AN ABSTRACT OF THE THESIS OF

CHEE TAO WANG (Name) for the Master of Science (Degree) in Physics (Major)

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Title Demonstration Apparatus for Alpha-Ray Scattering

Abstract approved [redacted] (Major Professor)

Apparatus has been constructed for demonstrating alpha-ray scattering by thin metal foils. A simple proportional counter filled with air at atmospheric pressure was used as an alpha-particle detector. Special consideration has been given the problem of observing the scattering phenomenon when a weak source of alpha-particles is used.

The experiments consisted of recording the number of alpha's scattered per unit time, N, as a function of the angle Θ, of scattering. According to Rutherford's theory this should obey the law,

$$N = K \csc^4(\Theta/2)$$

where K is a constant.

A plot of log N against $\log(\csc\Theta/2)$ should yield a straight line of slope 4. The experimental data, when plotted this way, did not give a straight line. An analysis was made of the effect of the wide angle of the alpha-ray beam which is necessary when using a weak source. The result was a much more complicated expression than Rutherford's for the number of scattered alpha's and it is given in terms of the geometry of the slit system used to define the beam. The resulting equation was of a form such that a log-log plot yielded a straight line of slope unity. When the scattering angles were chosen sufficiently large with reference to the alpha-ray beam width the measurements gave data which agreed with the new theoretical expression within the experimental error.

The proportional counter consists of a brass tube with a fine tungsten wire mounted inside on the axis. At one end of the cylinder is a mica window which is air tight, but thin enough to allow passage of the alpha-particles. The counter tube is placed in a fixed position inside a glass jar which can be evacuated. The alpha-ray source is a thin layer of polonium deposited on a flat piece of copper. The source, slit system, and scattering foil, are mounted on a movable arm controlled by means of magnets from outside the scattering chamber. An amplifier with quenching circuit increases the size of the pulses so that they are recorded by means of a Cenco mechanical recorder. A scaling unit was used, also, for fast counting rates. A separate power supply was used to maintain a difference of potential of approximately 3700 volts between the wire and cylinder of the counter tube.

DEMONSTRATION APPARATUS FOR
ALPHA-RAY SCATTERING

by

CHEE TAO WANG

A THESIS

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Typed by Mrs. A.D. Twombly

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DEMONSTRATION APPARATUS FOR ALPHA-RAY SCATTERING

INTRODUCTION

It is desirable to demonstrate outstanding experiments of great scientific significance to undergraduate students in physics. The scattering of alpha-particles by thin foils is an example of such an experiment. The following is an investigation of the possibility of studying alpha-ray scattering with a relatively weak radioactive source and an extremely simple Geiger counter as an alpha-ray detector. Ordinarily a great amount of work is involved in making a suitable counter. Special inert gases are often used. However, in this investigation ordinary air at atmospheric pressure was employed. If such a simple arrangement can be used for the above demonstration this apparatus would be readily available to laboratories with very limited facilities.

In 1911 Rutherford assumed that the positive charge of the atom, instead of being distributed continuously throughout a region of atomic dimensions, is concentrated in a very small volume less than 10^{-12} cm in diameter, and that this concentrated charge, known as the nucleus, is surrounded by electrons. He then tested the nuclear theory of the atom by scattering a narrow beam of alpha-rays from a thin gold foil and predicted in a classical article (6, p. 669-675), which is often regarded as the starting point of the modern ideas of atomic structure, that

$$N = \frac{N_o e^4}{M^2 V^4} \cdot n\, t\, Z^2 \cdot \frac{\csc^4(\frac{\theta}{2})}{r^2} \tag{1}$$

Where N is the number of alpha-particles per second which reach one square cm of a screen located at a distance r cm from the center of the foil at a scattering angle θ with the original beam. N_o is the corresponding number at zero angle when the foil has been removed while M is the mass and V the velocity, respectively, of the alpha-particles. Z is the number of electron units of charge on the nucleus, n is the number of atoms per cubic cm and t is the thickness of the scattering material for small values of t.

It is obvious that so far as a particular source of alpha-particles and a particular scattering material are concerned, the number N in the above equation is directly proportional to $\csc^4(\frac{\theta}{2})$ if the distance r is fixed. Thus

$$N = K \csc^4(\frac{\theta}{2}) \tag{2}$$

Where K is the constant of proportionality.

It is in this way, by allowing a single factor to vary at a time, that Eq.(1) has been checked experimentally.

Geiger and Masden were the first to completely verify Rutherford's predictions. In the original experiments a scintillation screen of zinc sulfide was used as the detector of the scattered particles. The procedures are difficult and tedious. It is the purpose of this work to construct an apparatus using as the detector a proportional Geiger counter for detecting alpha-particles, for the demonstration in the laboratory of the classical law as given by Eq.(2).

FUNDAMENTAL PRINCIPLES AND CHARACTERISTICS OF THE PROPORTIONAL GEIGER COUNTER

As a proportional counter is used as the alpha-particle detector in the experiment, its fundamental principles and characteristics will be discussed in detail.

A proportional counter is an ion-multiplying device which is sensitive to individual ionizing particles and operated in a certain region of applied voltage, so that a voltage pulse is produced in the output circuit with an amplitude proportional to the amount of initial ionization in the counter tube.

Thus, the problem of using a proportional counter is essentially one of obtaining an output pulse produced by some initial ionizing event of sufficient size to operate a recording mechanism.

An alpha-particle has a high specific ionization and it produces on the average some 30,000 ion-pairs per cm in air at standard conditions. The average electron or cosmic ray particle may produce 30 to 100 ion-pairs per cm, and a slow electron near the end of its range will not produce one-tenth as many ions per cm as an alpha particle (2, p. 59). Therefore, a proportional counter will distinguish between alpha-particles and electrons with no difficulty.

Proportional counters can be made in a variety of shapes and sizes. The most usual construction consists of a cylindrical cathode with an axial fine wire as the electron collecting electrode. Such a counter and its fundamental circuit are shown in Fig. 1. The axial wire

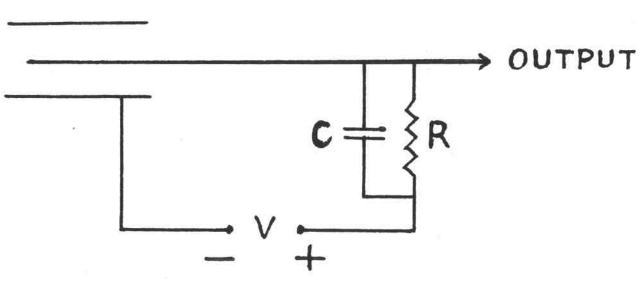


Fig. 1

is supported inside the tube by an insulating plug. It is called a Geiger point counter if the wire has a smooth fine point or a smooth ball on its end as was originally designed by H. Geiger. The open end which is sometimes made into a window covered with a thin foil provides an entrance for the alpha-particles into the tube inside which ionization takes place. It was found by some observers that a counter is best operated when the ionization chamber is filled with argon because of the fact that ionizing particles have a high specific ionization in this gas and the starting potential is relatively low (2, p. 76). Gases that tend to form negative ions, such as oxygen, water, and carbon dioxide are not well suited for use in counters. A potential of 1500 to 5000 volts is usually so applied as to make the wire positive with respect to the tube. The high resistance R, which is called the quenching resistance serves to pass a pulse to the detecting unit. The capacitance C includes the distributed capacity of the circuit. If the initial potential of the collecting electrode were V_o and the pulse caused it to drop to some value V_o', it would have a potential V, t seconds after dropping to V_o' given by

$$V = V_o(1-e^{-\frac{t}{RC}}) + V_o' e^{-\frac{t}{RC}} \qquad (3)$$

and, for example, if $R = 10^8$ ohms, $C = 10^{-11}$ farad and let $\Delta V = V_o - V_o'$, the voltage would rise to

$$V = V_o - \frac{1}{e}\Delta V$$

in $RC = 10^{-3}$ sec. after a pulse has taken place. It is evident that the collection of electrons, owing to which the collecting electrode voltage drops, must take place in less than this time. Since if the charge leaks off the collecting electrode through R as fast as it arrives, the drop in potential will be negligible. Thus the recovery of the wire after a pulse has occured is controlled by the RC time constant and this cannot be made shorter than the time to complete the collection of the electron avalanche by the wire.

Fig. 2 shows a typical voltage pulse from a self-quenching counter viewed on an oscilloscope (2, p. 61). It will be seen that the pulse is characterized by a rapid drop to full value and then by a slower recovery to normal.

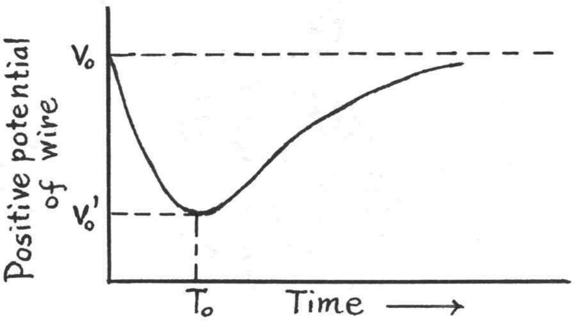


Fig. 2

When no potential is applied across the counter tube, there will be no fluctuations in the central wire potential, since the ion-pairs produced by the ionizing particles will disappear by recombination.

If a voltage is applied, the field established between the electrodes is not uniform but varies with the radius r in the case of axial symmetry as described above according to the relation

$$E_r = \frac{V}{r \ln \frac{r_2}{r_1}} \tag{4}$$

where V = voltage applied across the electrodes

r_1 = radius of the central wire

r_2 = inner radius of the tube

Eq.(4) shows that the electric field is most intense near the surface of the central wire, where r is small. Thus, any electrons produced in the volume of the counter tube are swept by the field to the central wire where they are collected and positive ions move to the cylinder.

As the voltage applied across the counter is raised, the counter goes through a continuous series of changes, starting at low potentials as an ionization chamber and continuing through the stage of a proportional counter, a Geiger counter, and finally at excessive potentials, to a breakdown. The operating characteristics of a counter in various regions for large and small ionizing events can be seen in Fig. 3.

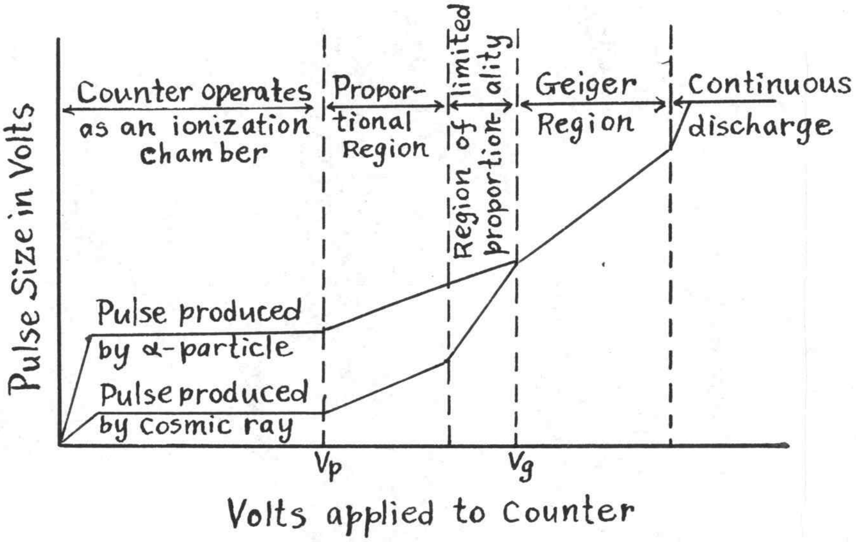


Fig. 3

As the potential is slowly raised, a voltage is reached at which ions, while being swept to the collecting electrode under the influence of the applied field, acquire sufficient energy in the last mean free path before reaching the collecting electrode to produce additional ions by collision. This voltage is usually defined as the threshold voltage Vp for proportional counter action. When the voltage across the counter is below the minimum Vp, at which there are no secondary electrons but only those produced in the initial ionizing event, the number of electrons which arrive on the central wire will be equal to the number which were produced in the initial ionizing event less the number which have disappeared by recombination; and the size of the pulse, i.e., the drop in potential of the central wire, dv, will be given by

$$dv = \frac{dQ}{C} = 1.602(10^{-7})n/C \qquad (5)$$

where dQ is the charge arrived at the wire, C as shown in Fig. 1 is the distributed capacity in micromicrofarads, n is the number of electrons arriving and the electronic charge is equal to $1.602(10^{-19})$ coulomb.

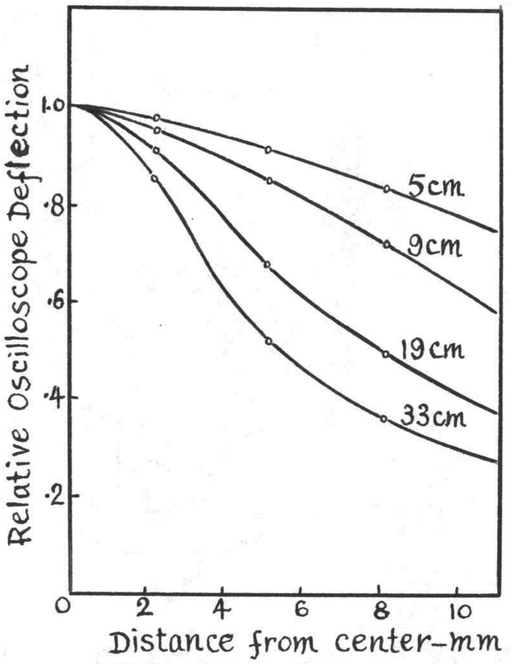
When the voltage across the counter is raised above Vp, the pulse will then be larger because of the additional ions formed by collision. If there are A ion-pairs formed by collision as each electron travels toward the central wire, the size of the pulse will be given by a modified form of Eq.(5), namely

$$dv = 1.602(10^{-7})An/C \qquad (6)$$

The quantity A is defined as the "gas amplification." It will range between unity at the threshold to a very large value in the Geiger counter region. Thus as long as A remains a constant, the counter will produce a pulse dv which is proportional to the number of ions n formed in the initial ionizing event. The voltage region in which A is a constant is called the proportional region.

When the voltage is raised further, the critical distance moves outward from the wire and the additional electrons produced form other ions by collision, thus producing what is familarly known as the Townsend avalanche. At these higher voltages the avalanche is not determined by the amount of the initial ionization, but only by the voltage across the counter. The minimum voltage at which all pulses are of the same size regardless of the size of the initiating event is defined as the starting potential for Geiger counter action. As the voltage is still further raised, eventually a continuous discharge is produced.

The above gives a description of the characteristics of a counter with respect to the applied voltage. One other important property of the proportional counter which deals with the gas pressure inside the ionization chamber and the distance from the central wire to the region where ionization takes place, was observed by Brubaker and Pollard (1, p. 255). They observed that if alpha-particles are shot into the counter parallel to, and at different distances from the central wire, the resulting deflection of an oscilloscope in the output circuit is found to decrease as the distance of the particle from the wire increases. Fig. 4 shows the counter response to alpha-particles at different distances from the wire; the counter being filled with air at four different pressures. The following is an explanation given by them for the fact that the size of the pulse decreases as the distance from the central wire increases, and for the effect of pressure upon the amount of this decrease. "The electrons



Response of counter to α-particles at different distances from the wire. Counter filled with air at four different pressures.

Fig. 4

freed by the alpha-particles are swept toward the wire and produce ions by collision in a small region close to the wire. If all the primary electrons reach this region the height of pulse produced should be independent of the distance (x) from the wire at which the primary ions were formed. Conversely, if the height of the pulse decreases as the distance x increases, some of the electrons must have become attached to larger particles before reaching the region in which ionization by collision takes place. Because of the high field existing at the distances from the wire used, it appears that there will be no appreciable recombination in the original column of ionization. It seems therefore that some of the electrons must become attached to atoms to form negative ions. Since on the Thomson theory of negative ion formation the chance that an electron will become attached in going a distance x increases with the number of impacts it makes, more electrons will thus be "lost" when x is large than when it is small. The resulting charge collected would thus decrease as x increased."

DESCRIPTION OF APPARATUS

The proportional counter and accessories.

The proportional counter consists of a brass cylinder 12.7 cm long, 1.3 cm in inner diameter and 1.95 cm in outer diameter with a screwed on cap , and a coaxial tungsten wire 0.27 mm in diameter and 4.5 cm in length supported by a brass rod about 3 mm in diameter as shown in Fig. 5.

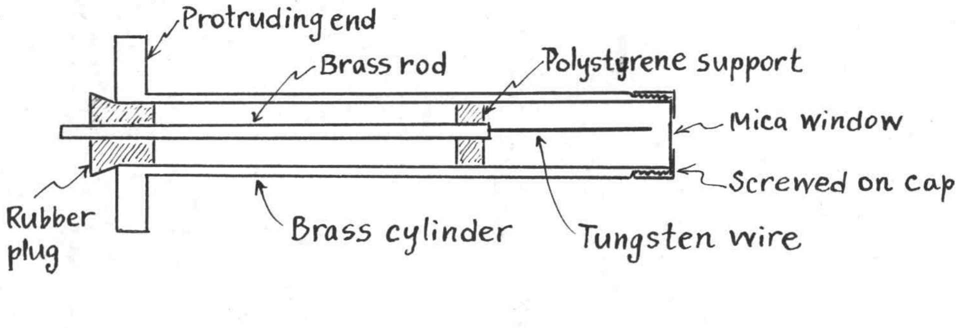


Fig. 5

The dimensions of the counter tube were so chosen as to be suitable for placing inside an evacuated glass jar through a hole in its side wall. On the end of the cap is an opening of about 2 x 3 mm^2 for the entrance of alpha-particles. The opening was made with nearly the same dimensions as that of the collimating slits through which a beam of alpha-rays is obtained. As the sensitivity of a counter to ionizing particles depends on the distance of the region from the central wire inside the chamber where ionization takes place the opening should be made at the center of the end cap. A piece of white mica 0.016 mm thick and about the same size of the inner area is sealed into the inside of the cap by means of a rubber gasket. So the whole counter tube is thus made air tight when the cap is screwed on to the cylinder. It is obvious that the mica window should be thin enough to allow passage of alpha-particles. The mean range of alpha-particles from polonium in air at 15°C and 760 mm is 3.83 cm. The density of air at this condition is 0.001226 gm/cc. The density of white mica (muscovite) is 2.76 gm/cc. So the mica window should not be thicker than

$$\frac{3.83 \times 0.001226}{2.76} = \frac{1.704}{100} = 0.017 \text{ mm}$$

otherwise the counter will be of no use as an alpha-particle detector. On the other hand, it should be thick enough to be able to withstand atmospheric pressure maintained inside the tube while outside the tube air is withdrawn to facilitate the travelling of the alpha-particles from their source to the counter. It was found that the mica window can be most easily made by first cutting a piece of considerable thickness to the desired size with a pair of scissors and then cleave it with the sharp point of a small sewing needle.

The free end of the wire should be carefully smoothed and put at a distance about the inner radius of the cylinder from the mica window. The wire diameter is one factor determining the operating voltage. Several wires of different diameter were tried and it was found that the one described above results in the lowest starting potential—3700 V. Sharp points in the high field region both on the inside wall of the cylinder and on the wire were carefully avoided, as these give rise to local ionization and spurious counts. The tungsten wire was made very smooth by electrolyzing in concentrated sodium hydroxide for a few minutes at 6 volts AC with a carbon rod as the other electrode. The wire is held in the axial position inside the cylinder with polystyrene and rubber plugs as shown in Fig. 5. The wire and the plugs are removable so that the inside wall of the cylinder as well as the wire can be easily cleaned. This sometimes was found quite necessary in order to keep the counter working normally, especially when the counter had been operating over a period of time, because any dust particle or moisture introduced inside the counter tube gives rise to spurious counts.

The counter is put inside the glass jar as shown in Fig. 6 through a hole in the wall with the protruding end tightly fixed with three screws to the cylindrical brass neck which is waxed on the glass wall. Inside the jar, fixed at the bottom, is a circular aluminum plate 15 cm in diameter which holds a smoothly rotating vertical axis rod 5.8 cm in height. On the free end of the rotating rod is fixed a level shaft 10 cm long for supporting the scatterer, the collimating slits and the alpha-particle source. At the lower part on the rod is fixed another shaft carrying a strong magnet at its free end close to the inside wall of the jar. Outside the jar is a calibrated circular rail on which is a movable pointer carrying another strong magnet. Both the jar and the circular rail are fixed on a wood board $1\frac{1}{2}$ cm x 29 cm x 40 cm, so that through the action of the two magnets the position of the two shafts inside the jar can be controlled by moving the pointer outside the jar along the circular rail without disturbing the vacuum during operation. Thus the whole thing can be so adjusted that the readings of the positions of the pointer

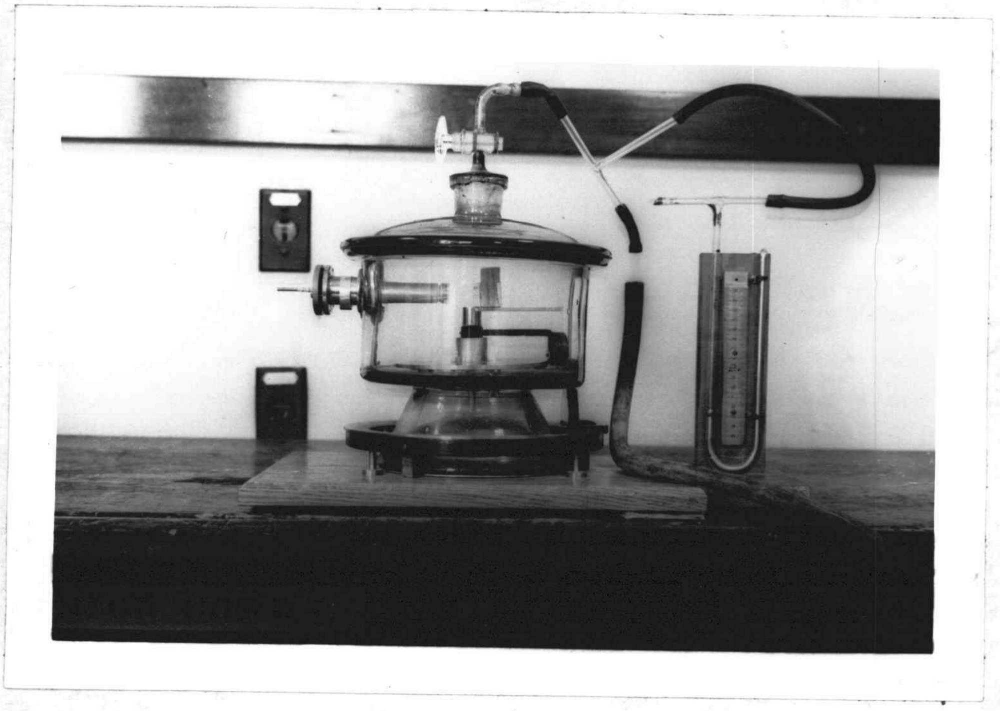


Fig. 6

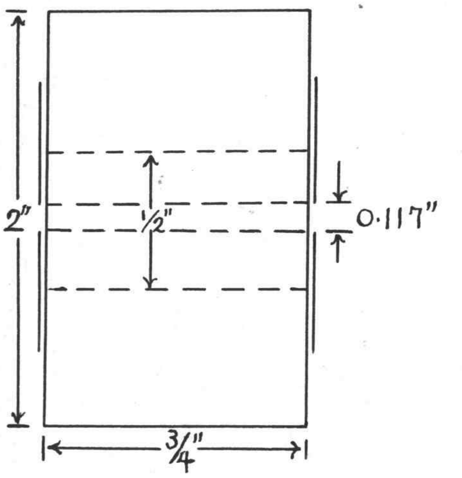


Fig. 7

on the calibrated rail will give the correct angular readings of the upper shaft inside the jar, i.e., the collimated alpha-ray beam makes with the axis of the counter tube. Of course, the counter tube should be preadjusted so that its axis coincides with the radius of the jar and is in a plane parallel to that of the upper level shaft.

A sheet of gold foil about 1½ cm square which is mounted on a frame and set up at the center of the vertical rotating rod on the supporting shaft serves as the scatterer.

The collimating slits consist of two pieces of aluminum each 1 mm thick and in each is drilled a hole 0.117 inches in diameter mounted separately in the front and back of a round hole ½ inch in diameter drilled on a small block 3/4" x 1 1/8" x 2" of the same material, as shown at Fig. 7. The dimensions of the slits and the thickness of the block on which the slits are mounted were so chosen as to suit the weak alpha-particle source used in the experiment.

The available alpha-particle source is polonium very thinly coated on one face of a 1/3 inch square copper obtained about April 1949 from Hammer Laboratories, 8139 Lemon Avenue, LaMesa, California. The intensity of the source is not known. As polonium has a half life of

140 days, it would be now only one fourth as intense as it was when originally received. Polonium was chosen as the source because it radiates alpha-rays only. In addition to this advantage, it has an alpha-ray activity about 500 times that of radium and in fact it has the highest alpha-ray activity of any of the elements in the uranium series.

In the arrangement the source is put behind one of the slits on the level shaft and in front of the other slit is the scatterer. The distance between the mica window and the scatterer is about one cm when the counter tube is wholly put inside the jar. This distance can be adjusted by putting a brass ring of desired length but of larger diameter than that of the tube between its protruding end and the neck waxed on the glass jar. The tube and the slits were carefully aligned in the set-up. The alignment may be readily checked by looking through the round hole on the rubber plug with the wire temporarily removed.

During operation the glass jar is covered with a lid and a Cenco-Hyvac Pump driven by a 1/8 H.P. motor is used to withdraw air from inside the jar. A mercury manometer serves to indicate the air pressure.

The detecting circuits.

A. The quenching circuit and the amplifier.

There are many circuits for quenching the discharge in non-self-quenching counters. In this work the famous Neher-Harper circuit (4, p. 940) as shown at Fig. 8 is used because of its great efficiency at high counting rates. The action of the circuit can be explained briefly as follows: The vacuum tube is biased close to a point slightly beyond plate current cut-off and the high voltage is applied to both the tube and the counter. When an ionizing particle passes through the counter there will be a current flow through both R_1 and R_2. The cylinder and the grid will become somewhat positive. The tube will then draw a large plate current through R_2, which will drop the potential of the central wire and extinguish the discharge and the circuit recovers itself. This recovery is very rapid because of the low values of the capacity and resistance R_2. A negative pulse will be transmitted to the circuits which follow by the coupling condenser which is well insulated, since high-voltages are used and any appreciable leakage will disturb the low-current counter circuit.

Because of the short duration of the pulse the output is amplified so that a sufficient gain is obtained to operate a recording mechanism. The amplifier was a slight modification of the new quenching circuit

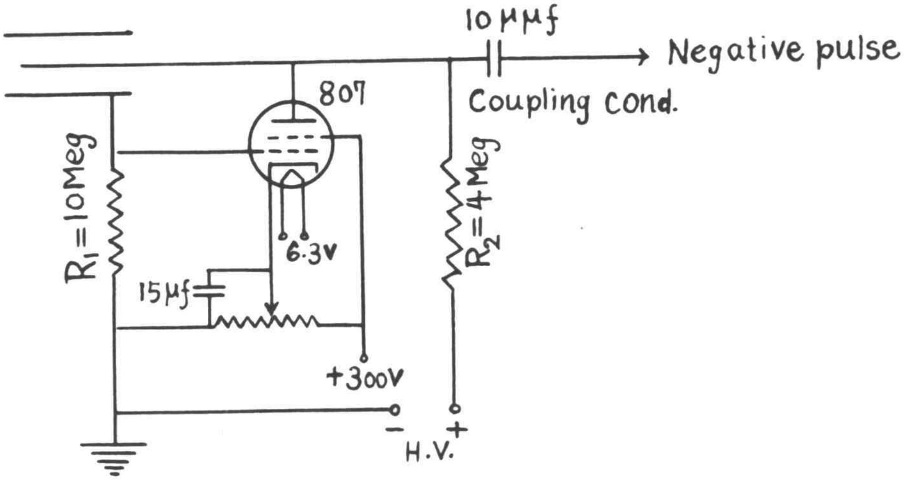


Fig. 8 The Quenching Circuit

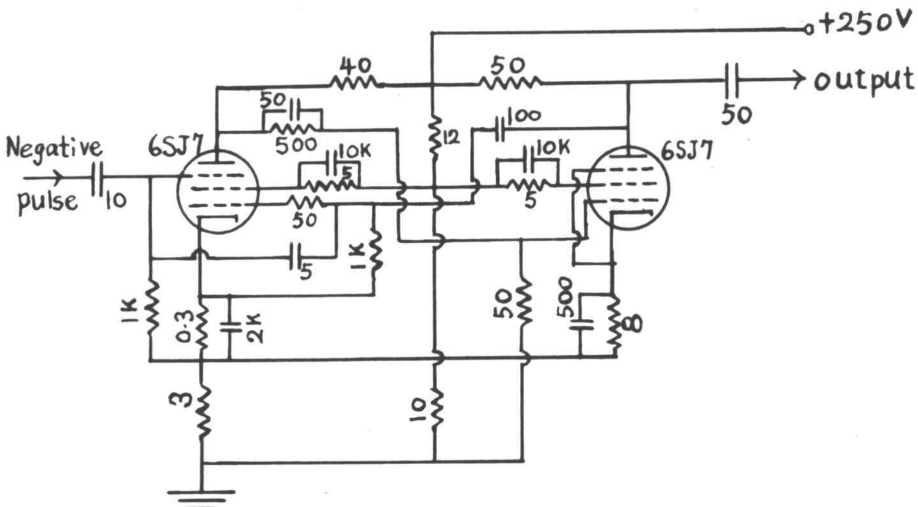


Fig. 9 The Amplifier Circuit
Resistances in kiloohms
Capacities in micromicrofarads

developed by Maier-Leibnitz (3, p. 500). This is shown in Fig. 9. It is a two-stage resistance coupled amplifier in which the voltage developed by the output of the second tube is applied to the input of the first tube. It works on the multivibrator principle but uses two different grids of the input tube for the signal pulse and for the feedback. Thus the frequency of oscillation developed by the regenerative feedback is readily controlled by the injected voltage. It has also been shown by its author (3, p. 501) that all amplified pulses are equal and the circuit gives satisfactory results when used with a Geiger counter.

The quenching circuit and the amplifier, with the requisite power supply, were built into a 17" x 7" x $2\frac{1}{2}$" aluminum chasis. The power supply is a conventional full-wave diode rectifier with a choke-input type filter, the circuit of which is shown in Fig. 10. Fig. 11 shows the apparatus as a combined unit.

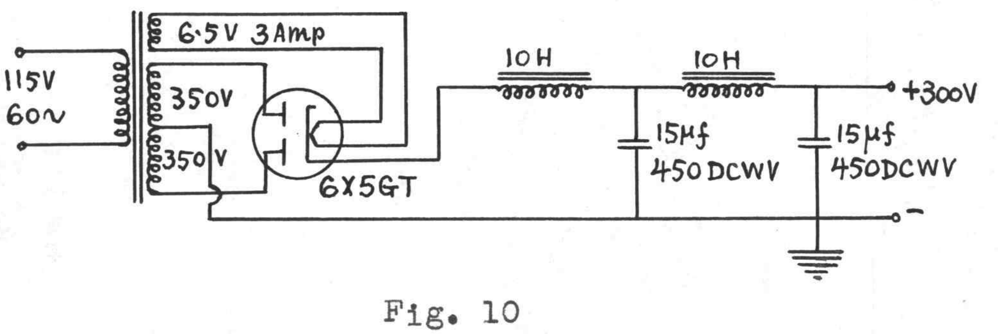
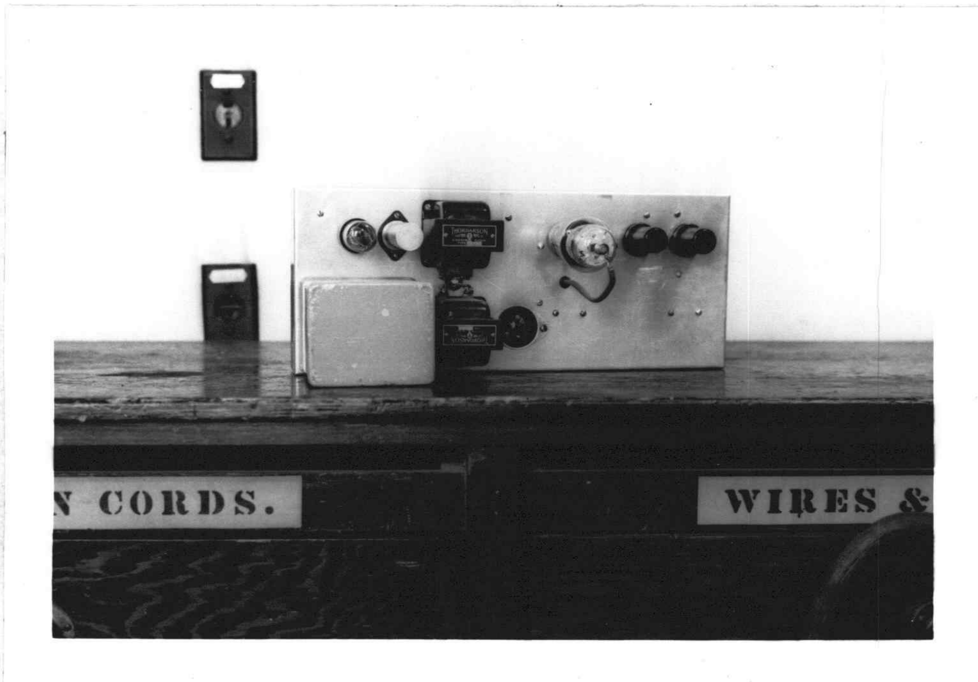


Fig. 10



Front View

Rear View

Fig. 11 The Quenching Unit

B. The recording circuit.

As the pulse received from the quenching circuit unit described above is not capable of operating a mechanical recording device, a multivibrator recording circuit has been used to produce an impulse capable of doing so. The recording circuit is shown in Fig. 12. In this circuit the second tube is a beam power amplifier which is biased below cut off while the first tube having zero bias is normally conducting. When a negative pulse is received on the grid of the first tube it is biased to cut off and a large positive pulse will be transmitted to the grid of the second tube. This will cause it to become highly conducting and a current of perhaps 50 milliamperes will flow through the mechanical recorder. The potential of the screen grid of this tube will drop considerably due to screen current and a large negative pulse will be impressed on the screen of the first tube through the condenser C. The first tube will thus remain non-conducting until the charge on C leaks off through the resistor R and after a time determined by the product RC, the first tube will again become conducting. As soon as this occurs a large negative pulse will be applied to the grid of the second tube and it will be quickly biased to cut off, stopping the current flow through the recorder circuit. Each negative input pulse will therefore send the circuit through one cycle of operation. The

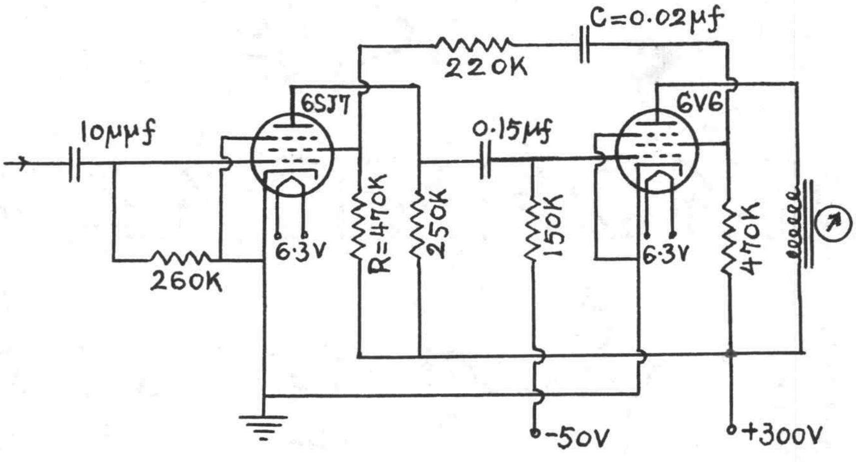


Fig. 12 The Recording Circuit

Fig. 13 The Recording Unit

length of time during which current flows through the output is determined by the product RC and it is independent of the duration of the initial pulse provided the initial pulse length is not longer than the natural period of the circuit. The output current is sufficient to operate a Cenco mechanical recorder. The power for the recording circuit may be obtained either from the local power supply of the quenching circuit unit described above or from that of the scaling bank which will be described later.

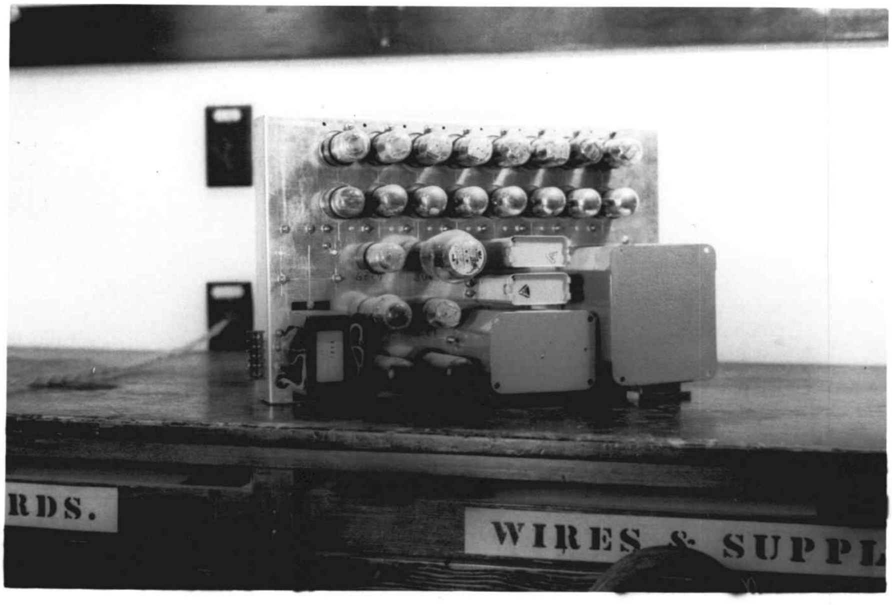
The Cenco recorder which has been used in the experiment to record mechanically the amplified pulses consists of a magnetically operated ratchet device for operating a dial from which the total count can be read. The recording circuit and the Cenco recorder is shown in Fig. 13.

C. The scaling bank.

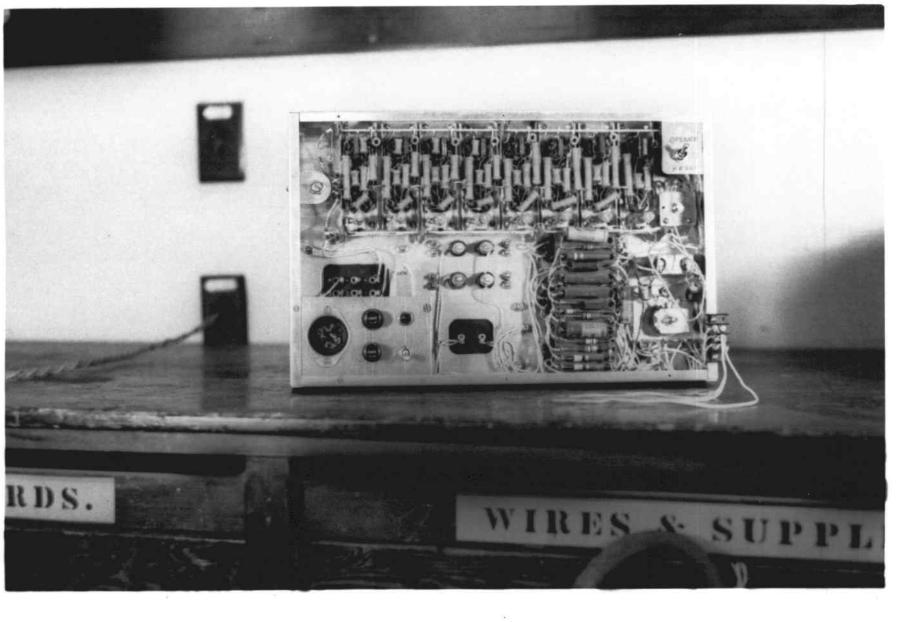
It was found that at fast counting rates, the Cenco mechanical recorder becomes jammed. Thus it is necessary to use a scaling device to scale the number of impulses per minute down to slower counting rates. An already built scaling bank in the laboratory which had been used for the purpose was available. It comprises eight scalers connected in series so that any scaler-of-two, -four, and so on up to 2^8 or - two hundred fifty six can be chosen according to requirement by connecting the output lead to the particular stage of the scalers. The requisite power supply was built with the scalers into a 2 x 11 x 17 inch aluminum chassis as shown in Fig. 14 (Photo of the Scaling bank). The circuit diagrams of the scaling unit and the requisite power supply are shown in Figs. 15 and 16 respectively.

The high voltage power supply.

The purpose of the high voltage supply is to provide the high potential for the operation of the proportional Geiger counter. Since the current taken by the counter is very small, the source need not furnish much power. Fig. 17 shows the circuit. The general arrangement of the apparatus is shown in Fig. 18.



Front View



Rear View

Fig. 14 The Scaling Bank

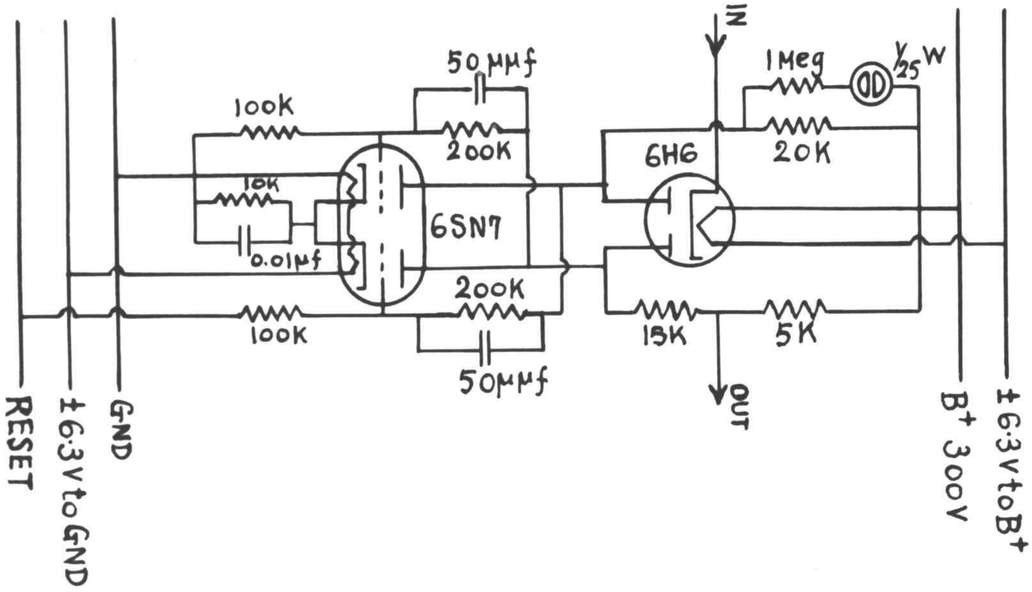


Fig. 15 Binary Scaling Unit

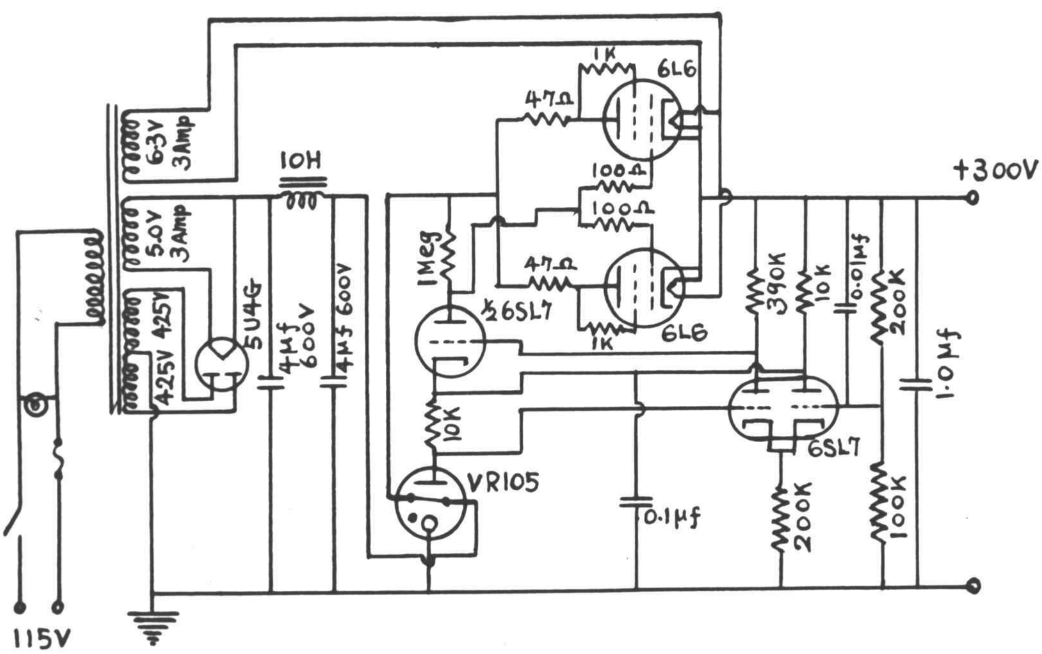


Fig. 16 Scaling Bank Power Supply

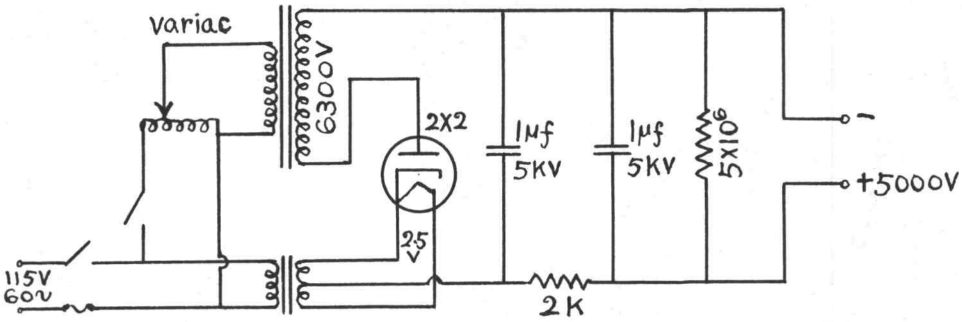


Fig. 17. The High Voltage Power Supply Circuit

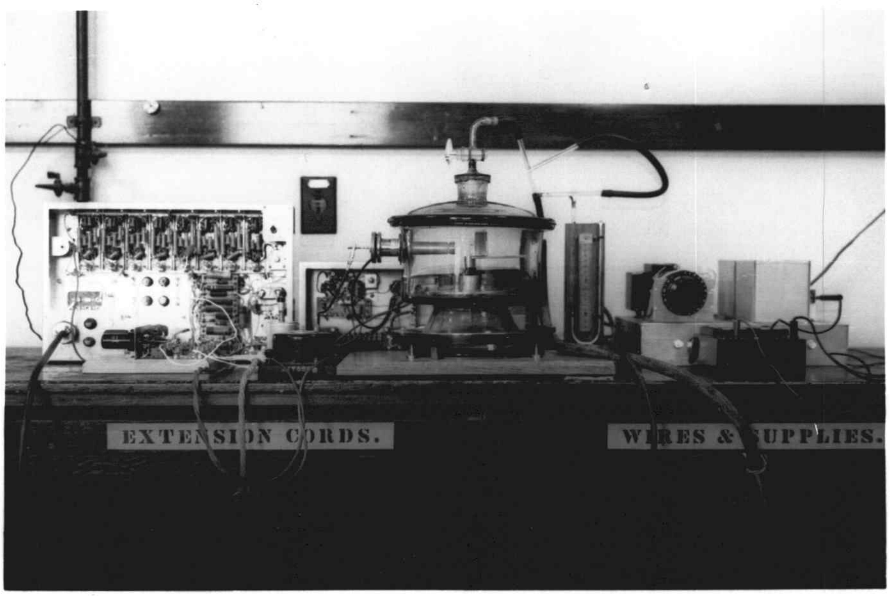


Fig. 18 General Arrangement of the Apparatus

OPERATION OF APPARATUS

As has been pointed out, the inside wall of the counter cylinder and the wire, as well as the insulating plugs, should be thoroughly cleaned before using. Washing with ammonia or organic solvents and cleaning with distilled water will remove dust, wax, grease or other extraneous matter. After cleaning, the tube should be perfectly dry before positioning the wire and the mica window cap, so that the air inside the tube will be dry. A very minute amount of charge leaking across an imperceptible moisture or grease film on the insulating plugs, as well as moist air inside the counter, may cause spurious counts.

The mean range of the alpha-particle in air at atmospheric pressure is only a few centimeters. So a good vacuum inside the jar is desirable to reduce loss in energy before reaching the counter. It was found helpful to put a rubber ring between the protruding end of the counter tube and the neck waxed on the glass jar, and to grease the glass jar lid and the joints leading to the manometer and the pump which are susceptible to leakage. The mica window cap should be tightly screwed to the tube. In doing so care should be exercised to avoid cracking the mica. A microscopic crack will reduce the air pressure inside the counter tube. It was observed in the experiment that once the air pressure inside the tube is reduced much below atmospheric the counter will stop functioning.

By adjusting the applied voltage to the proper value the counter can be made insensitive to cosmic rays or gamma rays. This can be readily seen from the fact that when no radioactive substance is brought close to the counter, it does not start counting even if the applied potential is raised as high as 5000 V.

The usual operating voltage in the experiment with the wire specified above is around 3800 V, and has never been higher than 4200 V at which continuous discharge sometimes takes place if the counter has already started counting. Any time a continuous discharge takes place in the counter, the high potential should be immediately reduced or disconnected to avoid probable damage to the wire point.

In as much as it is well known that air is not the best gas to use in a counter because of the possibility of the formation of negative ions, helium was tried. In this case the mica window was removed and the counter and jar together were first evacuated of air and helium at atmospheric pressure substituted. No attempt was made to find the cause but the counter did not function with helium.

EXPERIMENTAL RESULTS AND DISCUSSION

The experiment was first carried out with a counter tube about 2 cm shorter than the one described above and a different pulse amplifier circuit which is not decribed in this paper. The same quenching circuit was used but the scaling bank was not used and the recording circuit was different from that described in this thesis. The apparatus operated with some satisfaction but when the scaling bank was introduced for the sake of scaling down fast counting rates, the whole electronic circuits were found to oscillate. So the new amplifier circuit as shown in Fig. 9 was used instead and the whole quenching circuit unit rebuilt as described above.

Fig. 19 shows the characteristic of the counter. It will be seen that the proportional range is very short. The counter does not always start counting at 3700 V as shown. Once it was observed that the starting potential fell as low as 3400 V but ceased counting in a few minutes.

Several slits of different sizes and different arrangements involving distances between the counter and the scatterer and the two collimating apertures were tried. The following is a typical result obtained with a couple of apertures of 0.117 inch in diameter when air

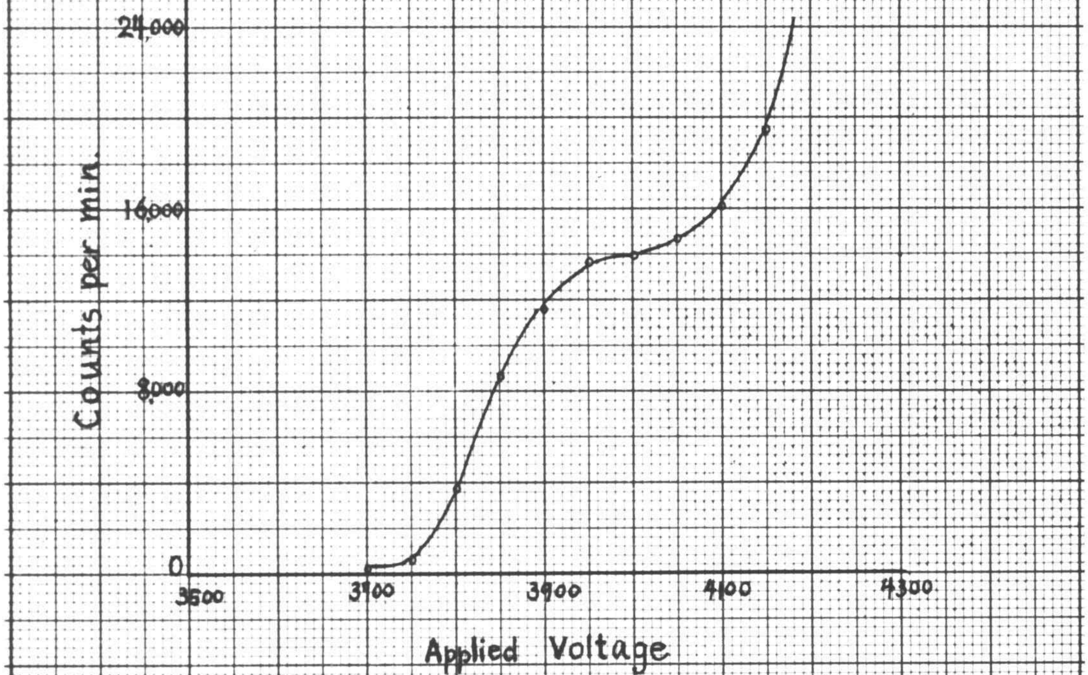

24,000
16,000
8,000
0
Counts per min.
3500
3700
3900
4100
4300
Applied Voltage

Fig. 19

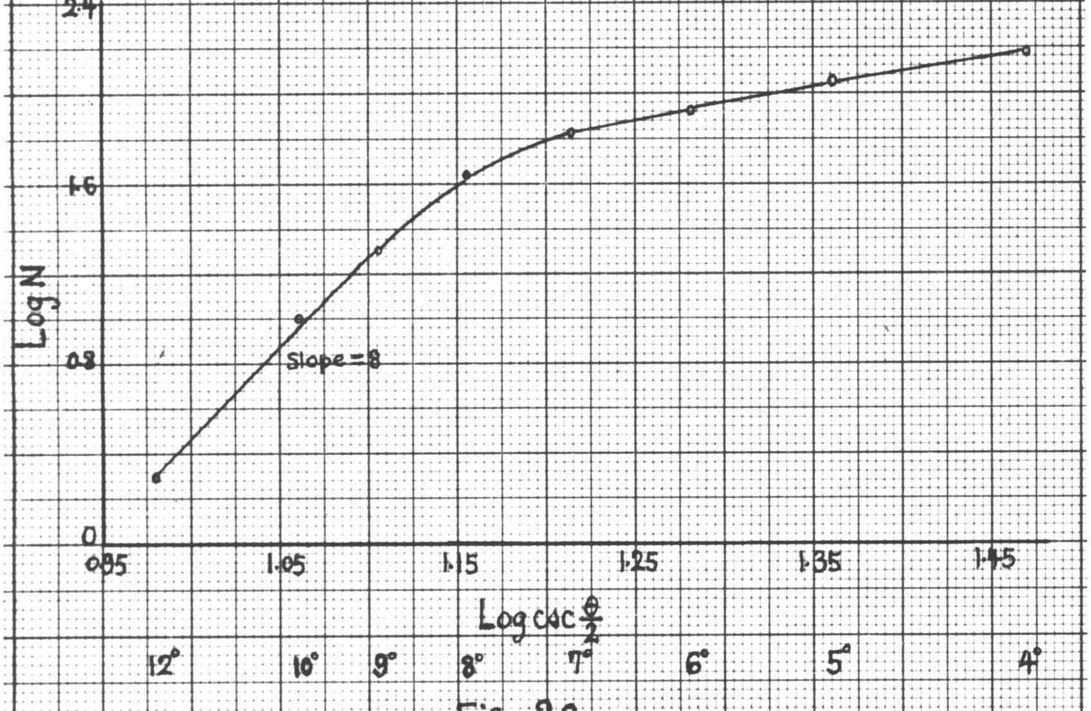

2.4
1.6
0.8
0
Log N
Slope = 8
0.95
1.05
1.15
1.25
1.35
1.45
Log csc $\frac{\theta}{2}$
12°
10°
9°
8°
7°
6°
5°
4°

Fig. 20

pressure inside the glass jar was reduced to 2 mm Hg and a potential of 4000 V was applied to the counter; distance between counter and scatterer = 1.20 cm, between collimating apertures = 1.905 cm, between scatterer and source = 2.1 cm.

θ, angles of scattering in degrees	N, number of counts per min.	log csc$(\frac{\theta}{2})$	log N
4	153	1.457	2.185
5	113	1.360	2.053
6	85	1.281	1.929
7	68	1.214	1.833
8	44	1.156	1.643
9	22	1.105	1.342
10	10	1.060	1.000
12	2	0.981	0.301

Fig 20 shows the curve plotted with log N against log csc $(\frac{\theta}{2})$ from the above data.

Following the results of Rutherford's theory the logarithm of the number of scattered alpha-particles was plotted as a function of the logarithm of csc $(\frac{\theta}{2})$. According to the theory the plot should yield a straight line of slope 4. It is obvious that the data taken at small angles represents alpha-particles in the incident beam which have penetrated the foil without being scattered. The scattered particles are those observed at relatively large angles. In Fig. 20 the data of importance is that taken for scattering angles of eight degrees or greater. In this region the curve is a straight line but the slope is approximately eight instead of four. However, Rutherford's theory assumes an infinitely narrow beam of incident alpha-particles. With a weak source it is necessary to use relatively large collimating apertures in forming the alpha-ray beam in order to have a sufficient number available for measurements. This means that an appreciable number of alphas strike the foil at angles greater or less than zero degrees. The result is that some alphas are scattered through angles less than θ even though the counter is set to detect particles at this angle. It is not surprising then, that the number of scattered particles does not change with scattering angles as Rutherford's theory predicts.

It is worth noting the ratio N/N_o for large scattering angles as can be calculated from Eq. (1) given on page 2. Whence one have

$$\frac{N}{N_o} = \frac{e^4ntZ^2}{M^2v^4r^2} \csc^4\left(\frac{\theta}{2}\right) \tag{7}$$

Where mass of alpha-particle $M = 6.598(10^{-24})$ gram,

velocity of alpha-particle $v = 1.597(10^9)$ cm/sec,

electronic charge $e = 4.803(10^{-10})$ esu,

atomic number of gold $Z = 79$,

distance from detector to the center of

foil $r = 1.2$ cm

By weighing, 1.5 cm square (2.25 cm^2) of the gold foil = 0.66 mg, density of gold = 19.33 g/cc, hence the thickness of foil

$$t = \frac{0.66 \times 10^{-3}}{2.25 \times 19.33} = 1.517 \times 10^{-5} \text{ cm}$$

Mass of the gold atom = $\dfrac{\text{atomic weight}}{\text{Avogadro's no.}} = \dfrac{79}{6.023(10^{23})}$

and the number of gold atom per c.c.

$$n = \frac{6.023(10^{23})}{79} \times 19.33 = 1.474(10^{23})$$

Substitution in Eq. (7) gives

$$\frac{N}{N_o} = 1.822 \times 10^{-6} \csc^4 \left(\frac{\theta}{2}\right) \qquad (8)$$

Thus, for $\theta = 10^{\circ}$, $\csc \left(\frac{10^{\circ}}{2}\right) = 11.474$

$$\frac{N}{N_o} = 3.16 \times 10^{-2}$$

Before concluding the above explanation for the observed data, however, it was desirable to investigate other possibilities. If the overall response of the counter was not linear with the number of alphas entering per sec. this could account for the observed results. To test this possibility the number of alphas entering the counter was varied by placing metal plates with different sized holes in front of the source so that the number of counts per unit time could be plotted as a function of the area of the holes. The results of this

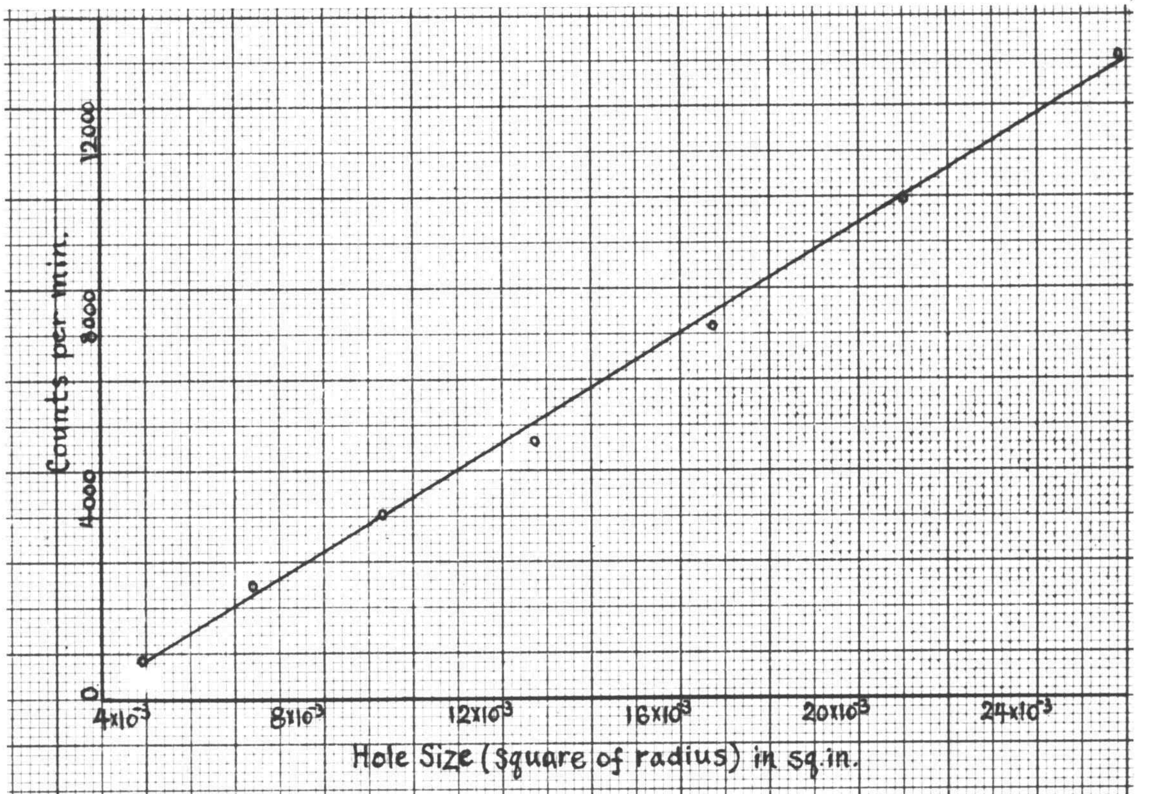

Counts per min.
0
4000
8000
12000
4x10^-3
8x10^-3
12x10^-3
16x10^-3
20x10^-3
24x10^-3
Hole Size (square of radius) in sq.in.

Fig. 21

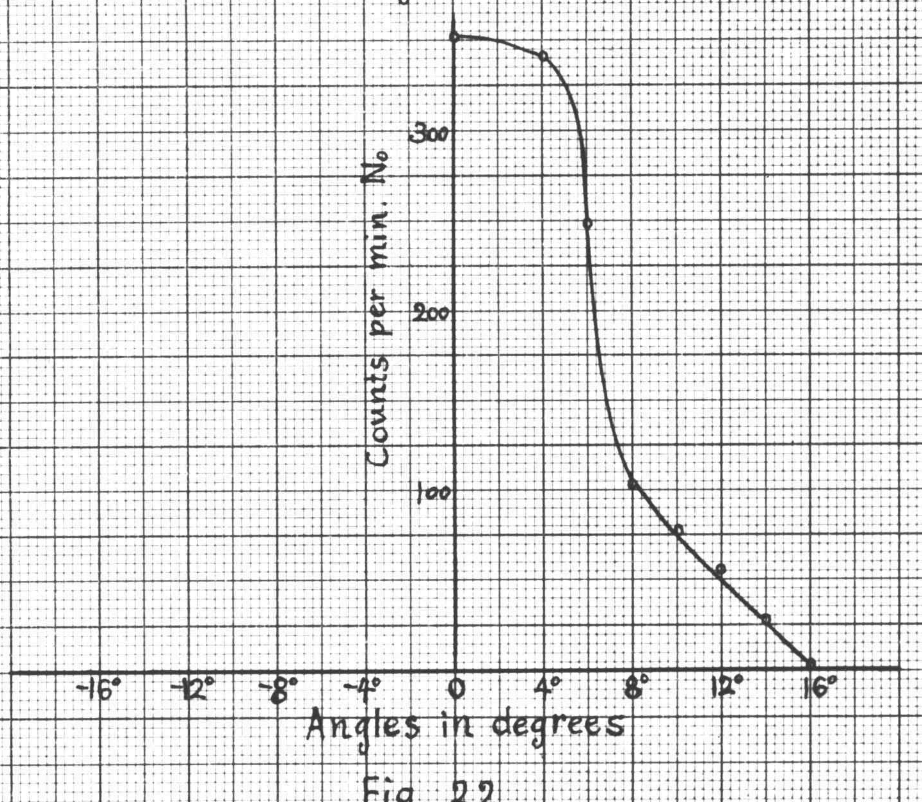

Counts per min. N₀
100
200
300
-16°
-12°
-8°
-4°
0
4°
8°
12°
16°
Angles in degrees

Fig. 22

experiment are shown in Fig. 21. The linearity of the counting apparatus is thus seen to be established.

Another possible source of error is the limitation on the counting rate of the Cenco mechanical counter. Results taken with and without a scaling circuit when the counting rate was not too fast gave good agreement so the observed results were in no way related to the limitation of the mechanical counter.

Fig. 22 was taken without a scattering foil and it shows the angular distribution of the incident beam. The geometrical arrangement in this case is shown in Fig. 23. An analysis of the scattering in a case of this kind will now be attempted.

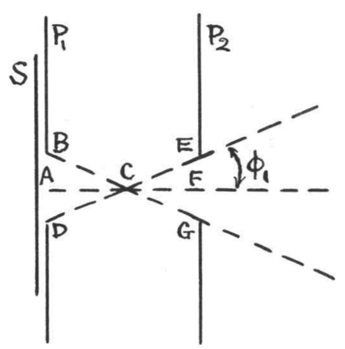


Fig. 23

Let the limiting angle Φ_1 have the meaning as shown in the above figure, where S is the source, and P_1 and P_2 are the two collimating apertures. AB = AD = EF =

FG = 0.0586 inch. AF = 3/4 inch. From the geometry of the figure we have

$$\tan \Phi_1 = \frac{EF}{CF} = 0.1562$$

or

$$\Phi_1 = 8^{\circ}52'$$

Thus, all the alpha-particles ejected from their source will be confined in the frustum of a cone of revolution with EG as the diameter of its upper base.

Now suppose a stream of alpha-particles striking the foil at an angle Φ with the normal be scattered at an angle θ as shown in Fig. 24 and let dN' = number of scattered particles per second per unit area that arrive at the detector at angle θ, and dN = corresponding number at zero angle when foil has been removed, then by Eq. (2) one get

$$dN' = KdN \csc^4 \left(\frac{\theta - \Phi}{2}\right) \qquad (9)$$

because the actual angle of scattering is $(\theta - \Phi)$.

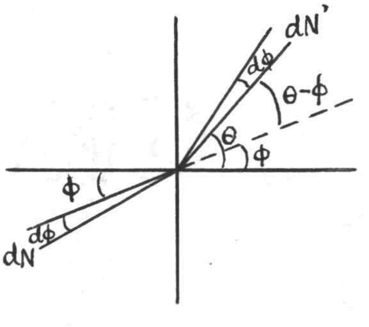


Fig. 24

From Fig. 22 it will be seen that the curve is symmetrical with respect to the vertical axis if the counts per minute at the opposite corresponding angles were taken and plotted. The angle around 8^o at which the number of counts N_o drops abruptly is roughly a measure of the broadness of the alpha-ray pencil passing through the aperture P_2 in Fig. 23, and is comparable to the calculated value of Φ_1, i.e; $8^o52'$. The curve in Fig. 22 also shows that N_o is an even function of the angle Φ, and is therefore representable by a Fourier series comprising only cosine terms. Thus, omitting the terms containing higher order of Φ for the sake of simplicity, one may write as a rough approximation

$$N_o = f(\Phi) = N_1 + N_2 \cos \Phi, \qquad -\Phi_1 \leqq \Phi \leqq +\Phi_1 \tag{10}$$

Where N_1 and N_2 are constants. It is obvious that at $\Phi = 0$

$$N_o = N_1 + N_2 \tag{11}$$

Differentiating Eq. (10) gives

$$dN = - N_2 \sin \Phi d\Phi \tag{12}$$

Thus Eq. (9) becomes

$$dN' = - KN_2 \sin \Phi \csc^4 \left(\frac{\Theta - \Phi}{2}\right) d\Phi \tag{13}$$

While

$$\sin\Phi \csc^4 \left(\frac{\theta - \Phi}{2}\right) = \frac{2 \sin\frac{\Phi}{2} \cos\frac{\Phi}{2}}{\left(\sin\frac{\theta}{2}\cos\frac{\Phi}{2} - \cos\frac{\theta}{2}\sin\frac{\Phi}{2}\right)^4} =$$

$$\frac{2 \tan\frac{\Phi}{2} \sec^2\frac{\Phi}{2}}{\left(\sin\frac{\theta}{2} - \cos\frac{\theta}{2}\tan\frac{\Phi}{2}\right)^4} = \frac{2 \tan\frac{\Phi}{2} \sec^2\frac{\Phi}{2}}{\left(A - B\tan\frac{\Phi}{2}\right)^4} =$$

$$\frac{2 A \sec^2\frac{\Phi}{2}}{B\left(A - B\tan\frac{\Phi}{2}\right)^4} - \frac{2 \sec^2\frac{\Phi}{2}}{B\left(A - B\tan\frac{\Phi}{2}\right)^3}$$

by letting $A = \sin\frac{\theta}{2}$, $B = \cos\frac{\theta}{2}$. Also $d\Phi = 2d\left(\frac{\Phi}{2}\right)$,

hence

$$dN' = -\frac{4KN_2}{B}\left[A \sec^2\frac{\Phi}{2}\left(A - B\tan\frac{\Phi}{2}\right)^{-4} - \sec^2\frac{\Phi}{2}\left(A - B\tan\frac{\Phi}{2}\right)^{-3}\right] d\left(\frac{\Phi}{2}\right) \qquad (14)$$

Integrating Eq. (14) from $-\Phi_1$ to $+\Phi_1$ gives

$$N' = -\frac{4KN_2}{B}\int_{-\Phi}^{+\Phi}\left[A \sec^2\frac{\Phi}{2}\left(A - B\tan\frac{\Phi}{2}\right)^{-4} - \sec^2\frac{\Phi}{2}\left(A - B\tan\frac{\Phi}{2}\right)^{-3}\right] d\left(\frac{\Phi}{2}\right)$$

$$= -\frac{4KN_2}{B^2}\left[\frac{A}{3}\left(A - B\tan\frac{\Phi}{2}\right)^{-3} - \frac{1}{2}\left(A - B\tan\frac{\Phi}{2}\right)^{-2}\right]_{-\Phi_1}^{+\Phi_1}$$

$$= KN_2 \left[2(AB - B^2 \tan \frac{\Phi}{2})^{-2} - \frac{4A}{3B^2}(A - B \tan \frac{\Phi}{2})^{-3} \right]_{-\Phi_1}^{+\Phi_1}$$

Let $KN_2 = \frac{K_1}{8}$, where K_1 is another constant, since K and N_2 are both constant, and

$$8M = \left[2(AB - B^2 \tan \frac{\Phi}{2})^{-2} - \frac{4A}{3B^2}(A - B \tan \frac{\Phi}{2})^{-3} \right]_{-\Phi_1}^{+\Phi_1}$$

$$= 2 \left[\frac{1}{(AB - B^2 \tan \frac{\Phi_1}{2})^2} - \frac{1}{(AB + B^2 \tan \frac{\Phi_1}{2})^2} - \frac{2A}{3B^2(A - B \tan \frac{\Phi_1}{2})^3} + \frac{2A}{3B^2(A + B \tan \frac{\Phi_1}{2})^3} \right]$$

$$= 2 \left[\frac{4AB^3 \tan \frac{\Phi_1}{2}}{(\overline{AB}^2 - B^4 \tan^2 \frac{\Phi_1}{2})^2} - \frac{4A(3A^2B \tan \frac{\Phi_1}{2} + B^3 \tan^3 \frac{\Phi_1}{2})}{3B^2(A^2 - B^2 \tan^2 \frac{\Phi_1}{2})^3} \right]$$

Or

$$M = \frac{AB^3 \tan \frac{\Phi_1}{2}}{(\overline{AB}^2 - B^4 \tan^2 \frac{\Phi_1}{2})^2} - \frac{A(3A^2B \tan \frac{\Phi_1}{2} + B^3 \tan^3 \frac{\Phi_1}{2})}{3B^2(A^2 - B^2 \tan^2 \frac{\Phi_1}{2})^3} \qquad (15)$$

Where $A = \sin\frac{\theta}{2}$, $B = \cos\frac{\theta}{2}$ and in the case shown in Fig. 23, $\Phi_1 = 8^o 52'$. Then

$$N' = \frac{K_1}{8}\left[8M\right] = K_1 M \qquad (16)$$

Since N' is the integrated value of dN' from $-\Phi_1$ to $+\Phi_1$ when θ is held constant, hence N' is the total number of scattered alpha-particles that reach the detector at the angle θ per sec. per unit area; and therefore the number of counts per minute registered by the counter corresponds to N'. So Eq. (16) should be used instead of Eq. (2) in this experiment, if, of course, the above assumptions are correct.

Based on Eq. (15) and (16) and the experimental results from which Fig. 20 was plotted the following data and Fig. 25 were obtained.

θ	N'	M	log N'	log M
9^o	22	60.7×10^5	1.342	6.783
10^o	10	12.8×10^3	1.000	4.107
12^o	2	4.6×10^2	0.301	2.669

The above calculation for the values of M began with 9^o because in this case $\Phi_1 = 8^o 52'$ and the actual scattering angle $(\theta - \Phi)$ in Eq. (9) can not be a negative quantity.

Fig. 25 does not give a curve of slope of unity as Eq. (16) would indicate. This is probably because that the angles θ's are still too small. As is revealed by Fig. 22, at small angles, there are still some

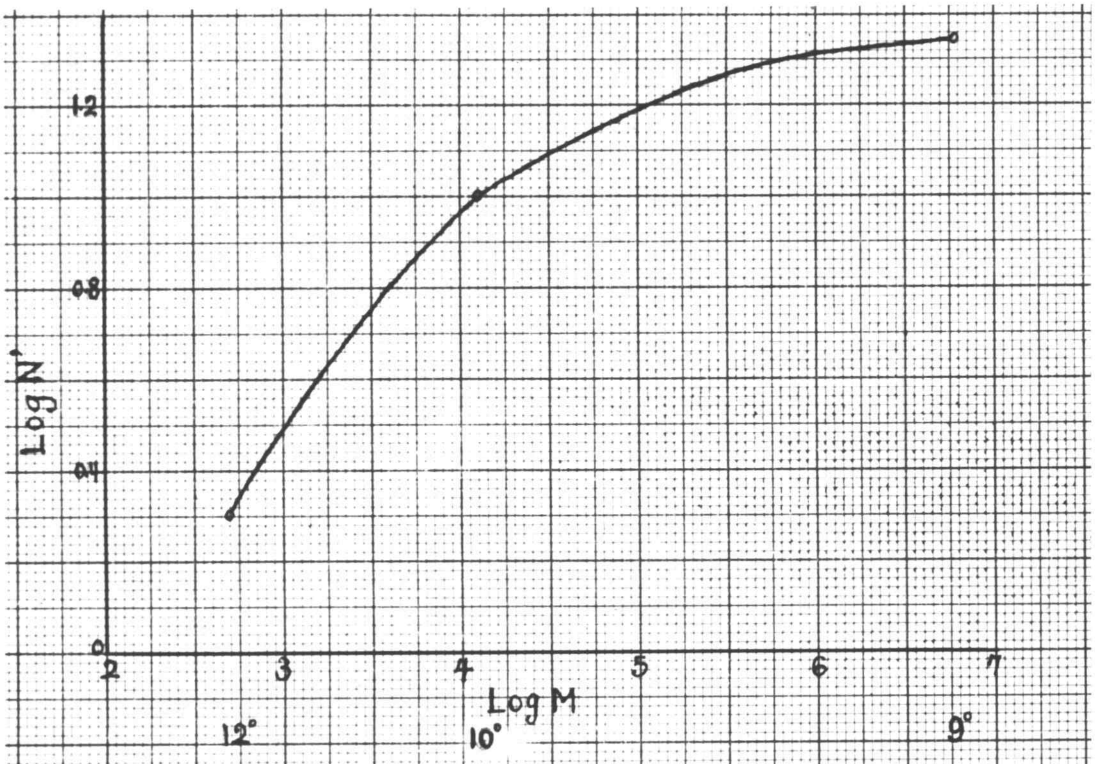

1.2
0.8
0.4
0
Log N'
2
3
4
5
6
7
Log M
12°
10°
9°

Fig. 25

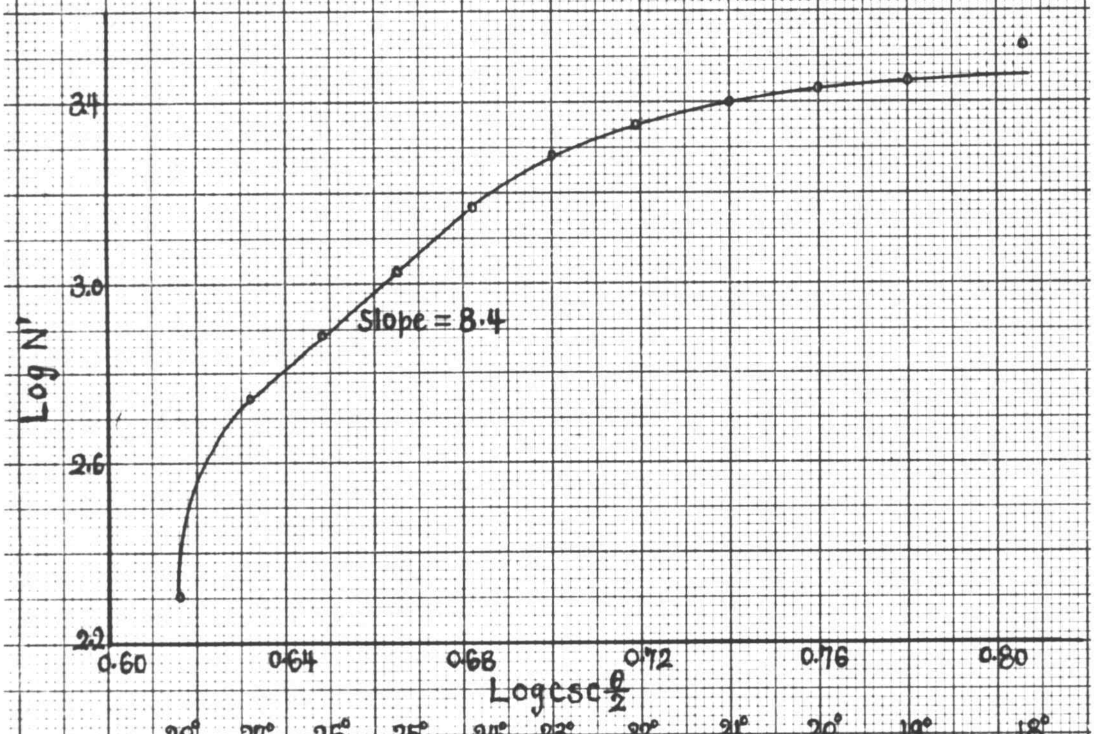

3.4
3.0
2.6
2.2
Log N'
Slope = 8.4
0.60
0.64
0.68
0.72
0.76
0.80
Log csc $\frac{\theta}{2}$
28°
27°
26°
25°
24°
23°
22°
21°
20°
19°
18°

Fig. 26

non-scattered particles mixed with the scattered ones.

As a further check of Eq. (16), an experiment was made by using a larger aperture instead of P_1 as shown in Fig. 23 so that some of the particles will be scattered at larger angles and detected by the counter. In this case Fig. 23 will be modified and AB = AD = 0.13 inch and the geometry gives

$$\frac{AB}{AF - CF} = \frac{EF}{CF}$$

or

$$CF = \frac{AF \cdot EF}{AB + EF} = \frac{3/4 \times 0.0586}{0.13 + 0.0586} = 0.233$$

Then

$$\tan \Phi_1 = \frac{EF}{CF} = \frac{0.0586}{0.233} = 0.2515$$

$$\Phi_1 = 14^\circ 8'$$

With this arrangement the following data and Fig. 26 and 27 were obtained. The slope of the curve shown in Fig. 27 at larger angles beyond 22° is very close to unity. This shows that the correction made with Eq. (16) seems to be quite reasonable.

θ	N'	M	log csc $(\frac{\theta}{2})$	log N'	log M
18°	3320	640.3	0.806	3.521	2.806
19°	2784	329.5	0.782	3.445	2.518
20°	2672	121.4	0.760	3.427	2.084
21°	2504	73.1	0.740	3.399	1.863
22°	2248	44.25	0.719	3.352	1.646
23°	1912	31.9	0.700	3.281	1.534
24°	1480	22.0	0.682	3.170	1.342
25°	1064	15.81	0.665	3.027	1.199
26°	784	11.72	0.648	2.894	1.069
27°	552	8.94	0.632	2.742	0.951
28°	200	7.0	0.616	2.301	0.845

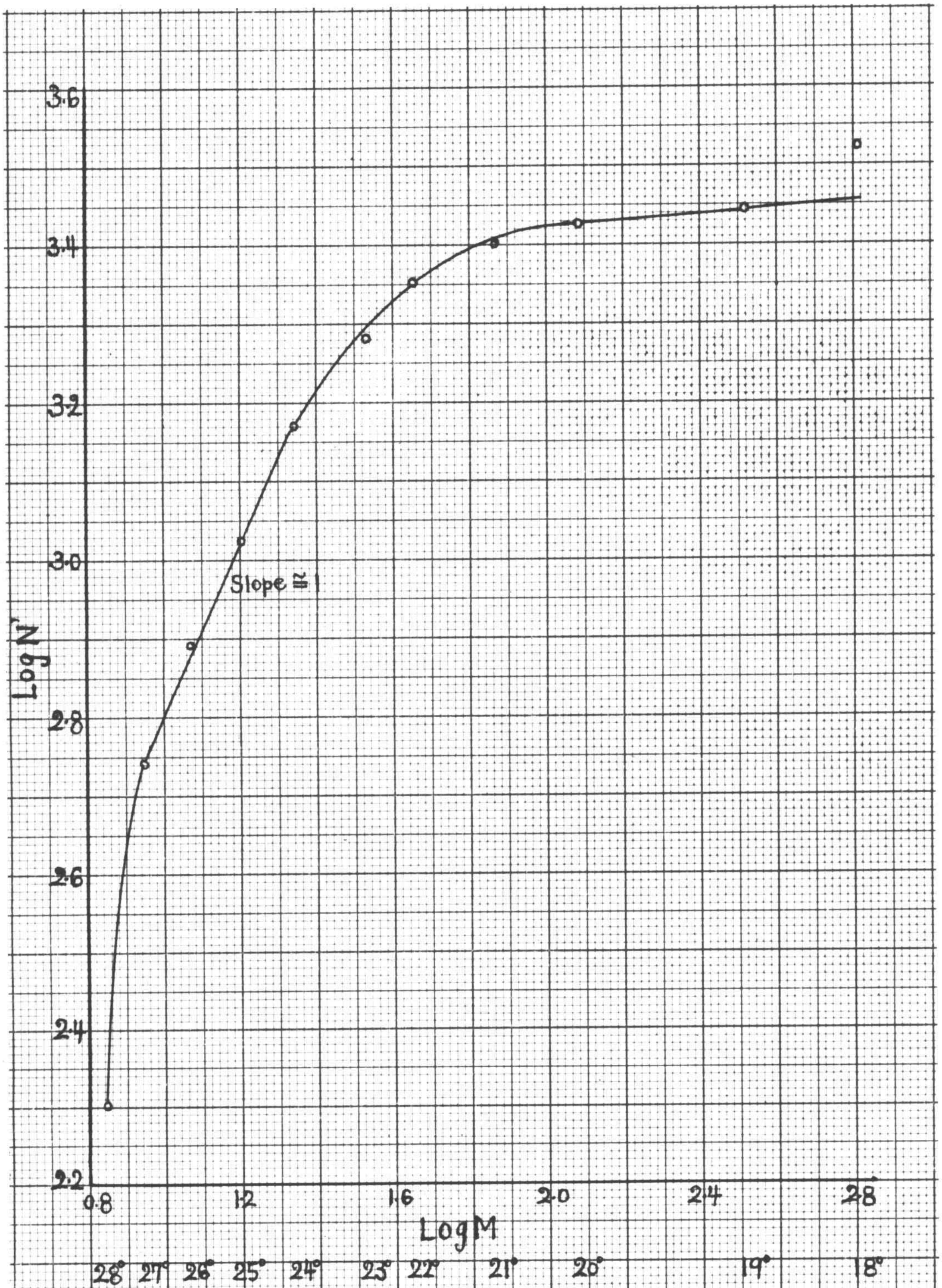

3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
Log N'
Slope ≅ 1
0.8
1.2
1.6
2.0
2.4
2.8
Log M
28° 27° 26° 25° 24° 23° 22° 21° 20° 19° 18°

Fig. 27

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