

THE MASSACHUSETTS INSTITUTE OF TECHNOLOGY
PHYSICS DEPARTMENT

8.13

Junior Physics Laboratory: Experiment #7

THE FRANCK-HERTZ EXPERIMENT
AND THE RAMSAUER-TOWNSEND EFFECT

Elastic and Inelastic Scattering of Electrons by Atoms

PURPOSE

The main purpose of these experiments is to measure three phenomena encountered in collisions between electrons and atoms: inelastic scattering resulting in quantized excitation of the target atom; ionization, resulting in the removal of an electron from the atom; and elastic scattering in a range of energies in which wave mechanical interference effects are prominent. 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. Why is xenon a good choice for demonstrating the Ramsauer-Townsend effect?
3. 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. $\sigma = \pi R^2$ 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

$$\log_{10} p = -3204/(T + 273.1) + 8.009,$$

where p is the pressure in mm of mercury and T is the temperature in °C. See CRC Handbook, p. D-197.)

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.

The Ramsauer-Townsend effect in the elastic scattering of low-energy electrons from xenon atoms will be studied in a commercial xenon-filled thyratron tube. Attention is focussed on the effect of wave-mechanical interference which results in a marked depression of the scattering cross section near a certain critical electron energy. Although the tube is intended for other purposes, namely to switch high currents, it happens to be well-suited to this experiment. The setup and procedure are taken from the paper by Kukolich (1968) a copy of which is appended to this guide as Appendix C.

SCATTERING OF ELECTRONS BY MERCURY ATOMS

The experiments on the excitation and ionization of mercury atoms are carried out with a mercury-filled 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, and 4. The three electrodes are 1) a cathode which emits electrons when raised to a temperature of

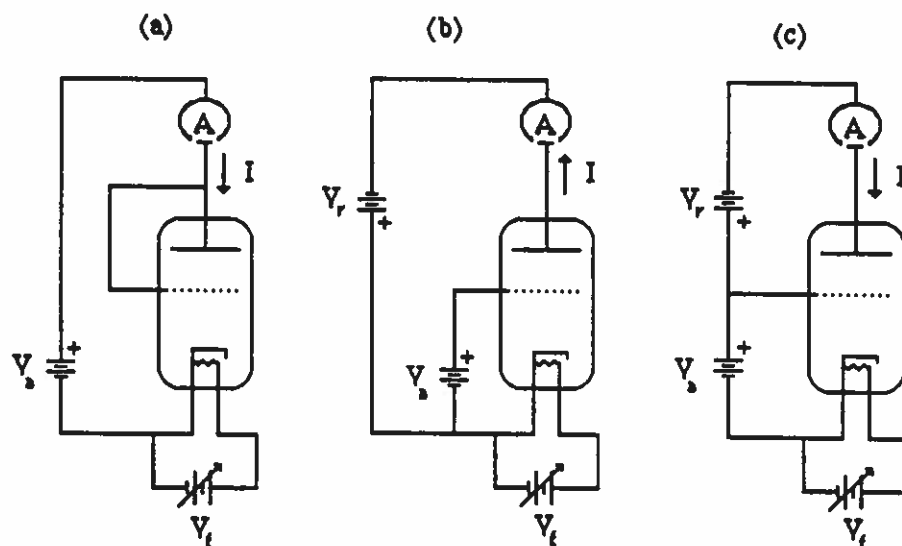


Figure 1. Schematic illustrations of the mercury-filled triode in the three configuration used in measurements of (a) thermionic emission and space charge limited current, (b) the ionization potential of mercury, and (c) the critical excitation potential of mercury.

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_{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_a .

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

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 Appendix A, 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 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

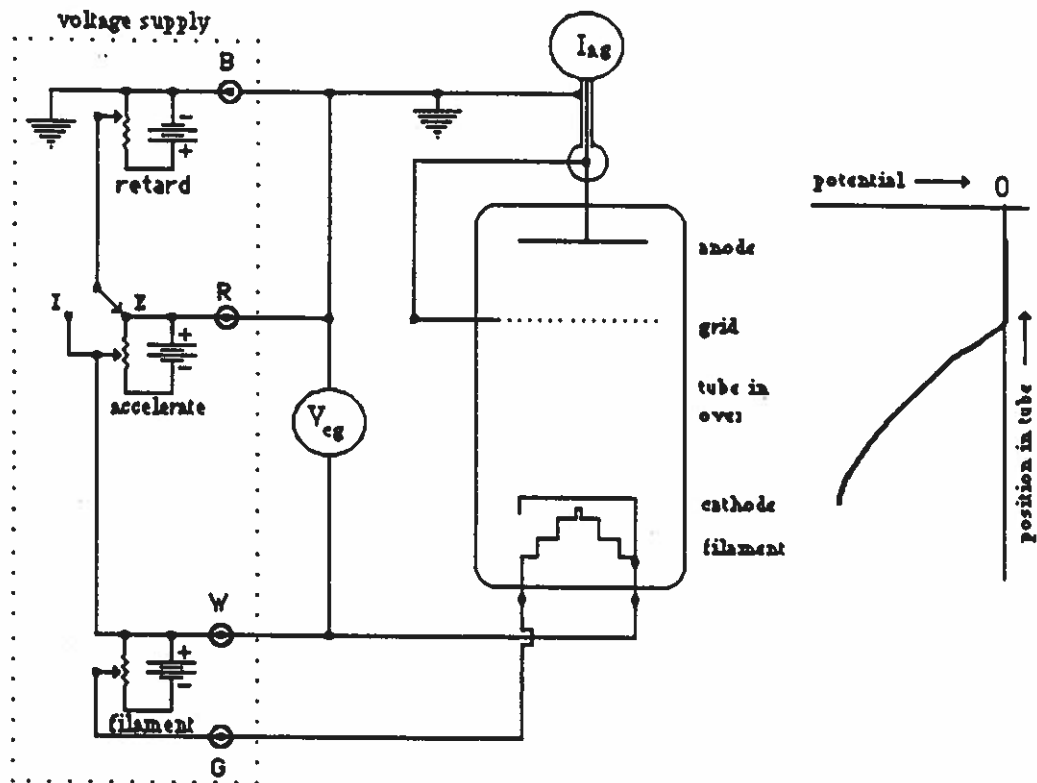


Figure 2. Schematic diagram of the tube and circuit for measurements of space charge limited current from thermionic emission. The variation of potential with position in the tube is indicated in the plot at the right. For this measurement the toggle switch should be set to the "E" (excitation) position and the "retarding" voltage control should be set to zero. The colors of the external banana plug female connectors are indicated by the letters B, R, W, and G 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.

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 plate should be connected to the electrometer with coaxial cables so that all electrons captured by the grid and plate 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 μ amp 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_F at a value for which I_{ag} is in the range 0.1 - 1.0 μ amp when $V_{cg} = -60$ v. Then tabulate and plot I_{ag} as a function of V_{cg} , shifting scales on the electrometer as needed. You may find that the current drifts substantially at any given setting of V_F and V_{cg} . Don't panic. The purpose of this section is to obtain a rough 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

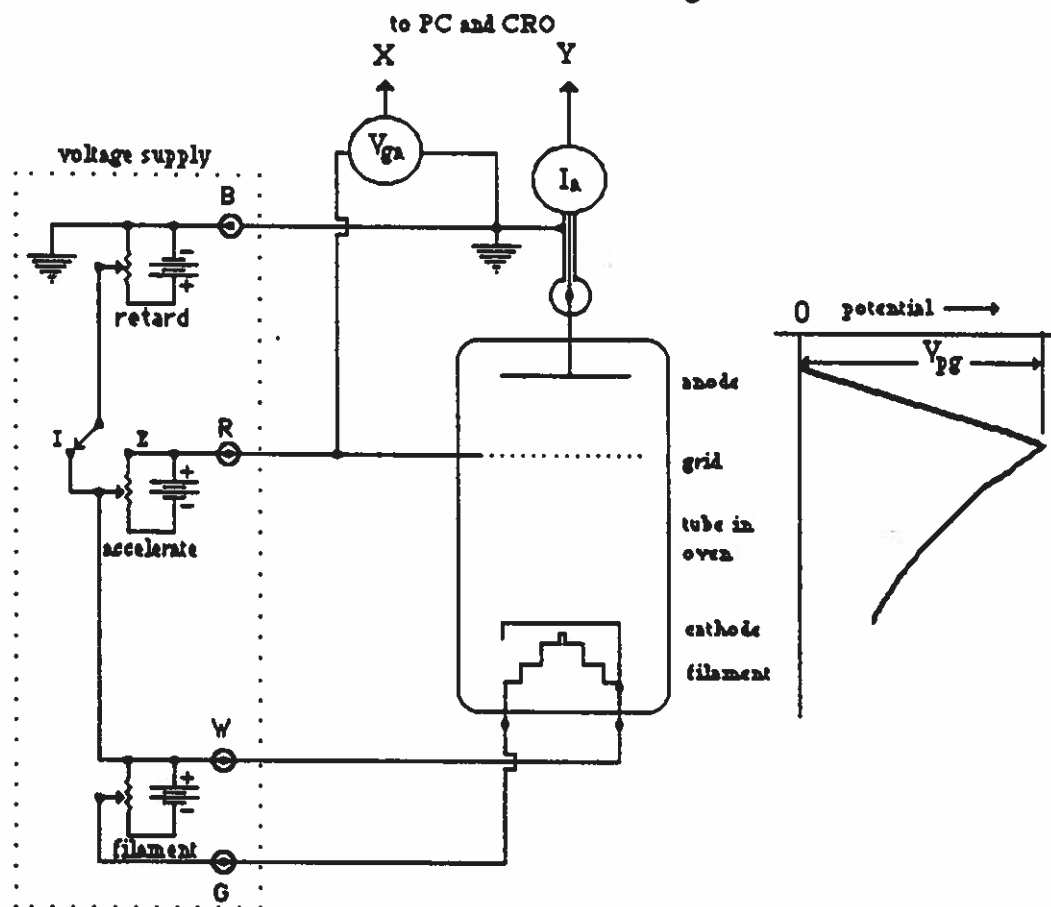


Figure 3. Schematic diagram of the mercury-filled triode in the configuration for measurement of the ionization potential of mercury. After you complete the connections check all the potential differences in your setup with the floating Fluke voltmeter and verify that they are consistent with the voltage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

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 positive 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.

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 $V_{cg} \approx -60\text{ v}$, 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 anode potential is 2 v below the cathode 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

- Set the accelerating voltage to its minimum value.
- Again set the filament voltage to a value that would give a total tube current (anode+grid) in the range 1.0-0.1 μamp at room temperature in the arrangement used in Section 1 above.
- Set the retarding voltage so the anode potential is 2 v negative with respect to the cathode.
- 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).
- 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.

Analysis

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

values. Adjust the tube temperature to $\sim 170^\circ\text{C}$.

b. Set the filament voltage to a value that would give a total tube saturation current (anode+grid) in the range $1.0\text{--}0.1\ \mu\text{amp}$ at room temperature, 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 picoamp 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 and plot the data on the IBM-XT so that you can later make a detailed analysis of the curve.

Analysis

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.

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, 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 1D model bears a relation to the real

3D scattering problem that is similar to the relation which the problem of the energy levels of a particle in a 1-dimensional box bears to the 3D problem of the hydrogen atom, i.e. suggestive, but fairly distant as far as numerical agreement is concerned. In the 1D 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 3D case there is only one maximum, and that only for an attractive potential.

As mentioned above, the present experiment is described by Kukolich in the article attached as Appendix C. 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

- a. With all voltages set to their minimum values connect the circuit as shown in Figure 7, using the Keithley electrometer to measure the anode current as before, and the Fluke multimeter to measure the accelerating voltage.
- b. Dip the tip of the thyratron 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.)
- c. With an accelerating voltage of 5 volts increase the filament heater voltage until the anode current is 10 μ amps (10^{-5} amps).
- d. 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 5 v down to zero both with and without the xenon vapor frozen out, taking special care in the region between 0 and 2 volts 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.

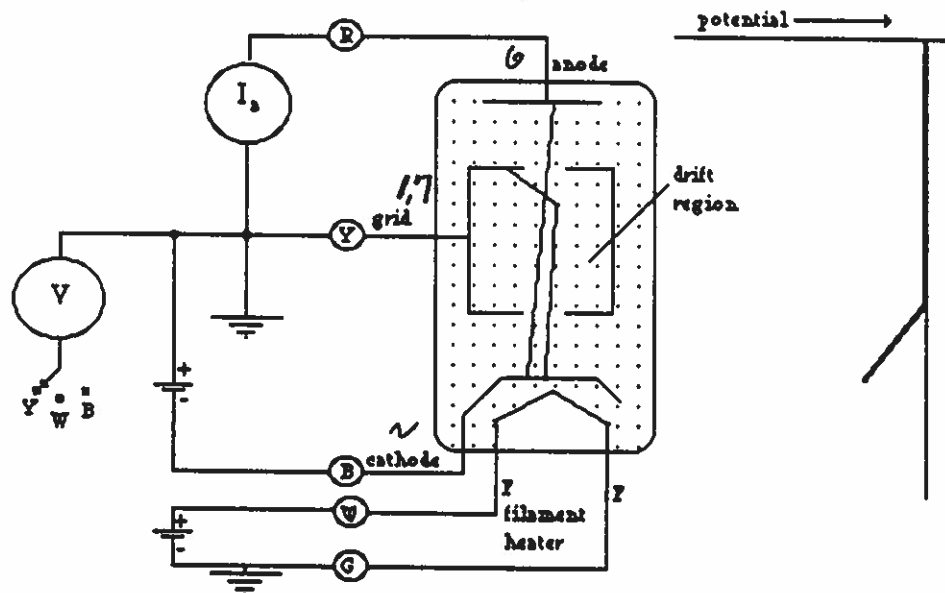


Figure 7. Schematic diagram of the 2D21 thyatron and circuit used in the measurement of the cross section of xenon atoms for elastic scattering of low energy electrons. The trajectories of two electrons are shown, one scattered by a xenon atom and the other undeflected.

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

$$I(V) = I_0(V) \exp[-n\sigma(V)l],$$

where n is the number of xenon atoms per 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 plate. The desired measure of the cross section would then be

$$\sigma(V) = \frac{1}{nl} \ln[I_0(V)/I(V)].$$

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 $\ln[I_0(V)/I(V)]$ 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.

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