

The Franck-Hertz Experiment and the Ramsauer-Townsend Effect: Elastic and Inelastic Scattering of Electrons by Atoms

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(Dated: August 5, 2003)

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 in the region of interest. Assume 1) that the cross section of a mercury atom for collision with an electron is geometrical (i.e. $\sigma = \pi R^2$ 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

$$\log_{10}(p) = -12.93 + 0.042 \times T - 2.90 \times 10^{-5} T^2 \quad (1)$$

where p is the pressure in kPa of mercury (1kPa = 0.0098692 atm = 7.5006 Torr) and T is the temperature in K. Data from CRC 82nd Edition, Table 6-105.

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 2,536Å 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.

APPARATUS

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 (2003) 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 similar apparatus as described in that text. The tube has a coaxial cylindrical geometry with an inner cathode and filament which serves as an electron source. The control circuit for this tube, as well as the heater oven, is contained within the Leybold power supply unit which also has a multifunction digital display for measurement purposes.

SAFETY PRECAUTIONS

1. Vacuum tube with mercury filling (approx. 5g). Danger of implosion by impact, fall or similar. In case of breakage, collect and eliminate the mercury (using mercury absorbents 306 83).
2. Do not apply any voltages to the cold tube (risk of short circuit by metallic mercury between the electrodes.)
3. If gas discharge occurs, as indicated by abrupt current rise, immediately set both grid voltages to 0V.
4. Handle the hot pieces of equipment using a heat-resistant cloth or gloves.
5. Ensure via control of the oven temperature (i.e. the oven voltage) that the maximum temperature limit for the Franck-Hertz tube is not exceeded (permanent operation 200°C, short-term peak value 220°C).

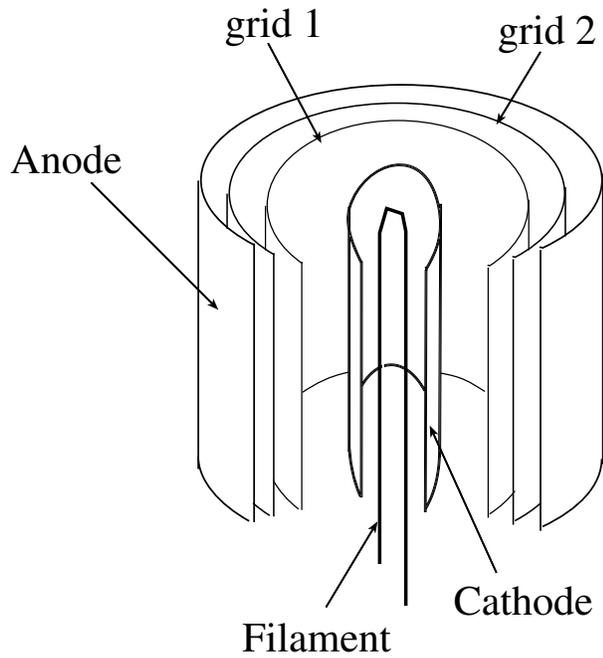


FIG. 1: Schematic representation of the Franck-Hertz tube.

FRANCK-HERTZ TUBE (555 85)

1. Vacuum tube with cylindrically arranged electrode system, discharge pins for leakage currents and with approx. 5g of metallic Hg.
2. Filament heater voltage and current: 3.15V, 0.4A (adapted to a 6.3V power supply by a resistor in socket 555 86).
3. Control voltage U_1 between cathode and grid g_1 : 0 to 4V DC.
4. Acceleration voltage U_2 between grid g_1 and grid g_2 : 0 to 40V DC.
5. Countervoltage U_3 between grid g_1 and collector A: 0 to 10V DC.
6. Maximum operating temperature: 200°C (continuous duty) 220°C (short-term)
7. Operating temperature: approx. 190°C
8. Mercury vapor pressure (at 200°C): 25 mbar approximately (or 18.75 torr)

Note figures 1 and 2 for a schematic and photo representation of the FH Tube. Also see Fig 3 for a schematic of the heater oven.

The FH tube has a coaxial cylindrical geometry, with an inner cathode and filament which serves as an electron source. The filament voltage or V_F can be adjusted with a screwdriver potentiometer at the back of the unit. Its



FIG. 2: Photograph of the Franck-Hertz tube.

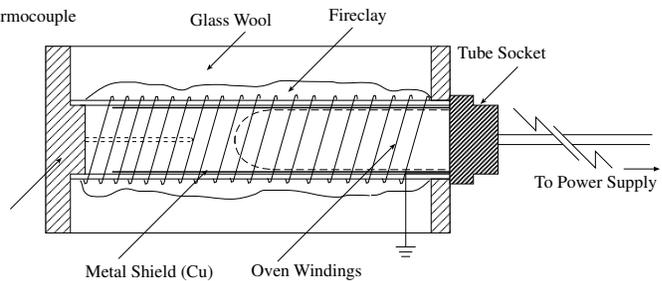


FIG. 3: Schematic of the heater oven with temperature probe

operating range is listed in the Leybold documentation as 5.9V...6.7V with a default of 6.3V. The front of the FH Power Supply Unit has an LED display which can be set to display all of the following quantities: the value of the control or driving voltage (U_1) range 0V...5V, the negative braking voltage (U_3) range 0V...10V, the acceleration voltage (U_2) range 0V...30V (actually this is more like 33V or 34V), the collector or total current (I) units (nA). Also the heater oven with which the FH tube is heated to vaporize the Hg inside is controlled by the PS Unit by means of a 6-pin DIN socket on the front of the unit. The set point for the temperature of the oven is v_s and the actual temperature is v , both of which are given on the display in degrees Centigrade. The oven has an operating range of about 145°C...220°C for short periods and 200°C for longer periods. It takes approximately 15-20mins for the oven to heat up from room temperature to 150°C. The PS unit reads this temperature information by means of a temperature probe, inserted into the oven and is connected with a DIN socket into the front of the unit (See Fig 3. Also, Leybold recommends using the tube only when it has been heated to at least the minimum oven settings (i.e. about 145°C)

SCATTERING OF ELECTRONS BY MERCURY ATOMS

The experiments on the excitation and ionization of mercury atoms are carried out with a sealed glass envelope containing four 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 145°C to 200°C.) The experiments will be performed with the three configurations of the tube and associated circuits illustrated in Figures 5, 6, and 7. The four electrodes are 1) a cathode which emits electrons when raised to a temperature of several hundred degrees by application of a voltage V_F to a heater filament, 2) a grid which is set at a positive potential V_{gc} relative to the cathode so that electrons emitted by the cathode are drawn toward it, and 3) a second grid which can be used to retard the motion of the electrons, and 4) an anode which serves as a measurement reference for the measurement of the current in the tube I_a .

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

It is wise to start each session by disassembling whatever wired-up circuit the previous users may have left, and then rewiring it yourself.

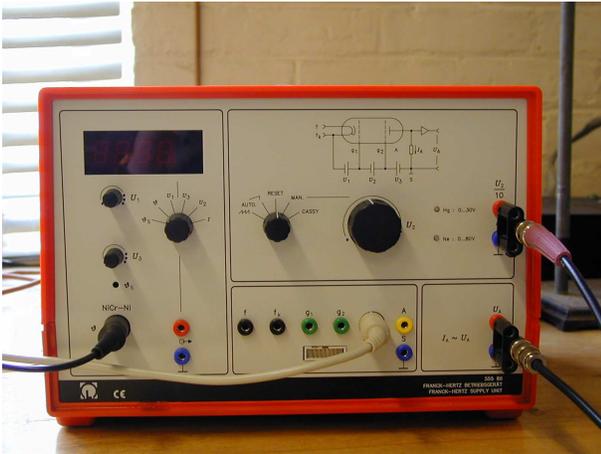


FIG. 4: Photograph of front panel of the Leybold Franck-Hertz control unit.

The FH Power Supply/control unit (See Figure 4) has on the front panel a mode switch that determines how the accelerating voltage is controlled. It is highly recommended that this switch remain at RESET until the FH tube is heated to at least 145°C as in this mode no voltages are applied to the tube. The other mode options are SAWTOOTH which ramps U_2 from 0V to 30V at a

rate fast enough for an oscilloscope display. The SINGLE RAMP mode does the same thing except much slower and could be used for an X-Y pen recorder. The MAN setting allows one to manually control U_2 by means of a large knob to the right of the mode switch from 0V to 30V. Finally, CASSY is a specialized setting for a particular measurement device which is not available here.

You will have control of five parameters—the filament voltage V_F which controls the temperature of the cathode, the control or driving voltage U_1 between cathode and g_1 , the retarding voltage U_3 between g_2 and the anode, the acceleration voltage U_2 between g_1 and g_2 , 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.

THERMIONIC EMISSION OF ELECTRONS AND SPACE CHARGE LIMITED CURRENT

Consider first the situation in the tube connected as shown in Figure 5. At low oven temperatures the va-

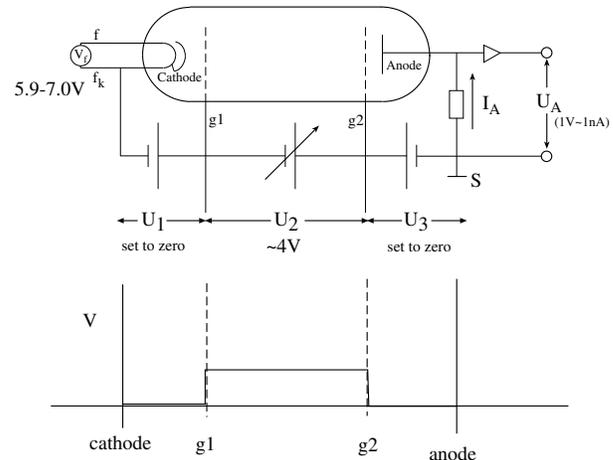


FIG. 5: Configuration for determining dependence of the anode current on the filament voltage V_F .

por pressure of the mercury is low enough 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 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 g_1 set to zero and g_2 set 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 (2003) for tube with ideal cylindrical geometry.

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 g_1 and g_2 , and also its dependence on the filament voltage which controls the temperature of the cathode. The measurements are made at the minimum oven operating temperature (approx. 150°C).

Procedure for Exploring the Dependence of the Total Current on the Filament and Accelerating Voltages

1. Connect the tube as shown in Figure 5 with the filament voltage set to its lowest value ($\sim 5.9\text{ V}$). Set the driving voltage (U_1) and the retarding voltage (U_3) to zero.
2. Set the accelerating voltage control so that U_2 , the potential difference between the two grids is held to about 4 V .
3. Now increase in steps the filament voltage and observe the dependence of the anode current on the filament temperature. Also try changing the value of the acceleration voltage and see if the dependence of the anode current on the filament voltage changes. **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 the anode current versus filament voltage with the heater oven at its lowest allowed setting.**

DETERMINATION OF THE IONIZATION POTENTIAL OF MERCURY

In this next experiment the tube is connected as shown in Figure 6 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 potential of g_2 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 positive current is registered by the electrometer. The experiment consists of measuring the anode current as a function of the potential difference between g_2 and the cathode. Analysis of the current-voltage relation yields a measure of the ionization potential.

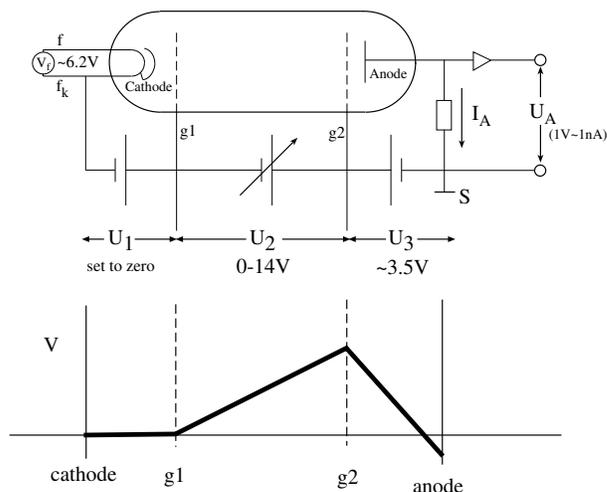


FIG. 6: Configuration for measuring the ionization energy of Hg.

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.

Connect the tube as shown in Figure 6. Set the filament voltage at the value which gives a total tube current in the range $0.1\text{--}1.0\ \mu\text{A}$ when $U_2 = \sim -30\text{ V}$, about 6.2 V . With the accelerating voltage U_2 initially set to zero (more accurately with the Leybold control box set to RESET) set the voltage of g_2 to about 3 V ($U_3 = 3\text{ V}$). Since U_3 opposes the voltage set by the accelerating potential (i.e. U_2) this is effectively a negative voltage with respect to the cathode at zero accelerating voltage. Now vary the acceleration potential from zero to about 15 V . 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

1. Set the accelerating voltage to its minimum value.
2. Again set the filament voltage to a value that would give a total tube current (anode + grid) in the range $1.0\text{--}0.1\ \mu\text{A}$ at the low oven temperature as was done above.
3. Set the retarding voltage so the anode potential is about 3V negative with respect to the cathode.
4. Tabulate and plot by hand the anode current I_a as a function of the accelerating voltage U_2 , 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).

Analysis

Estimate the value and uncertainty of U_2 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 U_2 plot at very small ($\text{pA}=10^{-12}$) currents in the region below 10 V. What causes it? (see Melissinos).

DETERMINATION OF THE EXCITATION POTENTIAL OF MERCURY

For the excitation potential measurement connect the tube as shown in Figure 7. Check all the potentials with the floating voltmeter. Set the oven temperature at $\sim 195^\circ\text{C}$ so that the mean free path of the electrons is short compared to the cathode-grid distance. Set the driving voltage U_1 to about 0.5V. Maintain the anode at a fixed negative “retarding” potential U_3 with respect to g_2 while the accelerating voltage U_2 between the cathode and grid is varied from 0 to ~ 30 volts. Electrons that pass through g_2 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 digital display, or by the scope.

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):

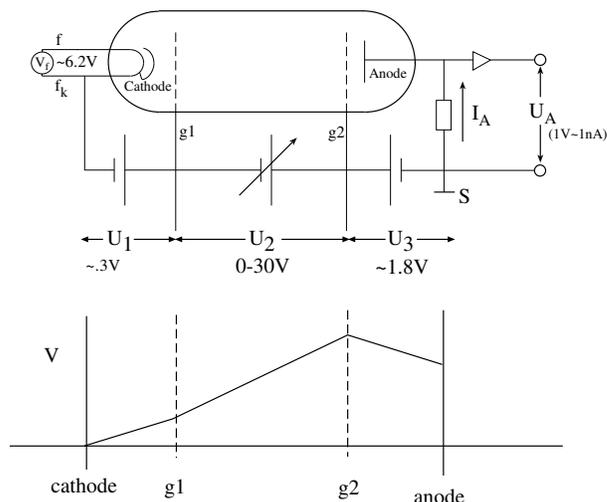


FIG. 7: Circuit arrangement for measurement of the critical excitation potential.

- 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 g_2 .
- 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 g_2 have the same energy.
- All electrons that pass through g_2 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 U_2 would appear as shown in Figure 8. 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 g_2 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 U_2 curve will depart considerably from the ideal for a variety of reasons.

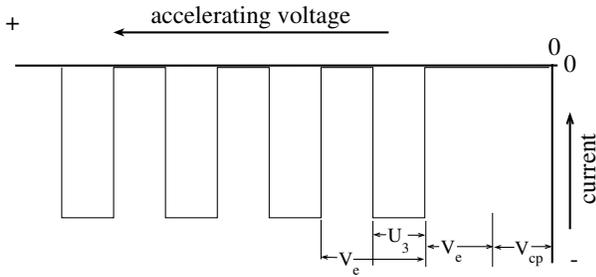


FIG. 8: Plot of anode current against accelerating voltage U_2 implied by set of idealized assumptions.

Figure 9 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.

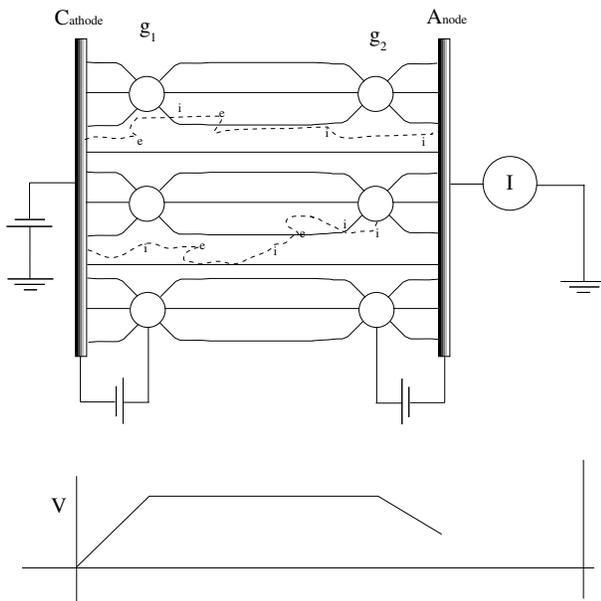


FIG. 9: UPDATE THIS!!!:=;Schematic illustration of the electric field lines in the measurement of the excitation potential. Two electron trajectories are illustrated. Elastic and inelastic scatterings are indicated by “e” and “i”, respectively. One electron is caught by the grid G. The other makes it to the anode A.

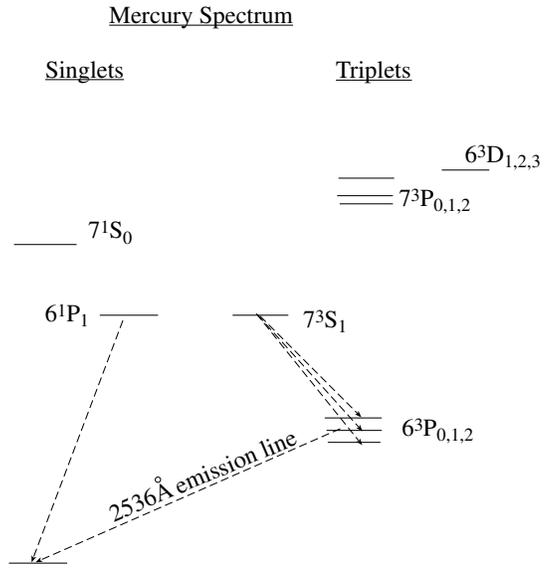


FIG. 10: A schematic of the spectrum of Hg.

Note that the lowest excited state of mercury is the 6^3P_0 state, which is metastable, i.e. dipole transition to the ground state is forbidden (See Fig. 10). Its lifetime is $\sim 10^5$ times that of ordinary allowed transitions. As the electrons accelerate toward g_2 they reach a position where they have sufficient energies to excite the 6^3P_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 6^3P_1 state is not metastable and decays immediately by emission of a 2536 \AA 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.

Procedure for Measuring the Excitation Potential of Mercury

1. Connect the tube as illustrated in Figure 7 with all the voltages set to their lowest absolute values. Adjust the tube temperature to $\sim 170^\circ\text{C}$.
2. Set the filament voltage to a value that would give a total tube saturation current (anode + grid) in the range $1.0\text{--}0.1 \mu\text{A}$ at the lowest allowed temperature that is 6.2V .
3. Set the retarding voltage at a value between 0.1

and 2 volts.

4. By hand or by using the ramp function, sweep the accelerating voltage, U_2 , from 0 to 30 volts and note the occurrence of maxima and minima in the anode current I_a . Using the scope, measure and tabulate the values of U_2 at the maximum and minimum values of the current, and the corresponding maximum and minimum anode currents.

Analysis

Derive from your data the value and error of the excitation potential. Referring to the plot of I_a vs. U_2 , 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 g_1 . You will need to correct the measurement of the ionization potential obtained earlier by this quantity.

THE RAMSAUER-TOWNSEND EFFECT

“The Ramsauer-Townsend effect may be thought of as a diffraction of the electron around the rare-gas atom, in which the wave function inside the atom is distorted in just such a way that it fits on smoothly to an undistorted wave function outside” (Schiff, 1949).

The result is a near extinction of the scattered S partial wave and a consequent suppression of the scattering cross section. The effect can be observed only when it occurs at an energy below that of the first excited state of the scattering atom. Otherwise it is masked by inelastic scattering. Noble gases provide specially suitable targets because they are monatomic, their outer electrons are in a closed shell, excitation of their lowest excited state requires a comparatively large amount of energy, and they do not attach electrons to form negative ions.

The Ramsauer-Townsend effect was discovered in 1921, before the invention of wave mechanics in 1926 and the discovery of the electron diffraction by Davisson and Germer in 1927. Its explanation in terms of the scattering of matter waves, first suggested by Bohr and worked out in detail by Mott (see Mott and Massey, 1965) and others on the basis of Schrödinger’s equation, was one of the early successes of the new wave mechanics.

The theoretical treatment of the elastic scattering of an electron by a noble gas atom requires the solution of the three dimensional Schrödinger equation for a free electron incident on a spherically symmetric attractive potential. This can be done by the method of partial waves

as explained in various intermediate texts on quantum mechanics (e.g. Bohm, 1951; Schiff, 1949; McGervey, 1971; and Dicke and Wittke, 1960).

The well-known model of a 1-dimensional, scattering problem, solved in many elementary quantum mechanics texts, is often put forward as exhibiting the essential features of wave mechanical behavior that one observes in the Ramsauer-Townsend effect. The 1-D model bears a relation to the real 3-D scattering problem that is similar to the relation which the problem of the energy levels of a particle in a 1-D box bears to the 3-D problem of the hydrogen atom, i.e. suggestive, but fairly distant as far as numerical agreement is concerned. In the 1-D scattering problem one finds the transmission coefficient has maxima at a series of discrete energies for both positive and negative potential wells, whereas in the 3-D case there is only one maximum, and that only for an attractive potential.

As mentioned above, the present experiment is described by Kukolich [1968]. A suitable xenon-filled tube is commercially available in the form of a thyratron switch tube. The depression of the scattering cross section at the critical energy is indicated by the reduction in the intensity of an electron beam directed from the cathode to the anode.

The apparatus and circuitry are illustrated schematically in Figure 7. Electrons emitted from the heated cathode are accelerated through a small potential difference toward the “grid” which is actually a metal box inside of which there is no electric field. The electrons that enter the box “drift” through it, and those that emerge from the far end are collected by the anode and measured as a current by the Keithley electrometer. At high vacuum, when the xenon gas is condensed on the glass walls of the thyratron by cooling in liquid nitrogen, the fraction of atoms emitted by the cathode that reaches the anode depends only on the geometry of the electrodes. When the xenon is vaporized, the fraction reaching the anode is reduced by elastic scatterings which deflect electrons from the trajectories that would otherwise bring them to the anode. The amount of the reduction is a measure of the elastic scattering cross section of the xenon atoms. One obtains the required data by measuring the anode current as a function of the accelerating voltage both with and without the xenon vapor.

Procedure for measuring the Ramsauer-Townsend effect in xenon

1. With all voltages set to their minimum values connect the circuit as shown in Figure 11, using the Keithley electrometer to measure the anode current as before, and the Fluke multimeter to measure the accelerating voltage.

2. Dip the tip of the thyatron in liquid nitrogen to freeze out the xenon. (**To reduce the likelihood of cracking the tube by thermal shock the filament voltage should always be zero when the tube is dipped into the liquid nitrogen.**)
3. With an accelerating voltage of 5 volts increase the filament heater voltage until the anode current is $10 \mu\text{A}$.
4. Leaving the filament voltage at the value just found, tabulate and plot the anode current (shifting to the nanoampere or picoampere scales where necessary) as a function of the accelerating voltage from 5V down to zero both with and without the xenon vapor frozen out, taking special care in the region between 0 and 2V where the interesting phenomenon occurs. It is wise to make your two sets of measurements at the same sequence of voltage values so that you can easily calculate the ratio of currents with and without the xenon frozen out. Compute and plot in your lab book the ratio against the accelerating voltage as you go along to monitor the trend of the data.

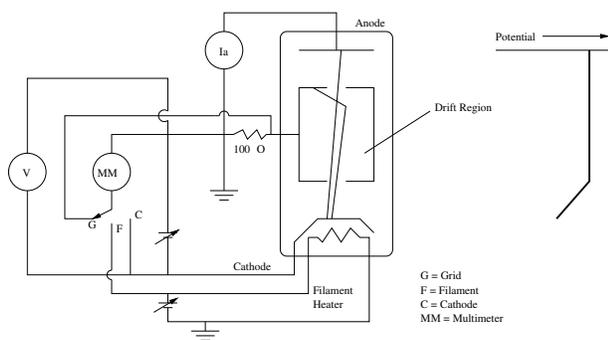


FIG. 11: Schematic diagram of the 2D21 thyatron and circuit used in the measurement of the cross section of xenon atoms for elastic scattering of low energy electrons. The trajectories of two electrons are shown, one scattered by a xenon atom and the other undeflected.

The liquid nitrogen needed to freeze out the xenon is available in room 4-335. Handle it carefully! Do not fill the Dewar flask to the brim! The tube need only be partially immersed to provide a cold place at which the gas can condense.

Analysis

The discussion about interpretation of the experiment in the article of Kukolich seems a little obscure. The following remarks may help. Call $I_0(V)$ the measured current with the xenon frozen out when the accelerating potential is V , and $I(V)$ the measured current at

the same accelerating voltage with the xenon gas free in the tube. If every electron scattered by a xenon atom were effectively removed from the beam, then these two measurements would be related by the equation

$$I(V) = I_0(V)e^{[-n\sigma(V)l]} \quad (2)$$

where n is the number of xenon atoms cm^{-3} , $\sigma(V)$ is the cross section of the xenon atoms for inelastic scattering the electrons of energy eV, and l is the path length from cathode to anode. The desired measure of the cross section would then be

$$\sigma(V) = \frac{1}{nl} \ln \left[\frac{I_0(V)}{I(V)} \right] \quad (3)$$

Actually, not every scattered electron is removed from the beam due to the poor geometry of the thyatron tube in this particular application. Therefore the value of the cross section derived from the simple analysis of the present experiment, assuming the quantity nl were accurately known, is somewhat less than the true value of the total inelastic scattering cross section.

Plot $\ln \left[\frac{I_0(V)}{I(V)} \right]$ against V . Discuss the sources and magnitudes of the errors and indicate your error estimates on the plot. Comment on the position of the minimum and its relation to the size of the xenon atom.

Suggested Theoretical Topics

1. Richardson's law.
2. Child's law.
3. Distribution in energy of electrons emitted by a hot metal.
4. Propagation of electrons through the Hg vapor.
5. Transmission of electrons through a rectangular potential well.
6. Partial-wave scattering theory of the Ramsauer-Townsend effect.

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