is no expected special

or periodic dependence on accelerating voltage of the number of electrons, having elastically scattered only, which arrive close in front of the anode.

The collisional distance we are interested in is for "inelastic" collisions, which transfer 4.9 eV of electron kinetic energy to excitation of the <u>Hg</u> atom to the $^3\underline{P}_1$ second excited state, and leave the electron somewhere within the accelerating field space with little or no kinetic energy. For this process, there is an energy scale factor, 4.9 electron volts. Such a collision has zero probability (inelastic cross section) for electron energies below 4.9 <u>eV</u> (elastic collisions may occur), and becomes likely beginning at a distance in which the accelerating field gives an electron 4.9 eV of kinetic energy. (The hot cathode thermally emits electrons with a kinetic energy spectrum dependent on the cathode temperature, related (probably not linearly) in turn to the cathode current and the oven temperature.) For cathode-anode distance of 8 mm and accelerating potential $V_a = V_{K-A}$, this distance $L_{4.9}$ will be

$$\textbf{Eq. 6} \qquad\qquad L_{4.9} = \left\{ \ 8 \text{ mm x } \frac{4.9}{V_a} \ \right\}.$$

Thus, the collision distance of interest is a specific (inverse) function of the accelerating potential. We will see later 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. A similar effect occurs in the photoelectric effect.)

Attainment of 4.9 <u>eV</u> electron kinetic energy thus represents a threshold for the excitation of interest ($^3\underline{P}_1$ second excited state). The excitation may occur at higher electron energy, but not at lower. The energy at which the excitation probability maximizes is not necessarily 4.9 <u>eV</u>; then the characteristic distance interval within cathode-anode space, $\underline{L}_{4.9}$ of Eq. 6 above, would be modified by replacement of <u>4.9</u> in the right hand side by the appropriate energy for maximum excitation of the 4.9 <u>eV</u> state. This will contribute a zero offset (intercept) in the experimental $\underline{I}_{collector}$ vs $\underline{V}_{anode}$ plot of current minima, in addition to that arising from the cathode-anode contact potential difference.

However, the spacing of successive excitation minima in the collector current should still be 4.9 volts. For instance, if peak excitation of the 4.9 <u>eV</u> state occurs at 5.1 <u>eV</u> of electron kinetic energy, then an electron inelastically scattered at 5.1 eV will have 0.2 <u>eV</u> after collision. After passing through another 4.9 volt accelerating potential difference, the electron will again have 5.1 <u>eV</u>.

II. Equipment

The essential components are a mercury thyratron tube, variable filament, anode and collector voltage supplies with necessary meters, a sensitive <u>dc</u> 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.

1. The oven

The oven consists of a steel cabinet, 24 x 16 x 15 cm., containing a heating element which uniformly heats the tube and all connections leading to it. The 300 watt heating element is mounted on the bottom of the housing.

A thermostat is incorporated, which can be regulated by the knob on the right side of the outside of the oven. This functions imperfectly (1-3 degrees drift). Exact settings are not critical; it is therefore preferable to bypass the thermostat by turning its setting to maximum. Then the temperature is limited by the power delivered from the variac, which gives adequate stability. A hole in the top of the cabinet is provided for a thermometer (wind a rubber band as a stop), the bulb of which should be at tube height.

2. Thyratron tube

A thyratron is simply a vacuum tube into which a small amount of mercury has been introduced before sealing off. Such tubes, therefore, contain saturated mercury vapor at a pressure corresponding to the temperature of the bulb.

The tube has an (approximately) plane-parallel system of three electrodes (triode), in order to reduce deformation of the electric field. In the tube used (Neva, supplied through Klinger), the electrodes are referred to, in order of electron motion, as cathode (K), anode (A) and collector (M). In addition, there are cathode heater (nominally 6.3 volts AC) connections H and K. (Note that Fig. 1.2 of Preston & Dietz, and Fig. 1.6 of Melissinos, show a different, cylindrical geometry of tetrode electrode structure, with indirectly heated cathode. Note also that a cathode heater-current varying rheostat should be connected to H, not to K)

The anode is a perforated screen, so many electrons will pass through. They can proceed to the collector, if their kinetic energy at the anode is greater than $eV_{retarding}$, where V_{ret} is the small, adjustable voltage between anode and collector. Otherwise, they slow, stop, and reverse direction to return to the anode.

A platinum ribbon with small barium oxide low work-function spot serves as a direct-heated thermionic cathode (electron emitter). A diaphragm connected to the cathode limits the current and eliminates secondary and reflected electrons, making the electric field more uniform.

The thermionic cathode will be much warmer than the thermometer temperature reading for the rest of the system, including anode and collector. Then, while the anode surface material may be a thin film of mercury, the cathode may be base material, giving rise to the contact potential difference which accounts in part for the zero offset in the excitation data plot, along with the difference between the energy of the excitation cross section weighted maximum (all states of triplet) and 4.9 eV. (Note that if all n's (valley or peak order numbers) are mis-identified by

one (or more) the slope of the n vs. V plot does not change, but the intercept will be affected.)

In order to avoid current leakage along the hot glass wall of the tube a protective ceramic ring is fused in glass between the anode and the collector electrode.

The tube is highly evacuated and coated inside with a getter which absorbs traces of air during the manufacturing process and acts as an absorbent during the entire lifetime of the tube to prevent any changes in performance.

3. Effect of inelastic scattering on collector current

For the Franck-Hertz excitation observations, electrons thermionically emitted from the cathode are accelerated to the anode. Those that pass thru the anode are decelerated in their further motion toward the grid. If the accelerating voltage between $\underline{K}$ and $\underline{A}$ is $\underline{V}a$, the number of possible inelastic collisions in this region is $\underline{n}_{collision} \leq \underline{V}a/4.9$. Thus the number of observed peaks and valleys can not exceed the available kinetic energy gain $e\underline{V}_a$ divided by the electron kinetic energy loss per excitation (4.9 $\underline{eV}$).   Fewer peaks may be observed, if (due to low oven temperature) the mean free path for inelastic scattering exceeds the distance required for the electron to attain 4.9 eV. However, as discuss earlier, the spacing between successive peaks or valleys should remain constant for all mercury densities. With adequate $\underline{Hg}$ vapor pressure, so that a large fraction of electrons undergo inelastic scattering, the number of peaks observed should increase with the applied cathode-anode ($\underline{K}$-$\underline{A}$) voltage $\underline{V}a$.

When the tube is hot (around 180 $\underline{°C}$), the acceleration distance between the cathode and the anode is large in comparison to the mean excitation length, thus insuring high collision probability. The separation between anode and collector is much smaller (approximately 2 $\underline{mm}$).

In the Franck-Hertz excitation energy measurement, there are discrete accelerating potentials $\underline{V}_{K-A} = \underline{V}a$ such that many electrons will have an inelastic collision too close enough to the anode the anode to regain enough electric accelerating field energy by anode position to overcome the retarding voltage V_{A-C} between anode $\underline{A}$ and cathode $\underline{C}$. There will thus be a dip in electron current to the collector $\underline{C}$.   The successive collector current minima thus represent successive maxima in the number of inelastic electron collisions exciting the $^3\underline{P}_1$

state, and occurring within a distance $\left\{ 8 \text{ mm x } \dfrac{V_{A-C}}{V_{K-A}} \right\}$ in front of the anode.

A plot of collector current vs. accelerating potential $\underline{V}_{A-C} = \underline{V}a$ will therefore show a succession of equally spaced valleys (and intervening peaks), separated by about 4.9 volts. The third such minimum represents electrons which have had two previous inelastic collisions within the acceleration region ($\underline{K}$ --> $\underline{A}$), with the third such occurring close in front of the anode . An $\underline{I}$-$\underline{V}a$ plot will be linear, but $\underline{I}$ will not be simply proportional to $\underline{V}a$.   The intercept of a linear fit offset

represents, in part, a contact potential arising from the difference in work functions between cathode (K) and anode (A). The effect is that the applied potential to attain the first minimum is greater than the accelerating potential actually seen by the electrons by, perhaps, 2 volts. Thus the first minimum would occur at around $(4.9 + 2) = 6.9$ volts, with successive intervals of 4.9 volts.

The intercept may also be affected by how far above 4.9 eV electron kinetic energy the maximum excitation probability occurs, since we will observe collector current valleys (production maxima in front of the anode), rather than onsets.
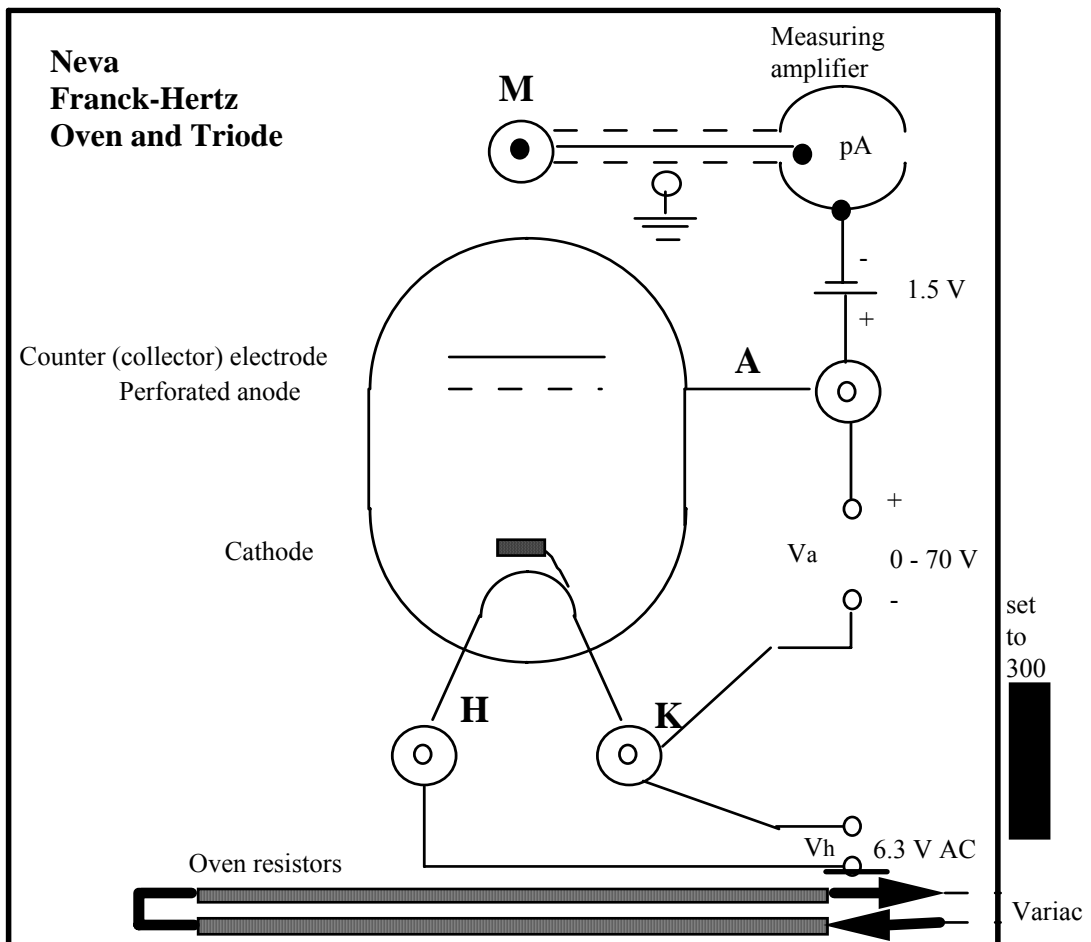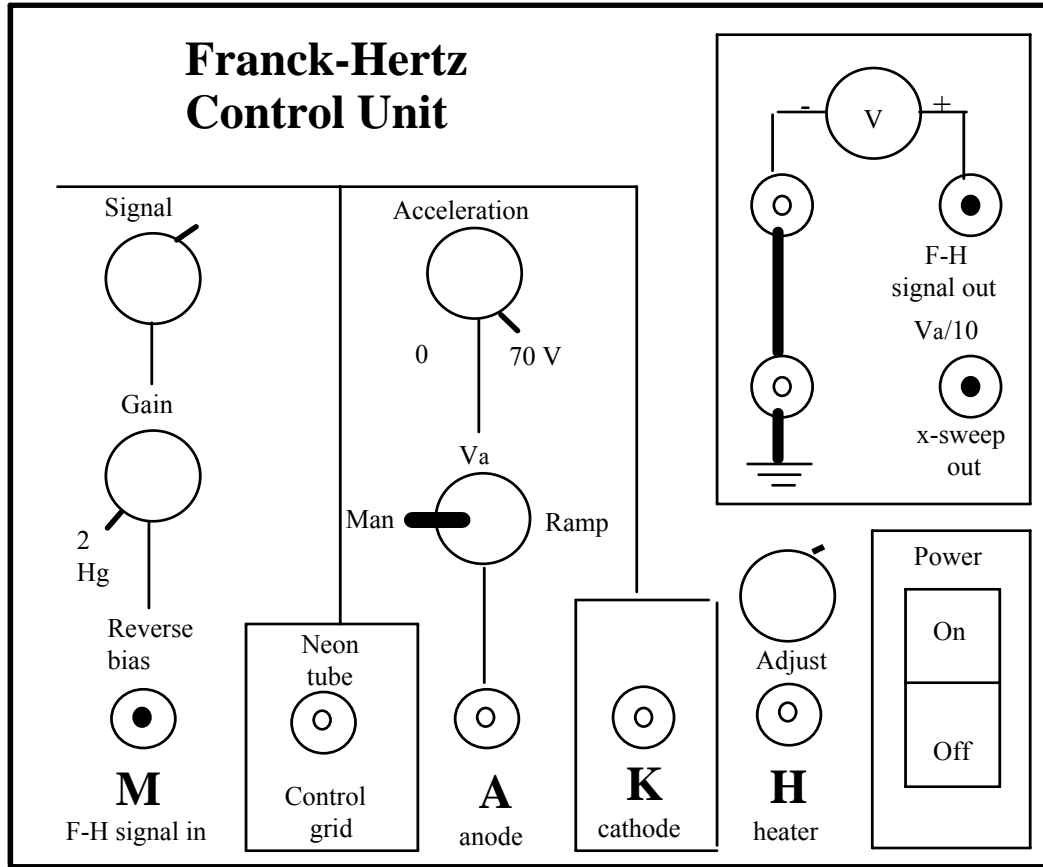
4. Ion current measurements

For a temperature around 100 °C, the mean electron path for collisional excitation falls between the range of lengths given by the distance between cathode and anode, and that between cathode and collector; thus some electrons may suffer their first collision between the anode and the collector.

III. Experimental procedure

1. Wire the apparatus according to the wiring diagram. Turn everything on, including the heater, and allow the system to warm up and come to equilibrium for about twenty minutes.

Do not touch the hot oven!

Franck-Hertz
Control Unit

Signal

Acceleration

0   70 V

Va

Gain

Man   Ramp

2
Hg

Reverse
bias

Neon
tube

Adjust

Power

On

Off

M

Control
grid

A

K

H

F-H signal in

anode

cathode

heater

V

−   +

F-H
signal out

Va/10

x-sweep
out

Neva
Franck-Hertz
Oven and Triode

M

Measuring
amplifier

pA

−
1.5 V
+

Counter (collector) electrode
Perforated anode

A

+

Cathode

Va

0 - 70 V

−

set
to
300

H

K

Vh   6.3 V AC

Oven resistors

Variac

2. Excitation potential measurements

Connect the various voltage supplies to the Hg tube according to the Neva wiring diagram, with a rheostat and AC ammeter in series to the H (heater) input for heater current variation.   (Omit this initially.)

The mean free path needed to perform this experiment is obtained at around 183° C. It is suggested you take measurements at three different temperature namely ≈195 °C, 185 °C, and 170 °C. For each temperature use three different filament currents by changing the sliding rheostat setting. Since the work function of the filament and anode (and, generally, for all metals) will not change appreciably with temperature, the peaks obtained in the three cases would be expected to occur at the same voltages. This procedure also tests that the kinetic energy distribution of the electrons coming out of the filament is not related to the peaks in the current. (kT is about 1/40 eV at room temperature.)

Caution: If the resistance in the sliding rheostat is too large, the filament may never heat up enough.

The measurement involves varying the potential applied between cathode and anode, and observing the collector current. Set V_{A-C} to a low value. Connect the supply output labeled $V_a/10$ to one input of a dual-trace scope, and the signal (collector current) output to the other, using banana-to-BNC cables. (Observe proper grounds; the little tab on the plastic banana plug is connected to the coaxial cable shielding, therefore to the ground (outer portion) of the coax BNC connector.)

With a DC digital voltmeter, observe the range of DC voltage between cathode and anode (K - A). Observe the AC heater voltage (H - K) and AC heater current, as the rheostat setting is varied. (Do not remove the coax cable between the collector ("signal "M") and the sensitive amplifier - you will then not have direct access to the collector.)

Set the V_a selector switch on sawtooth and observe the $V_a/10$ signal on the scope. You will not see a ramp! Rather, you will see a signal which appears to be half wave rectified, 60 Hz, AC line voltage.   Therefore, the periodically swept accelerating potential is not proportional to time. Va will be the maximum of this half sine-wave voltage.

Vary the cathode-anode accelerating potential V_a.   You should see a varying number N of valleys (depending on V_a), equally spaced vertically in voltage (but not horizontally in time, because the "sawtooth" is not a sawtooth).

Vary the retarding potential V_{A-C}. Observe and record the effect on peak position and width.   (Omit this initially.)

Select a suitable value of V_{A-C} and record the number of valleys N vs. V_a. Determine and record from the scope the voltages of the successive valleys

(collector current minima).

Set the accelerating voltage selector switch to zero and change to MANUAL. Connect the V_a/10 output to the horizontal input of the X-Y recorder, and the signal output to the vertical inputs. (Alternately, a dual trace scope may be used in X-Y mode with external sweep, reading voltage maximums or minimums directly from the scope trace; however, this does not provide hard-copy.) With V_a set to give as many minima as are clearly defined, find suitable gains to obtain a trace. Turn the control knob slowly while using the X-Y recorder to obtain a complete record for three oven temperatures, for three filament currents each. Vary the retarding potential if desired.

Calibrate the horizontal scale of the recorder with a digital voltmeter.

Higher sensitivity in the recorder may be used, if desired, to define more clearly the minima which occur at lower voltage.

3. Ionization potential measurement

Reduce the oven temperature to approximately 100 °C.

Given easy access to the collector, a retarding voltage between the anode and collector could be applied, greater in magnitude than the accelerating voltage between cathode and anode. Then no electrons should be able to reach the collector. However, when ionization occurred between the anode and collector, the positive mercury ions formed would be attracted to the collector and a collector current (opposite in sign to that observed in Franck-Hertz excitation) would be observed at the threshold value $V_a = V_{ionization}$. This is the method of Lenard. A larger spacing between anode and cathode is usual.

Since we do not have easy capability of making these changes, and of reversing the polarity of the sensitive amplifier to observe collector ion current , we will observe the onset of ionization by the sudden increase of collector electron current, representing gas multiplication (additional free electrons created by ionization when $V_a \geq V$ionization.

Observe with the scope as before. Record the value of Va for the onset of electron current increase and for avalanche breakdown. (Observe sudden tube glow.)

Photons released from the cathode-anode space as soon as the accelerating potential permits excitation may pass thru the perforated anode and release electrons from the collector. These will be attracted to the anode and produce a collector current in the same sense as positive ions attracted to the collector.

(The same photoeffect can occur during excitation current measurements, from anywhere in the cathode-anode space, modifying the curve shape.)

Obtain chart records as before, for a couple of temperatures.

IV. Analysis

1. **a.** Assign an index number n to each of the valleys in the 9 runs you have, consistent between data sets as best you can judge.

   b. Determine the center of each valley.

   c. Find a least square linear fit of the data separately for each oven temperature-filament current combination (Kaleida Graph or other). Show fit and errors on the graph. (KG Curve Fit - general will conveniently show fit errors directly for each fit parameter, using the Plot - Display Equation command, whereas the the Linear fit gives the R or R^2 fit parameter.)

   Make a graph of intercept variation with filament current (constant oven temperature) and with oven temperature (constant filament current).

2. Determine the onset of current increase for each ionization curve. Find the average and the standard deviation of the set.

V. Discussion

1. Is there any consistency to the intercepts determined by the various data sets? If so, compare the correction voltage V_0 with the contact potential, assuming the grid is nickel and the cathode is oxide coated (work function about 1.0 volt.) V_0 is the voltage intercept at zero peak number ($n = 0$).

2. Calculate the mean free paths of electrons for <u>elastic scattering</u> in mercury vapor, for one temperature you used in each of the excitation and ionization measurements. (This is not the mean free path for excitation of the atom.)

3. Confirm, by calculation, the correctness of the conversion factor given in Eq. 1 for converting from wave numbers to electron volts.

4. Why would cathode temperature fluctuations cause a variation in the anode current?

5. In a hypothetical experiment, suppose that the accelerating potential is set to 50 volts and that, initially, the variable rheostat which controls the filament current is set to its maximum value. Now consider decreasing the resistance of this rheostat (and thus increasing the filament current), while keeping the tube temperature and accelerating voltage of the tube constant. Suppose you then measured the anode current. Draw and explain a graph of the expected filament current behavior vs. anode current.

6. Why are the peaks and valleys of the excitation function rounded?

7. 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" <u>Hg</u> vapor pressure ("high" = probability of an inelastic scattering occurs in a voltage interval << than that between threshold energy and the energy for maximum cross