(revised 1/23/23)

RAMSAUER - TOWNSEND EFFECT

Advanced Laboratory, Physics 407,
University of Wisconsin
Madison, Wisconsin 53706

Abstract

The scattering cross section of electrons on noble gas atoms exhibits a very small value at electron energies near 1 eV. This is the Ramsauer-Townsend effect [1] and provides an example of a phenomenon which requires a quantum mechanical description of the interaction of particles. The Ramsauer-Townsend effect is easily demonstrated using a xenon thyratron [2].

Theory

The Ramsauer-Townsend effect can be observed as long as the scattering does not become inelastic by excitation of the first excited state of the atom. This condition is best fulfilled by the closed shell noble gas atoms. Physically, 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. The effect is analogous to the perfect transmission found at particular energies in one-dimensional scattering from a square well. See pp. 156-167 of Ref. [3] (which can always be found in the Physics 407 lab room) for an elementary treatment. This is the first model which you will use to analyze the data. A three-dimensional treatment using partial waves is given in Ref. [4], pp 396-402. Ref. [5] may also be helpful.

Apparatus

Thyratron - (RCA 2D21): this tube contains Xenon gas. The assembly is mounted on a stand so that the hot filament of the tube is uppermost, allowing the tube to be dipped into liquid nitrogen. (Note that the voltages being used here are NOT the voltages which are normally used in thyratron circuits).

Regulated DC Power Supply: The supply provides the voltage to accelerate the electrons. the supply provides 0 to 30 volts but is difficult to adjust for very low voltages. For this reason a control box containing a potentiometer is used to accurately set the lower voltages.

4-Volt Transformer: the transformer provides the power for the thyratron filament. The tube normally uses 6.3 volts AC but by running the cathode at a lower temperature the spread in electron energies is reduced. The transformer is contained in the control box.

Dewar Flask: the dewar will hold the liquid nitrogen necessary for freezing out the Xenon in the thyratron tube. The cold data is used to correct for thyratron geometry effects.

Digital Multimeters - (6 1/2 digit Keithley 2100): these are high impedance meters used to measure the plate voltage, V_p; the shield voltage, V_s; and the cathode to shield voltage, $(V - V_s)$. Note that both inputs are floating.

Ramsauer.py: a python data-logging program. Records all the DVM readings in a .csv file which you can name. Also plots in real time the $V - V_s$ readings and both V_p and V_p as a function of $V - V_s$.

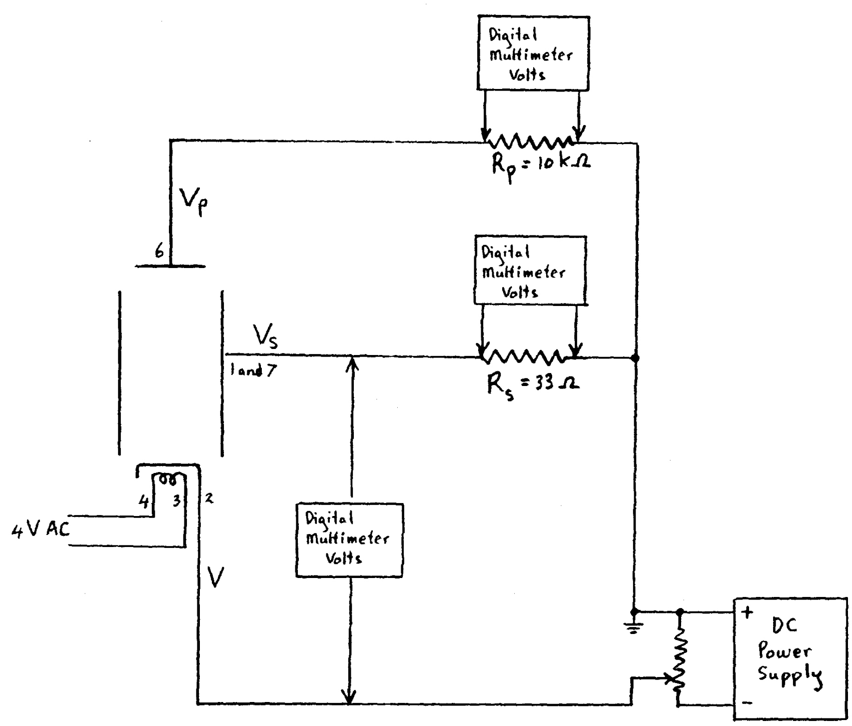

Figure 1: Circuit diagram.

<u>Thyratron Socket Wiring Color Code</u>

Pin	Internal Connection	Color of Wire
1	grid #1	green*
2	cathode	black
3	heater	red
4	heater	red
5	shield (grid #2)	no connection
6	anode	yellow
7	shield (grid #2)	green*

* grid #1 and shield (grid #2) are joined externally

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Demonstration of the Ramsauer–Townsend Effect in a Xenon Thyratron

STEPHEN G. KUKOLICH
Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 15 January 1968; revision received 15 April 1968)

The anomalously small scattering of electrons near 1 eV energy by noble gas atoms may be easily demonstrated using a 2D21 xenon thyratron. This experiment is suitable for a lecture demonstration or for an undergraduate physics laboratory. The probability of scattering and the scattering cross section may be obtained as a function of electron energy by measuring the grid and plate currents in the tube.

The scattering cross section for electrons on noble gas atoms exhibits a very small value at electron energies near 1 eV. This cross section is much smaller than that obtained from measurements involving atom–atom collisions. This is the Ramsauer–Townsend effect and provides an example of a phenomenon which requires a quantum mechanical description of the interaction of particles. If the atoms are treated classically as hard spheres, the calculated cross section is independent of the incident electron energy and we cannot account for the Ramsauer–Townsend effect. If the noble-gas atoms are considered to present an attractive potential (e.g., square well, screened Coulomb) of typical atomic dimensions, the solution of the Schrödinger equation for the electrons indicates that the cross section will have a minimum at electron energies near 1 eV. Reviews of the Ramsauer–Townsend effect are given by Mott and Massey[1] and Brode.[2]

[1] N. F. Mott and H. S. W. Massey, *The Theory of Atomic Collisions* (Oxford University Press, London, 1965), 3rd ed., Chap. 18.

[2] R. B. Brode, Rev. Mod. Phys. **5**, 257 (1933).

The problem of scattering of electrons by a square well is considered in many introductory quantum physics texts.[3–7] The one-dimensional model predicts that the scattering will go to zero whenever half the electron wavelength in the well is a multiple of the well width. The difficulty with this model is that only one distinct minimum is observed.

A slightly better model of the xenon atom is a three dimensional square well. Then the scattering cross section will have a very small value when the phase shift δ_0 of the $l=0$ partial wave is π. Here the scattering due to the $l=0$ partial wave will vanish and the scattering due to higher l partial waves will be small if the width of the

[3] L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Co., New York, 1955), Chap. 5.

[4] E. Merzbacher, *Quantum Mechanics* (John Wiley & Sons, Inc., New York, 1955), Chaps. 6, 12.

[5] D. Bohm, *Quantum Theory* (Prentice-Hall Inc., Englewood Cliffs, N.J., 1951), Chaps. 11.9, 21.51.

[6] A. Messiah, *Quantum Mechanics I* (North-Holland Publ. Co., Amsterdam, 1961), Chaps. III-6.

[7] R. M. Eisberg, *Fundamentals of Modern Physics* (John Wiley & Sons, Inc., N.Y., 1961), Chap. 15.

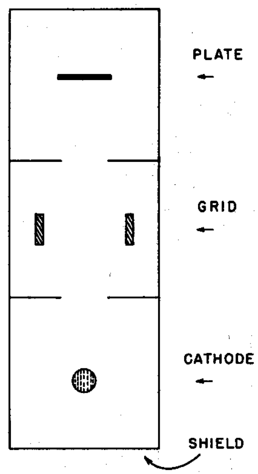


FIG. 1. Cross section of the 2D21 thyratron.

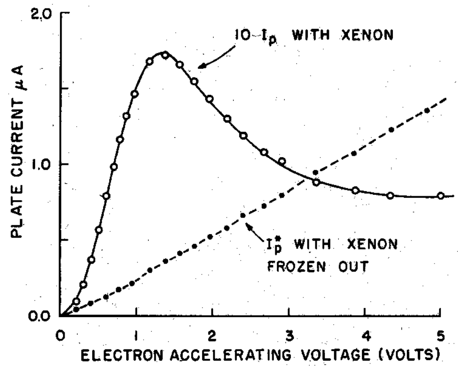


FIG. 3. The plate current I_p as a function of the voltage V, and $I_p{}^*$ the plate current with the xenon frozen out with liquid nitrogen.

well is small.[1] When the $l=0$ phase shift becomes 2π, or higher l phase shifts become π at higher values of electron energy, the dips in the cross section will not be as prominent since contributions from other values of l will not be small. The well parameters may be adjusted to give a minimum at the observed energy. This model predicts the Ramsauer–Townsend effect in a qualitative way, but does not give quantitative agreement over a wide range of electron energies. The results of more accurate calculations with a screened coulomb potential are given by Mott and Massey.[1]

I. THE EXPERIMENT

The 2D21 thyratron is very well suited for a demonstration of the Ramsauer effect. The shield (grid 2) is a boxlike structure with three sections connected by apertures (see Fig. 1). The electron beam originates at the cathode in the first section, passes through the second section, and part of it is collected on the plate in the third section. The xenon pressure in the tube is approximately 0.05 Torr. A diagram of the circuit is shown in Fig. 2. The shield current is proportional to the intensity of the electron beam at the first aperture. After the first aperture the beam passes through an equipotential region where the scattering takes place. In this region the beam intensity is $J=J_0e^{-x/\lambda}$, where λ is the mean free path. If the plate is a distance l from the first aperture, the intensity at the plate is $J_p=J_0e^{-l/\lambda}$ or $J_p=J_0(1-P_s)$, where P_s is the probability of scattering. The plate current is $I_p=I_sf(V)(1-P_s)$, where I_s is

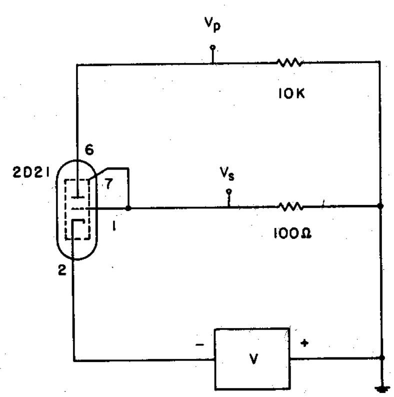


FIG. 2. Diagram of the circuit for the Ramsauer effect experiment. The filament of the 2D21 (pins 3, 4) is heated by 4 V dc.

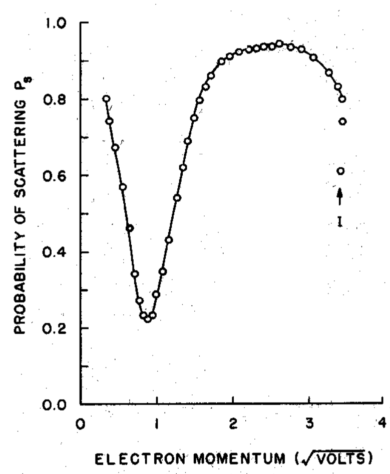


FIG. 4. The probability of scattering P_s as a function of $(V-V_s)^{1/2}$, where $V-V_s$ is the electron energy. Ionization occurs at "I".

the shield current and $f(V)$ is a geometrical factor which contains the ratio of the angle intercepted by the plate to the angle intercepted by the shield and a factor due to space charge effects near the cathode. To measure $f(V)$ we freeze out the xenon by dunking the top of the tube in liquid nitrogen. This reduces the xenon pressure to $\sim 10^{-3}$ Torr and P_s becomes very small so we get $f(V) \cong I_p^*/I_s^*$. Now we have $P_s = 1 - I_p I_s^*/I_s I_p^*$. Figure 3 shows that I_p has a maximum near 1 eV and that I_p/I_p^* approaches one there, indicating that there is very little scattering. At higher energies I_p/I_p^* is very small indicating a large probability of scattering. A plot of P_s calculated from the data using the above equation is shown in Fig. 4.

The probability of scattering is related to the mean free path by the relation $P_s = 1 - e^{-l/\lambda}$. For the 2D21 $l = 0.7$ cm so we can calculate λ. The cross section σ is related to λ by $n\sigma = 1/\lambda$, where n is the number of atoms per unit volume. A plot obtained from our values of P_s is shown in Fig. 5. A similar set of data for P_c ($P_c = P/\lambda$, where P is the pressure in Torr) given by Brode[7] is shown in Fig. 6. In the 2D21 fairly large angular deflections must be produced to scatter an electron out of the beam (greater than ~ 0.2 rad) so the cross section measured in the 2D21 will be smaller than Brode's data.

II. EXPERIMENTAL DETAILS

The filament of the 2D21 is operated on 4 V dc. This is lower than the recommended value of 6.3 V, but tends to reduce space charge effects. Since the cathode temperature is lower, the thermal kinetic energy of the electrons is smaller and this will result in a narrower distribution of electron energies. The shield and plate currents are obtained by measuring the voltages V_s and V_p with two Keithley model 600A electrometers (see Fig. 2). The voltage source V is a well regulated and filtered supply which may be varied between 0–15 V. The electron energy plotted in the figures is $V - V_s$. We have not included a correction for the contact potential difference between the cathode and the shield. This contact potential difference is approximately 0.4 V and was measured by noting that ionization occurs when $V - V_s$ is 0.4 V less than the tabulated ionization potential. A similar value was obtained by measuring the value of V required to cut off the electron current to the shield. The voltages V_s and V_p range from a few millivolts to a few tenths of a volt. The data may be displayed on an oscilloscope by using an audio oscillator for the source V and for the x axis of the 'scope.

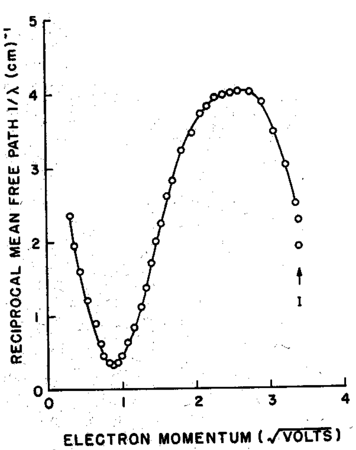


FIG. 5. The cross section times density $n\sigma = 1/\lambda$ as a function of $(V - V_s)^{1/2}$, where $V - V_s$ is the electron energy. Ionization occurs at "I".

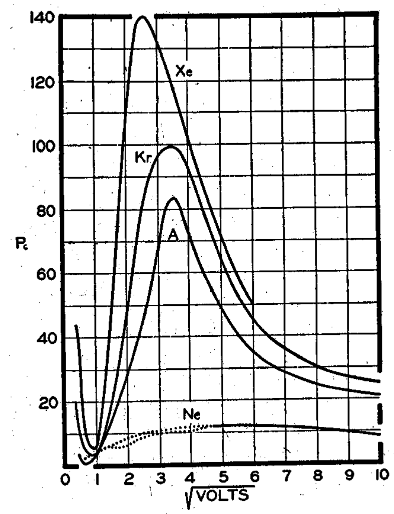


FIG. 6. The probability of collision P_c (=pressure times $n\sigma$) as a function of $(V)^{1/2}$ where V is the electron energy (from Brode see Ref. 2).

ACKNOWLEDGMENT

This experiment was suggested by Professor R. Weiss as a demonstration in an introductory course in quantum physics given by him at MIT.

![RCA]

2D21 THYRATRON

GAS TETRODE, MINIATURE TYPE

GENERAL DATA

Electrical:

	Min.	Av.	Max.	
Heater, for Unipotential Cathode:				
Voltage (AC or DC)	5.7	6.3	6.9	volts
Current, with heater volts = 6.3	0.54	0.60	0.66	amp
Cathode:				
Heating Time, prior to tube conduction	10	-	-	sec

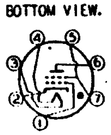
Direct Interelectrode Capacitances (Approx.):°		
Grid No.1 to Anode	0.026	μμf
Input	2.4	μμf
Output	1.6	μμf
Ionization Time (Approx.): For conditions: dc anode volts = 100; grid-No.1 square-pulse volts = 50; peak anode amp. during conduction = 0.5	0.5	μsec
Deionization Time (Approx.): For conditions: dc anode volts = 125; grid-No.1 volts = -100, grid-No.1 resistor (ohms) = 1000; dc anode amp. = 0.1	35	μsec
For conditions: dc anode volts = 125; grid-No.1 volts = -10; grid-No.1 resistor (ohms) = 1000; dc anode amp. = 0.1	75	μsec
Maximum Critical Grid Current, with ac anode-supply volts (rms) = 460, and average anode amp. = 0.1	0.5	μamp
Anode Voltage Drop (Approx.)	8	volts
Grid-No.1 Control Ratio (Approx.) with grid-No.1 resistor (megohms) = 0; grid-No.2 volts = 0	250	
Grid-No.2 Control Ratio (Approx.) with grid-No.1 resistor (megohms) = 0; grid-No.2 resistor (megohms) = 0; grid-No.1 volts = 0	1000	

° Without external shield.

Mechanical:

Mounting Position	Any
Maximum Overall Length	2-1/8"
Maximum Seated Length	1-7/8"
Length, Base Seat to Bulb Top (excluding tip)	1-1/2" ± 3/32"
Maximum Diameter	3/4"
Bulb	T-5-1/2
Base	Small-Button Miniature 7-Pin
Basing Designation for BOTTOM VIEW	7BN

Pin 1 - Grid No.1
Pin 2 - Cathode
Pin 3 - Heater
Pin 4 - Heater



Pin 5 - Grid No.2
Pin 6 - Anode
Pin 7 - Grid No.2

← Indicates a change.

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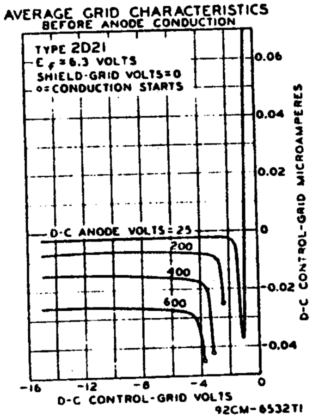
2D21 THYRATRON

AVERAGE GRID CHARACTERISTICS BEFORE ANODE CONDUCTION



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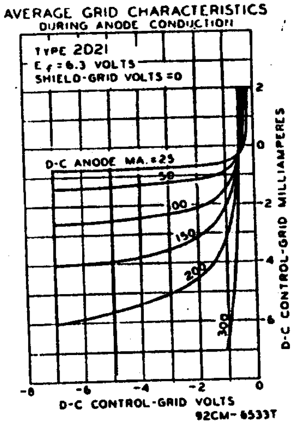
AVERAGE GRID CHARACTERISTICS DURING ANODE CONDUCTION



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2D21 THYRATRON

RELAY and GRID-CONTROLLED RECTIFIER SERVICE

Maximum Ratings, *Absolute Values*:

PEAK ANODE VOLTAGE:		
Forward	650 max.	volts
Inverse	1300 max.	volts
GRID-No.2 (SHIELD-GRID) VOLTAGE:		
Peak, before anode conduction	-100 max.	volts
Average, during anode conduction■	-10 max.	volts
GRID-No.1 (CONTROL-GRID) VOLTAGE:		
Peak, before anode conduction	-100 max.	volts
Average, during anode conduction■	-10 max.	volts
CATHODE CURRENT:		
Peak	0.5 max.	amp
Average■	0.1 max.	amp
Surge, for duration of 0.1 sec. max.	10 max.	amp
GRID-No.2 CURRENT:		
Average■	+0.01 max.	amp
GRID-No.1 CURRENT:		
Average■	+0.01 max.	amp
PEAK HEATER-CATHODE VOLTAGE:		
Heater negative with respect to cathode	100 max.	volts
Heater positive with respect to cathode	25 max.	volts
AMBIENT TEMPERATURE RANGE	-75 to +90	°C

Typical Operating Conditions for Relay Service:

RMS Anode Voltage	117	400	volts
Grid-No.2 Voltage	0	0	volts
RMS Grid-No.1 Bias Voltage□	5	-	volts
DC Grid-No.1 Bias Voltage	-	-6	volts
Peak Grid-No.1 Signal Voltage	5	6	volts
Grid-No.1-Circuit Resistance	1.0	1.0	megohm
Anode-Circuit Resistance♯	1200	2000	ohms

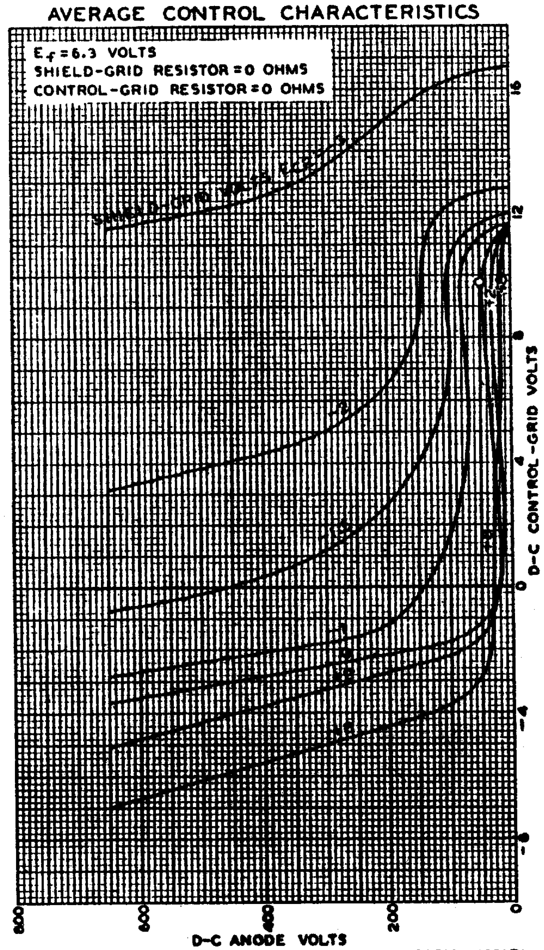
Maximum Circuit Values:

Grid-No.1-Circuit Resistance	10 max.	megohms

■ Averaged over any interval of 30 sec. max.
□ Approximately 180° out of phase with the anode voltage.
♯ Sufficient resistance, including the tube load, must be used under any conditions of operation to prevent exceeding the current ratings.
→ Indicates a change.

2D21

AVERAGE CONTROL CHARACTERISTICS



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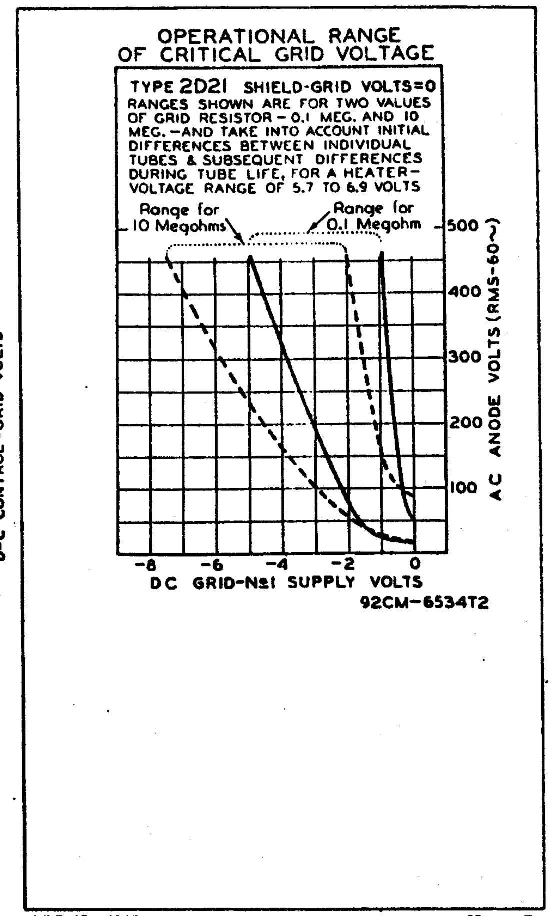
2D21

THYRATRON



JUNE 15, 1948 — TUBE DEPARTMENT — CE-6534T2

Procedure

1. Read the preceding article by S.G. Kukolich (Am. J. Phys. **36**, 701-703 (1968)) and review the quantum-mechanical theory of one-dimensional scattering of electrons from a finite square well.

2. Set up the circuit as in the diagram on page 4. Note location of ground.

3. Allow 5 minutes for the tube filament, cathode and multimeters to heat up and become stable.

4. Launch the Command Prompt app, do "cd Desktop" and then "cd Ramsauer Program" to get to the right directory, and then type "python Ramsauer.py" at the command prompt to launch the data-logging program. Connect the bottom DVM (V1) to measure the voltage difference between shield and filament $-(V - V_s)$ (make sure to get the sign as specified), the middle DVM (V2) to measure the shield voltage V_s, and the top DVM (V3) to the measure the plate voltage (V_p). Click "initialize" before the first data point, and then "read data", "save data", and "append data" every time you take a data point. After taking a data point press "local" on the front of V1 so you can adjust $V - V_s$ properly.

5. Measure the voltages V_s and V_p as a function of the cathode to shield voltage $(V - V_s)$ with the thyratron at room temperature. Use values of $(V - V_s)$ approximately as follows:

from	0.25	to	1.00	volts in steps of	0.1	volts
	1.00	to	2.00	volts in steps of	0.1	volts
	2.00	to	3.00	volts in steps of	0.2	volts
	3.00	to	5.00	volts in steps of	0.5	volts
	5.00	to	10.00	volts in steps of	1.0	volts

   The purpose of the uneven steps is to give the best detail between 0.3 and 1.0 on the plot of $\sqrt{V - V_s}$. Above 10 V the Xenon begins to ionize and the tube currents become large.

6. Turn off the filament and gently immerse only the lower blackened part of the thyratron in liquid nitrogen. Allow it to cool for 15 minutes then turn on the filament again and allow a further 5 minutes for temperatures to stabilize. The Xenon will have condensed and frozen at the cold end of the tube.

7. Repeat measurements of Step 4 above at the same values of $(V - V_s)$ to obtain V_s^* and V_p^*. Adjust the tube from time to time to keep the lower end in the liquid nitrogen.

8. Plot I_p and I_p^* against $\sqrt{V - V_s}$.

9. Calculate the probability of transmission (no scattering):

$$T = \frac{I_p I_s^*}{I_s I_p^*}.$$

   Since $V_p = I_p R_p$

$$V_p^* = I_p^* R_p$$
$$V_s = I_s R_s$$
$$V_s^* = I_s^* R_s,$$

   it is easier to calculate:

$$T = \frac{V_p V_s^*}{V_s V_p^*}.$$

   Plot T against $\sqrt{V - V_s}$ (which is proportional to the electron momentum).

   Plot T against $V - V_s$ (which is proportional to the electron energy).

   Note the value of $(V - V_s)$ corresponding to maximum T.

10. Compare this value to the value deduced from the data of Ramsauer and Kollath [1] of 0.71 ± 0.07 V, and note any discrepancy.

11. Attempt to correct your result for the contact potential difference. The contact potential may be estimated by measuring the value of $V - V_s$ which makes the grid current I_s equal to zero. If there were no contact potential, $I_s = 0$ would correspond to $V - V_s = 0$. You will find that the required value of $V - V_s$ to make $I_s = 0$ is a reverse polarity. Reverse the power supply voltage and make careful measurements with increasing $(V - V_s)$ so that the the value of $(V - V_s)$ which makes $I_s = 0$ can be determined. The value of this offset voltage is approximately the contact potential. Does the correction make the discrepancy between your value and Ramsauer's value larger or smaller?

12. Assume that the diameter of a Xenon atom is about 2.8 Å (Xenon is smaller than Cesium (5.5 Å) because Xenon has closed shells). From your data and using one-dimensional Quantum Mechanics estimate the average depth of the square well seen by the electrons.

13. A somewhat more realistic result for the depth of the square well seen by the electrons can be made by using the three-dimensional square well as a model. Theory predicts that the scattering will be a minimum when the phase shift δ_0 of the $\ell = 0$ partial wave is $n\pi$ provided that all other partial wave contributions are negligible. The condition that the wave function and its derivative must be continuous at the boundary $r = a$ then becomes [6]

$$\alpha a = \tan \alpha a \, ,$$

where $\alpha = \sqrt{2m_e(E + V_0)/\hbar^2}$ and V_0 is the depth of the square well. Use this relation to make another estimate of the depth of the square well.

14. Extra credit: does your value of the contact potential depend on the temperature?

15. Extra credit: make a more accurate measurement of the contact potential, and measure an additional correction due to the non-zero initial energy of the thermionic electrons emitted by the filament, using the method of Ref. [7].

References

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