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THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY PHYSICS DEPARTMENT

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Junior Physics Laboratory: Experiment #7

THE FRANCK-HERTZ EXPERIMENT

Elastic and Inelastic Scattering of Electrons by Atoms

PURPOSE

The main purpose of these experiments is 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.

PREPARATORY QUESTIONS

1. Considering that the energy of the first excited state of the mercury atom is about 5.0 eV above that of the ground state, what is the maximum amount of energy that an electron with 4.0 electron volts of kinetic energy can impart to a mercury atom with which it collides? Same question for a 6.0 eV electron. 2. Prepare a log-log plot of the mean free path (in cm) of electrons in mercury vapor against the temperature (in degrees centigrade) of the tube. Assume 1) that the cross section of a mercury atom for collision with an electron is geometrical (i.e. $\sigma = R^2$ where R is the radius of the outer electronic shell of the mercury atom), and 2) that the mercury vapor in the tube is in thermodynamic equilibrium with liquid mercury. (The vapor pressure of mercury in the temperature range of interest is well represented by the formula

 $\log 10(p) = -2.719 + 2.51 \times 10^{-2} T - 2.68 \times 10^{-5} T^{-2}$

where *p* is the pressure in mm of mercury and *T* is the temperature in °C. See CRC Handbook, 75th edition, p. 4-125 and 1-34)

3. Plot the expected curve of current against accelerating voltage, in the Franck-Hertz experiment with mercury vapor, showing the positions of the peaks and valleys on an absolute voltage scale.

INTRODUCTION

Franck and Hertz described the first observation of quantized excitation in 1914, one year after Bohr published his theory of the hydrogen atom with its concept of quantized energy states. They discovered that electrons moving through mercury vapor with an energy equal to or greater than a certain critical value near 4.9 eV can excite the 2,536 Å line of the mercury spectrum. Electrons with less than the critical energy merely bounce elastically when they collide with mercury atoms and fail to excite any electromagnetic emission at all. The experiment provided crucial evidence in favor of the Bohr theory.

A version of the Franck-Hertz experiment, employing a mercury-filled vacuum tube with four electrodes made by the Leybold Company, is described by Melissinos (1966) to which the reader is referred for a discussion of the physical principles and the measurement objectives of the Franck-Hertz experiment. The present Junior Lab version of the experiment uses a later version of the Leybold equipment which consists of a mercury-filled triode and an oven with glass windows through which one can view the action. A power supply and control circuit built in the Junior Lab shop provides adjustable filament voltage for heating the cathode, adjustable accelerating grid voltage, and an adjustable retarding voltage. The same triode tube and power supply are used in the measurement of the ionization potential.

SCATTERING OF ELECTRONS BY MERCURY ATOMS

The experiments on the excitation and ionization of mercury atoms are carried out with a mercuryfilled triode which is a sealed glass envelope containing three electrodes and a drop of mercury. (Mercury is an ideal element for a study of excitation phenomena because its vapor is monatomic and its vapor pressure can be readily controlled over the range useful for this experiment by adjusting the temperature in the range from room temperature to 200° C.) The experiments will be performed with the three configurations of the tube and associated circuits illustrated in Figure 1 and in more detail in Figures 2, 3,



Figure 1. Schematic illustrations of the mercury-filled triode in the three configuration used in measurements of (a) thermionic emission and space charge limited current, (b) the ionization potential of mercury, and (c) the critical excitation potential of mercury. Note that the arrows indicate the direction of positive current - electrons move in the opposite direction.

and 4. The three electrodes are 1) a cathode which emits electrons when raised to a temperature of several

hundred degrees by application of a voltage $V_{\rm F}$ to a heater filament, 2) a grid which is set at a positive potential $V_{\rm cg}$ relative to the cathode so that electrons emitted by the cathode are drawn toward it, and 3) an anode which is connected to an ultra-sensitive Keithley electrometer for the measurement of the anode current $I_{\rm a}$.

All of the measurements in these experiments can be made with total tube currents (i.e. cathode current=anode+grid current) of 1 µamp or less. To prolong the useful life of the tube care should be taken not to exceed 1 µamp.

It is wise to start each session by disassembling whatever wired-up circuit the previous users may have left, and then rewiring it yourself. Only in this way can you know for sure how the circuit is connected.

An ultra-sensitive Keithley electrometer is used to measure the current from anode to laboratory ground. (**Be sure to check the zero set**). The electrometer has an analog output in the back of its chassis which can be connected by coax cable with grounded sheath to the IBM-XT interface box for recording on your own floppy disc as directed in the "Computer and Software Guide", and to the y input of the oscilloscope operating in its x-y mode for convenient visual display. An electronic voltmeter is used to measure the accelerating voltage relative to laboratory ground. It too has an analog output in the back which can be connected to the IBM XT and to the x input of the oscilloscope. Both of these meters have their chassis at laboratory ground potential and therefore can only be used to measure currents or voltages from a given point to laboratory ground. In most of the measurements neither the grid nor the cathode are at ground potential in which case the electronic voltmeter cannot register the accelerating potential directly. A separate isolated Fluke multimeter is provided to enable measurement of the potential difference between any two points.

You will have control of four parameters - the filament voltage V_F which controls the temperature of the cathode, the accelerating voltage V_{cg} between cathode and grid, the retarding voltage between the grid and the anode, and the oven temperature *T* which controls the vapor pressure, and hence, the density of the mercury vapor. Your first job is to explore the effects of filament voltage and oven temperature on the total current.

1. THERMIONIC EMISSION OF ELECTRONS AND SPACE CHARGE LIMITED CURRENT

Consider first the situation in the tube connected as shown in Figure 2. At room temperature the vapor pressure of the mercury is so low that the mean free path of electrons is large compared to the dimensions of the tube. The cathode, heated by the filament, emits electrons in a process called thermionic emission in which electrons near the top of the Fermi distribution in the metal penetrate the potential barrier at the surface and escape. The emitted electrons have a distribution of kinetic energies



Figure 2. Schematic diagram of the tube and circuit for measurements of space charge limited current from thermionic emission. The variation of potential with position in the tube is indicated in the plot at the right. For this measurement the toggle switch should be set to the "E" (excitation) position and the "retarding" voltage control should be set to zero. The colors of the external banana plug female connectors are indicated in the diagram. The voltmeter labeled V_{cg} is the Keithly electronic voltmeter connected so as to measure the accelerating voltage between the cathode and grid.

which is approximately a Maxwell-Boltzmann distribution with a mean energy E_0 near kT, where T is the cathode temperature. In the steady state, with the grid at a positive potential relative to the cathode the emitted electrons form a cloud of negative charge over the surface of the cathode. This cloud gives rise to a contribution to the electric field that tends to suppress the emission by forcing lower energy electrons back to the cathode, thereby causing a condition known as space charge limited current. The physics of thermionic emission and space charge limited current is discussed by Melissinos (1976) for tube with ideal cylindrical geometry. Our tube, designed for other purposes, has a different geometry that does not lend itself to a "clean" experiment in thermionic emission. Nevertheless the qualitative characteristics of space-charge limited current can be observed with it. The first part of the experiment is

an exploration of the dependence of the total tube current on the accelerating voltage, i.e.potential difference between cathode and grid, and on the filament voltage which controls the temperature of the cathode. The measurements are made at room temperature.

Procedure for exploring the dependence of the total current on the filament and accelerating voltages.

a. Connect the tube as shown in Figure 2 with the filament voltage set to its lowest value (~1.2 v). The grid and anode should be connected to the electrometer with coaxial cables so that all electrons captured by the grid and anode flow through the electrometer. Use a two-prong banana plug-to-BNC adaptor at the grid terminal on the oven and a BNC "T" connector at the electrometer (take care as to which side of the banana plug adaptor is connected to the inner conductor of the cable).

b. Set the accelerating voltage control so that V_{cg} , the voltage of the cathode relative to the grid (which is grounded through the electrometer), is about -60 v. Increase V_F in small steps until the total current is about -1 µamp or until V_F is at its maximum value. Tabulate and plot the total current (grid+anode) I_{ag} versus V_F as you proceed.

c. Set $V_{\rm F}$ at a value for which $I_{\rm ag}$ is in the range 0.1-1.0 µamp when $V_{\rm cg} = -60$ v. Then tabulate and plot $I_{\rm ag}$ as a function of $V_{\rm cg}$, shifting scales on the electrometer as needed. You may find that the current drifts substantially at any given setting of $V_{\rm F}$ and $V_{\rm cg}$. Don't panic. The purpose of this section is to obtain a <u>rough</u> idea of how the cathode current, i.e. the total tube current, is affected by the cathode temperature and the accelerating voltage. Don't spend a lot of time trying to perfect these particular data.

Since the tube characteristics change significantly with usage, you should start each session with a similar rough check of I_{ag} versus V_F with V_{cg} set to ~-60 v and the oven at room temperature.

2. DETERMINATION OF THE IONIZATION POTENTIAL OF MERCURY

In this next experiment the tube is connected as shown in Figure 3 so that the anode is maintained at a negative potential of a couple of volts with respect to the cathode. In this condition it is energetically impossible for any electrons to reach the anode. When the grid potential is made positive with respect to the cathode, electrons are accelerated to the grid. Some pass through the grid into the space between the grid and anode, but all are eventually pulled back and collected by the grid. However, if the electrons that enter the space between the grid and anode have sufficient energy to ionize the mercury atoms, then the resulting positive mercury ions are drawn to the anode and a <u>positive</u> current is registered by the electrometer. The experiment consists of measuring the anode current as a function of the grid to cathode potential difference. Analysis of the current-voltage relation yields a measure of the ionization potential.

The first task is to determine the optimum oven temperature for measurement of the ionization effect. If the vapor pressure of the mercury is too low, then electrons entering the grid-to-anode region with sufficient energy to cause ionization will have a small probability of collision (long mean free path) and the ion current collected by the anode will be too small for accurate measurement. If the vapor

pressure is too high, then electrons will suffer inelastic collisions in the space between the cathode and grid as soon as their energies slightly exceed the energy required to raise mercury atoms to their first excited (not ionized) state and will therefore never attain sufficient energies to cause ionization.



Figure 3. Schematic diagram of the mercury-filled triode in the configuration for measurement of the ionization potential of mercury. After you complete the connections check all the potential differences in your setup with the floating Fluke voltmeter and verify that they are consistent with the voltage plot shown in the figure.

Connect the tube as shown in Figure 3. Set the filament voltage at the value which gives a total tube current in the range 0.1-1.0 µamp when V_{cg} =~60 v, as determined in section 1 above. Set the accelerating voltage V_{cg} to 15 v (measure with the floating voltmeter connected between cathode and grid), which is a few volts above the ionization potential. Set the retarding voltage so the cathode potential is 2 v above the anode potential. Measure and plot the anode current as a function of oven temperature (do not exceed 200°C).

Explain what you observe in terms of the effect of temperature on the mean free path of the electrons. In light of your results select an optimum temperature for the following measurement of the ionization potential and adjust the variac so as to maintain that temperature.

Procedure for measuring the ionization potential

a. Set the accelerating voltage to its minimum value.

b. Again set the filament voltage to a value that would give a <u>total</u> tube current (anode+grid) in the range 1.0-0.1 µamp at room temperature in the arrangement used in Section 1 above.

c. Set the retarding voltage so the anode potential is 2 v negative with respect to the cathode.

d. Tabulate and plot by hand the anode current I_a as a function of the accelerating voltage V_{cg} , using the picoampere and nanoampere scales (to avoid damaging the tube by a discharge do not exceed an accelerating voltage of 15 v in this part of the experiment).

e. If you want a computer plot of the current-voltage relation, connect the analog outputs of the electrometer and digital voltmeter to the IBM XT computer, switch the accelerator control to 'ramp', and record a run of I_a versus V_{ag} for automatic plotting.

<u>Analysis</u>

Estimate the value and uncertainty of V_{cg} when ionization just begins in the region between the grid and the anode. Using results from the subsequent experiment on the excitation potential, you will be able to correct your result for the effect of the contact potential.

There is interesting structure in the I_a versus V_{cg} plot at very small (picoampere) currents in the region below 10 v. What causes it? (see Melissinos).

3. DETERMINATION OF THE EXCITATION POTENTIAL OF MERCURY

For the excitation potential measurement connect the tube as shown in Figure 4. Check all the potentials with the floating voltmeter. Set the oven temperature so that the mean free path of the electrons is short compared to the cathode-grid distance. Maintain the anode at a fixed negative "retarding" potential V_r with respect to the grid while the accelerating voltage V_{cg} between the cathode and grid is varied from 0 to ~60 volts. Electrons that pass through the grid with less than enough energy to overcome the retarding potential are turned back to be collected by the grid. Higher energy electrons reach the anode and are registered as a negative current by the Keithley electrometer.

Consider, now, the following idealized description of the excitation potential experiment. We make the following assumptions (all inaccurate in varying degrees as the previous experiments have shown):

* All electrons emerge from the cathode with zero velocity.

* The number of electrons emerging from the cathode is unaffected by the accelerating field between the cathode and grid.

* The energy of an electron is unaffected by collisions with the mercury atoms as long as their

energy is below that of the first excited state. Therefore all electrons at a given position between the cathode and grid have the same energy.



Figure 4. Circuit arrangement for measurement of the critical excitation potential.

* All electrons that pass through the grid with energies less than the retarding potential between the grid and anode (+) are pulled back and collected by the grid; all electrons with energy more than the retarding potential are collected by the anode.

* The inelastic cross section of mercury for electrons with energies above the critical value is so large that such electrons travel a negligible distance before suffering inelastic collision.

Were all these assumptions valid, a plot of anode current I_a against accelerating voltage V_{cg} would appear as shown in Figure 5. The separation between successive current increases (or decreases) is equal to the excitation potential of the first excited state of the Hg atom. The width of the minima is determined by the retarding potential between the grid and the anode. The difference between the

accelerating voltage at the first drop and the excitation potential is the difference between the work functions of the cathode and grid metals, i.e. the contact potential between the two metals. In reality the I_a versus V_{cg} curve will depart considerably from the ideal for a variety of reasons.



Figure 5. Plot of anode current against accelerating voltage V_{cg} implied by set of idealized assumptions. The plot is oriented as it would appear on the oscilloscope and on the graphic display of the IBM XT computer.

Figure 6 illustrates the electric field with the voltages set for the measurement of the excitation potential in the idealized case of plane parallel electrodes. Also shown are the trajectories of two electrons, each interrupted by elastic and inelastic collisions. At gas pressures so low that the mean free path of the electrons is large compared with all relevant distances the motion is ballistic and the fraction of the electron current intercepted by the grid is approximately the fraction of area covered by the fine grid wires. At gas pressure so high that the mean free path is short compared with all dimensions, including the wire diameter the electron orbits jitter along the field lines. Regardless of their energy they are mostly intercepted by the grid since most of the field lines end there.

The electrometer must be connected between the source of current and laboratory ground; since the resistance of the electrometer is very small, the anode potential remains very close to ground potential. In the measurement of both the excitation and ionization potentials the accelerating voltage is between the cathode and grid. Neither of these electrodes is at ground potential. In the excitation potential determination (i.e. the Franck-Hertz experiment) the Keithley electronic voltmeter is arranged to record the anode-to-cathode voltage. The accelerating potential can be measured directly with a floating (Fluke) voltmeter connected between cathode and grid.

Note that the lowest excited state of mercury is the $6^{3}P_{0}$ state, which is metastable, i.e. dipole transition to the ground state is forbidden. Its lifetime is ~10⁵ times that of ordinary allowed transitions.

As the electrons accelerate toward the grid they reach a position where they have sufficient energies to excite the $6^{3}P_{0}$ state, and will do so. Because the excited atoms decay slowly, their number builds up to the point where most of the electron-mercury atom interactions become elastic collisions off of excited atoms. The $6^{3}P_{1}$ state is not metastable and decays immediately by emission of a 2536 Å photon. Franck and Hertz detected these photons through a window in their tube. Having measured the threshold voltage *V* at which the photons appeared, they could derive a value for $h = Ve\lambda/c$. The agreement with the values obtained previously by Planck, Einstein, and Bohr from their theories of the blackbody spectrum, the photoelectric effect, and the hydrogen spectrum, respectively, was a striking and historic confirmation of the new quantum theory.



Figure 6. Schematic illustration of the electric field lines in the measurement of the excitation potential. Two electron trajectories are illustrated. Elastic and inelastic scatterings are indicated by "e" and "i", respectively. One electron is caught by the grid G. The other makes it to the anode A.

Procedure for measuring the excitation potential of mercury

a. Connect the tube as illustrated in Figure 4 with all the voltages set to their lowest absolute values. Adjust the tube temperature to $\sim 170^{\circ}$ C.

b. Set the filament voltage to a value that would give a <u>total</u> tube saturation current (anode+grid) in the range 1.0-0.1 µamp <u>at room temperature</u>, as measured above in part 1.

c. Set the retarding voltage at a value between 0.1 and 2 volts.

d. By hand, sweep the accelerating voltage, V_{cg} , from 0 to 60 volts and note the occurrence of maxima and minima in the anode current I_a (probably best done on the picoampere scale). Using the Fluke multimeter, measure and tabulate as accurately as you can the values of V_{cg} at the maximum and minimum values of the current, and the corresponding maximum and minimum anode currents.

e. Record the data on the IBM-XT so that you can later make a detailed analysis of the curve. <u>Analysis</u>

Derive from your data the value and error of the excitation potential. Referring to the computer plot, at what point between each successive pair of minima do you think the next set of excitation events begins? Derive an estimate of the value and error of the contact potential (see Melissinos for a discussion of the physics of contact potential) between the cathode and grid. You will need to correct the measurement of the ionization potential in section 2 by this quantity.

REFERENCES

P. R. Bevington & D. K. Robinson 1992, *Data Reduction and Error Analysis for the Physical Sciences*, 2nd Edition, McGraw Hill.

A. C. Melissinos 1966, Experiments In Modern Physics, pp.8-17 (Academic Press Inc.).

F. K. Richtmeyer, E. H. Kennard & C. Lauritsen 1955, *Introduction to Modern Physics*. pp. 275-278 (McGraw-Hill, NY).

SUGGESTED THEORETICAL TOPICS

- 1. Richardson's law.
- 2. Child's law.
- 3. Distribution in energy of electrons emitted by a hot metal.

APPENDIX A CIRCUIT DIAGRAM

