A STUDY OF A PARALLEL PLATE IONIZATION CHAMBER

Thesis for the Degree of M. S.

MICHIGAN STATE UNIVERSITY

Rasool Javahery

1961

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A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
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MASTER OF SCIENCE

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ACKNOWLEDGMENTS

The author desires to express his sincere thanks and gratitudes to Dr. William H. Kelly, and Dr. Herbert H. Balotin who have been very patient and helpful in guiding the author in this study.

Further gratitudes are expressed to Dr. S.K. Haynes, Head of the Department of Physics and Astronomy; the National Academy of Sciences; and the authorities of Teheran University who have made it possible for the author to continue this research.

ABSTRACT

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ABSTRACT

In this thesis the theory of ionization chamber, proportional counter and geiger counter is studied. The shape of pulses and the effect of grid is discussed. We used the parallel plate ionization chamber and we introduced different parameters such as voltage difference across the electrodes, dimension of collector (collector with and without guard ring) and pressure. We showed that the characteristic of ionization chamber is a function of these parameters.

Also we showed that this parallel plate ionization chamber practically cannot be a proportional counter.

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I. INTRODUCTION

Charged particles in penetrating through matter may lose energy by collision with atoms. These collisions may result in ionization by ejecting electrons (usually valence electrons). If the energy of a particle reaches some specific value (ionization energy) it can ionize atoms. The average energy loss per unit path length for heavy particles in matter has been calculated [1] as:

$$-\frac{dE}{dx} = \frac{2\pi N Z z'^2 e^4}{E}\left(\frac{M_0}{m_0}\right)\left[\log\frac{2m_0 v^2}{I} - C\right] \qquad (1)$$

E is the energy of the incident particle; v is the velocity and Z'e the charge of the incident particle, N the number of atoms per unit volume of material, Ze their nuclear charge, I the average exitation potential, M_0 atomic rest mass of matter and m_0 electron rest mass. m is the mass of heavy particle. C is a constant. The average energy loss of electrons per unit length can be written as:

$$-\frac{dE}{dx} = \frac{2\pi N Z e^4}{E}\log\left[\sqrt{1.39}\,\frac{E}{I}\right] \qquad (2)$$

In this equation the factor $\frac{M_0}{m_0}$ is missing. Dividing equation (1) by equation (2) gives the ratio of the change of energy per unit length for a heavy particle and an electron. Let us assume that the heavy particle and the electron have the same energy. Then this ratio is a large number. Therefore, usually the change of energy per unit length for ejecting electron will not be sufficient to produce significant ionization. However, if a strong electric field is introduced, these electrons can be accelerated to sufficient energy to produce further ioniza-

tion,(secondary ionization). In fact, these secondary electrons can themselves be accelerated to the point at which they produce significant ionization.

If charged particles expend all their energy through collisions, it is always the more energetic particles that give a larger number of electrons. This thesis is concerned with a study of ionization counters and the influence of different parameters on their operation.

It is important to study factors which change collecting time; the effect of small amount of impurity in the gas contained in the chambers; different types of ionization counters; and also how one can change the character of the ionization counter by changing other factors. Here we consider only ionizations which are produced originally by alpha particles, and not by beta or gamma decays.

Let us first discuss the different types of ionization counters.

II. COUNTERS

Gas filled counters indicating the arrival of single particles can be classified as ionization counters, proportional counters, and geiger counters. These ionization counters are chambers with at least two electrodes. The collecting electrode is normally at ground potential and the other electrode is at a negative potential with respect to ground.

We assume that ionization takes place in the chamber, with say, n=10 electrons being released. When V the potential difference between the electrodes is very small (of the order of a few volts or less), all 10 electrons will not arrive at the collector, since some electrons will recombine with positive ions.

This effect is called recombination. As V increases the number of electrons collected at the electrode will increase. At V_1 saturation is achieved and all ten electrons arrive at the collecting electrode. Saturation continues until some specific voltage V_2 is reached. The region from V_1 to V_2 is called the ionization region. There is no recombination effect in this region.

At V_2 electrons acquire sufficient energy between collisions to ionize the atoms with which they collide (secondary ionization), and the number of electrons arriving at the collector rises above ten in an approximately exponentially fashion with V (as will be shown later).

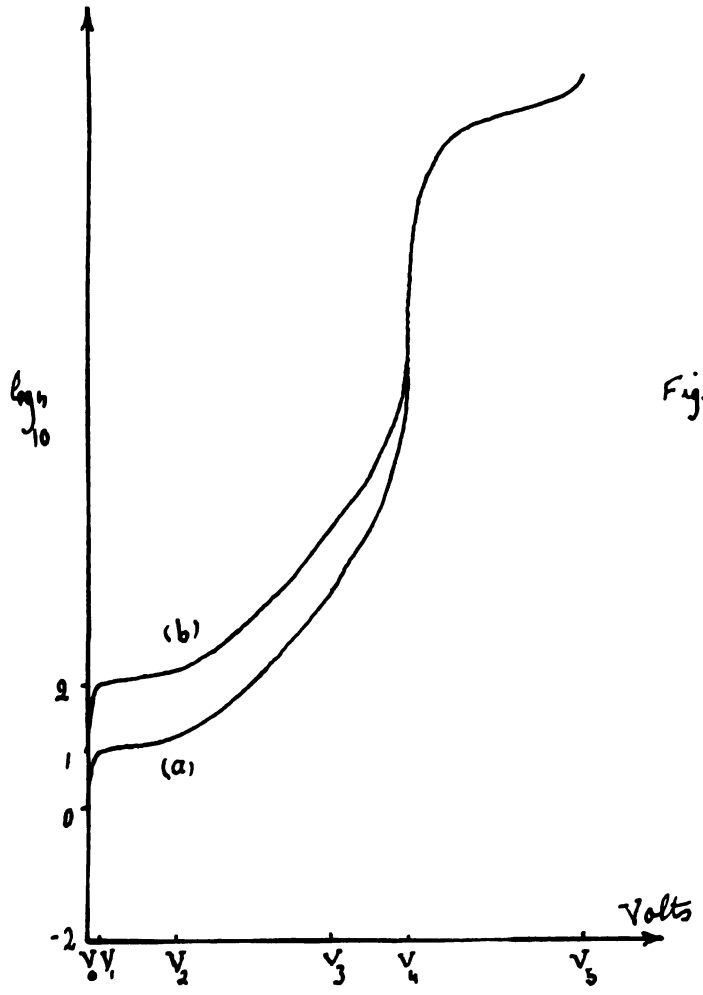

Fig. 1- Ionization Regions.

Each electron originally present produces a small avalanche of secondary electrons by secondary ionization close to the collector, since as the electrons get closer to the collector the total number of secondary electrons increases.

The region between V_2 and V_3 is called the proportional region, and counters operating in this region are called proportional counters.

In ionization counters and proportional counters the number of electrons collected is proportional to the energy of the particle detected. The greater the energy the larger will be the pulse height. In the ionization region the pulse height is independent of applied voltage, in the proportional region

the pulse height is a function of voltage.

Let us consider these two regions more carefully. We shall imagine that we use a source which emits alpha particles of two different energies. Therefore, the initial number of electrons which are released are different.

Curve (a) in Fig. 1 corresponds to n =10 initial electrons. In region V_1 to V_2 the curve is a horizontal line. If initially 100 electrons are liberated, curve (b) results. This curve is also horizontal in region between V_1 to V_2, but it is different from curve (a) by one on a $\log_{10} n$ scale.

There are interactions between avalanches produced by each initial electrons. At V_3 the positive ions from one avalanche hinder the development of the next avalanche. Therefore the discharge with 100 electrons will be more effected than the one for 10 electrons, and n begins to decrease relative to curve (a). Thus (a) and (b) are no longer one unit apart in this region but approach each other.

In the V_3 to V_4 region the final number of electrons in the pulse is no longer proportional to the initial ionization as it was in region V_2 to V_3, though the greater number of initial electrons still gives the higher pulse.

Between V_3 and V_4 the curves rise rapidly. At V_4, (a) and (b) join to form a single curve. Region V_3 to V_4 is called the "region of limited proportional counter". The very rapid rise of n at V_4 means that one avalanche breeds

one or more further avalanches, and this breeding continues until a considerable space charge due to positive ions is built up near the collector. This space charge affects the field at the collector quite considerably, so the number of avalanches rises less rapidly and further breeding is suppressed. The final charge developed is then determined not by the number of initial electrons but principally by the positive ion space charge.

The region from V_4 to V_5 is the geiger region. In this region the pulses are independent of magnitude of primary ionization and their sizes are uniform and depend on the threshold voltage V_4. In this case the discharge spreads from primary ionization through the whole counter chamber.

The potential between two electrodes as a function of position between the electrodes is shown in Fig. 2. Curve (a) shows the potential between two plates without any space charge and curve (b) shows the potential with space charge.

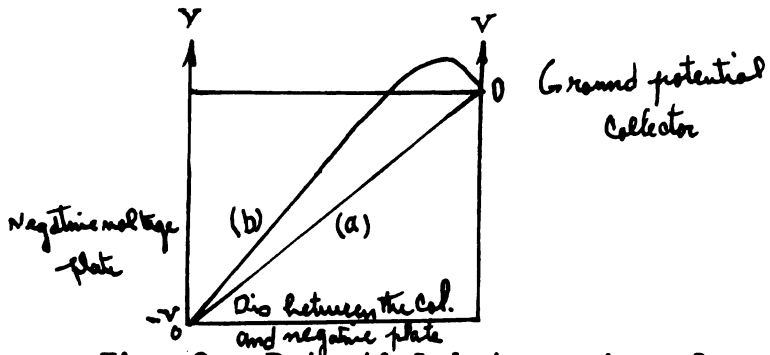

Fig. 2 - Potential between two electrod.
(a) no space charge.
(b) space charge from positive ion.

III. REVIEW OF LITERATURE

(a) The velocity of electrons in the ionization chamber.

The approximate velocity of an electron in an ionization chamber has already been established.[2]

For two parallel plates namely positive collector and negative plates, the field between the plates is given by $E=\frac{V}{d}$. The plate separation d is assumed to be small compared with the plate diameter. The velocity in terms of field is given by $v=K\frac{E}{P}$. Therefore $v=\frac{KV}{Pd}$ (3) K is a constant and P is pressure.

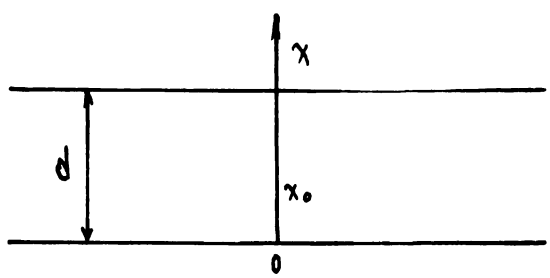

Fig. 3 - Parallel plates chamber.

For example: for V=3000 volts, d=5 cm., P=40 psi and using the value of K for argon gas, the velocity is $v=10^6$ cm/sec.

The diagram for a parallel plate chamber is shown in Fig. 3. The two electrodes (plates) are separated by a distance (d) and the x axis is taken perpendicular to the lower plate at point O.

b) The pulse shape in parallel plates chamber.

Here we shall use the same diagram as before, viz. Fig. (3).

Let us assume that n positive and n negative ions are formed at the average distance x_0 from the lower plate. Because of the electric field E, these ions move in direction of x, and the average work done on these electrons will be:

$$\int_{x}^{x_0} ne\,E\,dx$$

From conservation of energy,

$$\frac{cV^2}{2} - \frac{cV_0^2}{2} = \int_{x_0}^{x} Ene\,dx \qquad (4)$$

C is the capacity of the system, V_0 is the initial potential difference between the electrodes before ionization takes place, V is the potential difference at any time t, and E the field intensity. The left hand side of the above equation can be written:

$$\frac{c}{2}(V^2 - V_0^2) = \frac{c}{2}(V-V_0)(V+V_0)$$

Let us use the approximate values $V-V_0 \simeq 10^{-3}$, and V_0=1000 volts. Therefore $V+V_0 \simeq 2V_0$. Let $V - V_0 = V_c$; V_c is the sum of the two voltages due to positive and negative ions on the collector. Therefore:

$$cV_cV_0 = ne\int_{x}^{x_0} E\,dx \qquad (5)$$

and substituting for $E=\frac{V}{d}$, we obtain:

$$V_c = \frac{neV}{cV_0d}(x_0-x) \qquad (6), \text{ hence } V_c = \frac{ne}{cd}(x_0-x) \qquad (7)$$

since $\frac{V}{V_0} \simeq 1$.

Changing the variable x to t, and using:

$$x - x_0 = \int_{x_0}^{x} dx = \int_{0}^{t} v\,dt = vt \qquad (8)$$

Where v is the velocity of electrons, we obtain:

$$V_c = \frac{ne\,v\,t}{cd} \qquad (9).$$

Now let us use the symbols $\bar{v}$ and $\bar{v}$ the drift velocity

of negative and positive ions. Then:

$$\overset{+}{V}_c = \frac{ne\overset{+}{v}t}{cd} \qquad (10) \qquad \bar{V}_c = \frac{ne\bar{v}t}{cd} \qquad (11)$$

The average final value V_c and V_c from equation (7) will be:

$$\bar{V}_{cf} = -\frac{ne}{cd}(d - x_o) = \frac{ne}{c}\left(1 - \frac{x_o}{d}\right) \qquad (12)$$

$$V_{cf} = \frac{ne x_o}{cd} \qquad (13)$$

These equations show that for the two parallel plate chamber, the pulse is a function of x_o, and also the pulse height is a function of x_o.

Returning to equations (10) and (11) we note that the positive ions are heavier than electrons and their drift velocity is smaller than that of electrons, $\bar{v} \simeq 1000 \overset{+}{v}$. The pulse due to negative charges rises with slope $\frac{ne\bar{v}}{cd}$ until time $t_1 = \frac{x_o}{\bar{v}}$, where t_1 is the average time the negative ions take to travel between the plates. After this time the pulse is due to positive ions and it rises very slowly. Its slope is: $\frac{ne\overset{+}{v}}{cd}$

The total final voltage from equations (9) and (10) is found by taking:

$$V_{cf} = V_{cf} + \overset{+}{V}_{cf} = -\frac{ne}{c} \qquad (14)$$

The final pulse rise reaches $-\frac{ne}{c}$ in time t_2 which is the average time for collection of positive ions.

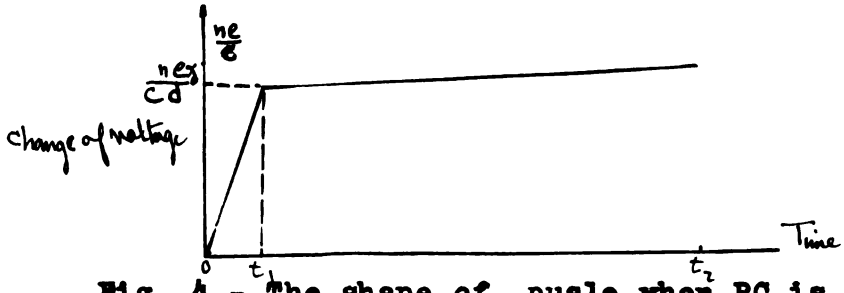

Fig. 4 - The shape of pusle when RC is infinite. (The time scale is distorted).

Another parameter for pulse shape is the clipping time. This time is equal to RC where R is resistance and C is capacity of the system. In the previous discussion we chose RC equal to infinity. The results gave us Fig. 4. Usually the time constant (clipping time) is smaller than t_2 and greater than t_1 as we saw before, the pulse rises proportional to time. This is shown in Fig. 5 by curve (a). As the electrons reach the collector, they decay through the circuit. This decay is an exponential function of time, $e^{-t/RC}$; curve (b). The resulting pulse is shown as curve (c) in Fig. 5.

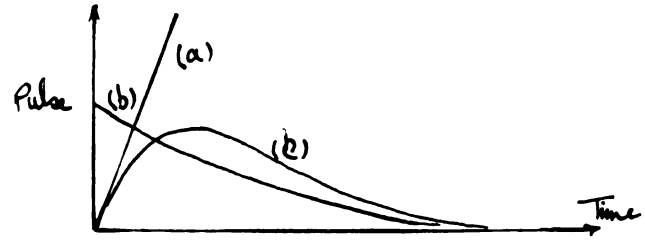

Fig. 5 - The shape of pulse when $RC \ll t_2$.

Of-course for different values of RC the pulse shapes are different. This is illustrated in Fig. 6.

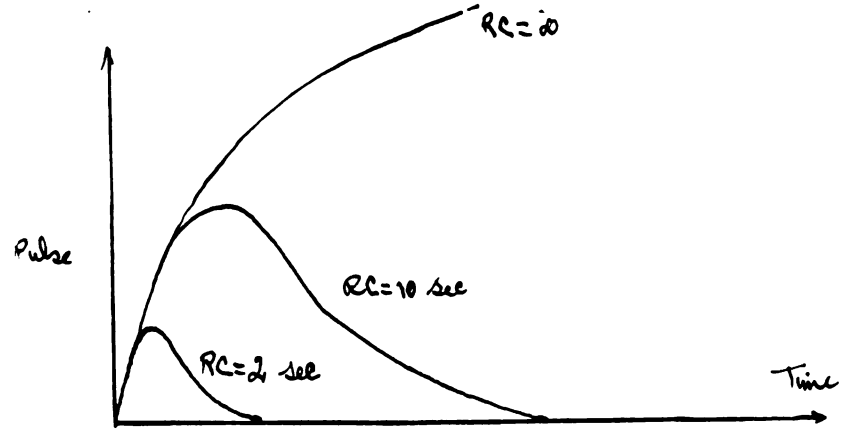

Fig. 6 - Pulse shape for different values of RC.

c) Chamber with Grid

It is desirable to have a chamber in which the output voltage pulse does not depend upon the track of positive ion or its orientation. This is made possible by the addition of another electrode. Let us consider a parallel plate chamber with a grid as shown in Fig. 7, where r is the radius of the grid wire and L, the distance between two wires.

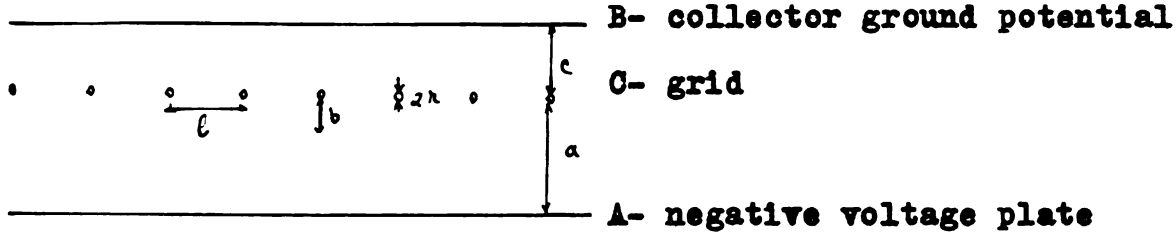

Fig. 7 - Parallel plates chamber with a grid.

Let us consider what effect the grid has on the positive charge. With the grid in position, some of the field lines end at the grid instead of on the plates. We saw before that for two parallel plates the effect of positive ions on the electrode is given by:

$$V^{+}_{cf} = \frac{ne}{C}\frac{x_0}{d} = \frac{ne}{C}\left(1 - \frac{b+c}{d}\right)$$

Similarly the effect of positive ions on the grid is proportional to $\frac{ne}{C}\left(1 - \frac{b}{a}\right)$.

Through this action the collecting electrode is in some measure protected from the positive ions. The degree of this shielding can be calculated.[3] The effect of positive ions on the collector which remains after complete collection of

electrons is $\overset{+}{V} = \frac{ne}{c}\sigma\left(1 - \frac{b}{a}\right)$ (15) where σ depends upon the construction of grid, and its location. For very small σ the pulses are equal to each other and they are proportional to the initial number.

If $\frac{2\pi r}{\ell}$ is not too large, $\sigma \simeq \frac{\ell}{2\pi c} \log \frac{\ell}{2\pi r}$ (16) where $\left(\frac{\pi r}{\ell}\right)^2$ is neglected, since it is much smaller than $\log \frac{\ell}{2\pi r}$.

Iv . CONSTRUCTION & PERFORMANCE OF APPARATUS

Let us assume that polonium is placed in an ionization chamber containing argon gas and let the alpha particles entering from the source cause an ionization event inside the sensitive volume. A positive and negative ion pair is produced. The collector of the ionization chamber is connected to the pre-amplifier, linear amplifier, and auxiliary electronic equipment. This collector is connected to positive voltage with respect to the screen cylinder. After ionization the electrons will go to the collector and the positive charge will go to the screen cage (negative voltage).

The collector, high voltage plate and the grid are all located inside the ionization chamber and are parallel to each other. There is a cylindrical screen wire located inside the chamber. It is connected to the two high voltage brass plates which create a sensitive volume inside the chamber. The screen wire is attached to the top disk of the ionization chamber by a ceramic insulator. The container of ionization counter is grounded.

The collector is a polished copper disk. The grid is made of .006" tungsten wire spaced two millimeters apart. It has a negative voltage with respect to the collector. The polonium is deposited on aluminum disk and it is located at the bottom of sensitive volume.

A piece of mylar plastic insulator is attached to the wall

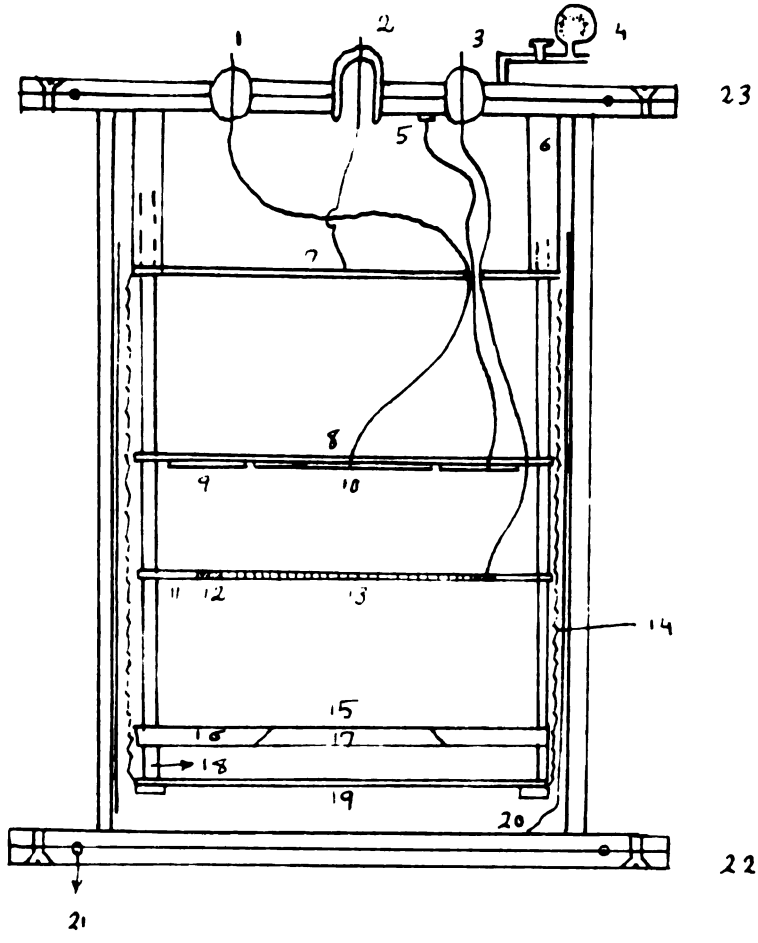

Fig. 8 - The Ionization Chamber (Scale 1/2)

1, 2, 3 (sealed glasses) grid- negative high voltage and collector respectively.
4- Gauge and valve.
5- Ground connection for guard ring.
6- Germice insulator.
7- Brass disk.
8- Plastic holder.
9- Guard ring (grounded)
10- Collector
11- Plastic ring.
12- Brass ring.
13- Grid
14- Screen brass.
15- Source
16- Plastic ring.
17- Mylar plastic.
18- Brass rod.
19- Brass disk.
20- Mylar plastic.
21- "O" ring.
22- Brass plate.
23- Brass plate.

of ionization chamber. Three sealed glasses are inserted in the top disk of ionization chamber, and are connected to different electrodes inside the chamber. However, the guard ring of the collector is connected to the wall (ground) of the ionization chamber. The ionization chamber assemply is shown in Fig. 8.[4]

The ionization chamber is also connected to the vacuum pump and gas tank. To fill the ionization chamber with argon gas, valves E, D and C, are closed but A and B are open. Fig. 9 . The air is pumped out and after a while there is a rather good vacuum inside the ionization chamber. Then we close B and open E and D and C respectively. We can measure the pressure of the tank and the pressure of the ionization chamber by gauges G and F. To be sure that the amount of oxygen inside the ionization chamber is very small for each experiment we flush the ionization chamber with argon gas three times.

To protect against leakage in the ionization chamber "O" rings are used between the top and bottom disks and the cylinder.

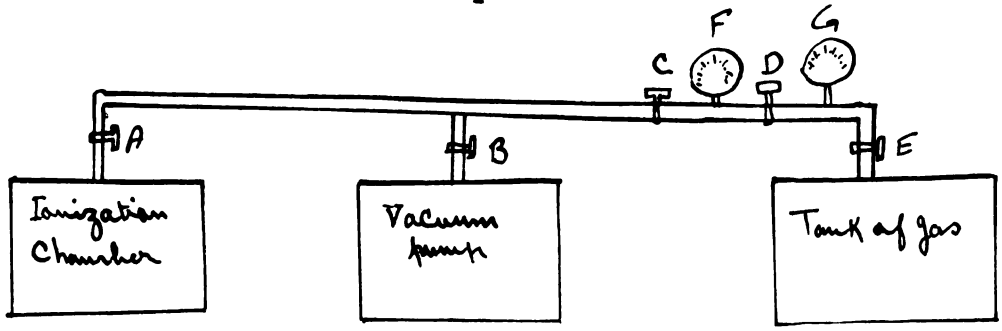

Fig. 9 - Connection between ionization chamber, vacuum pump and tank of gas.

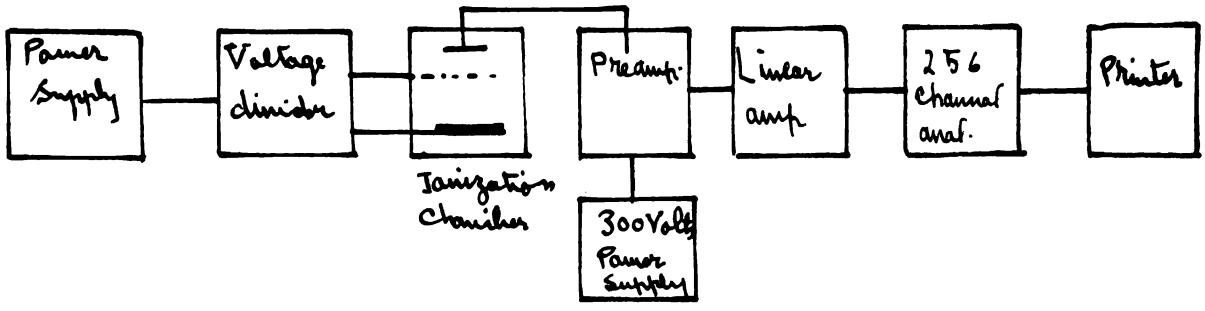

FIG. 10 - Block circuit diagram.

Remarks regarding Proportional Counters

Ionization counters are usually of two different forms: parallel plates chambers; and cylindrical chambers with a collecting wire in the center. These two chambers are shown in Fig.11 .

The field about the center wire in a cylindrical chamber is convergent, therefore this region is the one in which most of the secondary ionization takes place, since there the electrons have enough energy to ionize the gas molecules.

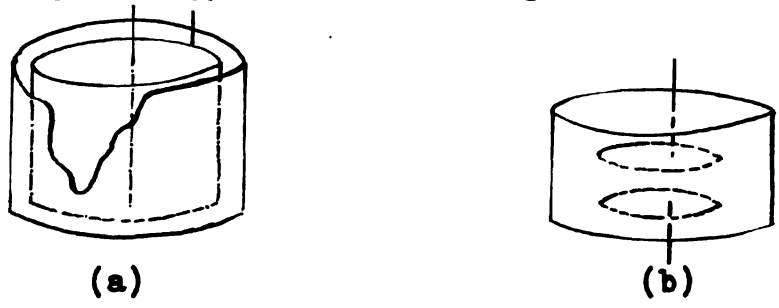

Fig. 11 - a) cylindrical counter
b) parallel plates counter

Calculation of multiplication in proportional counters is carried out[5] under the following three assumptions:

1) The photo-electric effects in the wall and other elements of counter are negligible.

2) Recombination of electrons with positive ions is negligible.

3) Combination of electrons with neutral atoms is also negligible.

Under these assumptions the multiplication is given by:

$$M = \exp\left[\frac{B N_m a V_0}{\log b/a}\right]^{\frac{1}{2}} \left[\sqrt{\frac{V_0}{V_t}} - 1\right]$$

This equation applies for cylindrical counters.

N_m is no. of gas molecules per unit volume.

B is a constant, characteristic of the particular gas; for argon it is 1.81.

V_t is the threshold voltage.

V_0 is the applied voltage.

b is the radius of cylindrical.

a is the radius of center wire.

V. EXPERIMENTAL RESULTS

a) Effect of Pressure

1. The mean free path of an ion in a gas is approximately given by $L = \frac{1}{n\pi r^2}$ [6], where n is the number of atoms or molecules per cm^3 and r is the average molecular radius. We can write this equation as follows: $L \propto \frac{K}{n}$ At low pressure n is small and therefore L is large. Some of the alpha particles produce ionization electrons far from the sensitive volume and they are not collected by the collector. Conversely, for high pressure, the mean free path is small and in general all electrons are created in sensitive volume and all are collected by collector. This is shown in Fig. 13 curve (a). From the above it is clear that there is a saturation effect which starts at some definite pressure.

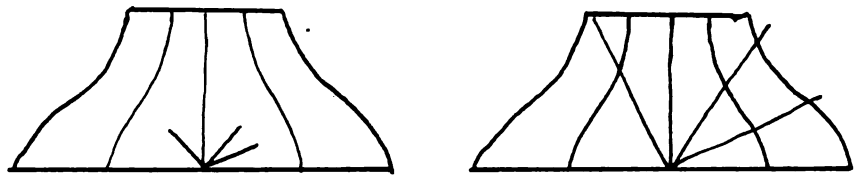

Fig. 12 - Field lines between plates and the effect of pressure on the mean free path of a particle.

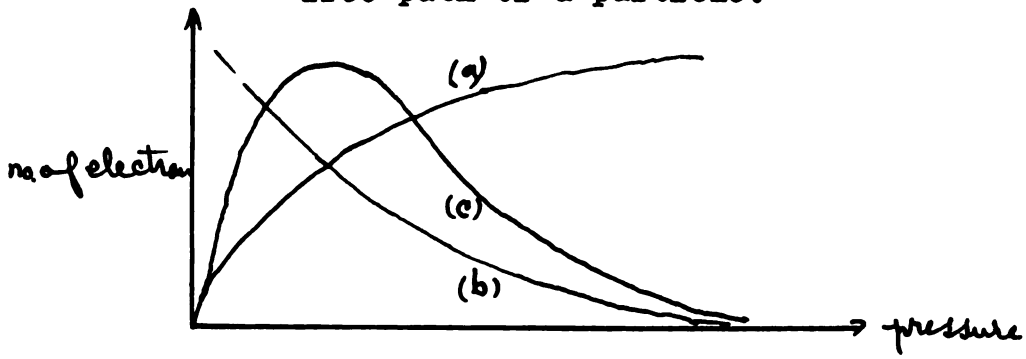

Fig. 13 - Pulse height against pressure.

2. As we showed before, the drift velocity is proportional to E. On the other hand, the probability for recombination increases with decreasing velocity of electron. At higher pressures the electrons do not gain enough energy to be completely free of recombination. Thus we must conclude that at higher pressures some of the electrons recombine with positive ions; curve (b), Fig. 13 shows this effect.

Now using the results of 1 and 2, it can be seen how the pressure affects the number of electrons collected, called pulse height. The resulting pulse shape is the product of the two component curves. Curve (c) showes the form of the pulse as a function of pressure. Fig. 14 shows how the pulse height is found to vary with pressure.

b) Here we wish to discuss this effect for large size collectors. The field lines are shown in Fig. 15. The sensitive volume is greater than the one with the small collector. As we mentioned, for small size collectors the probability of collecting electrons at the collector is smaller at lower pressures. This is also true for large size collectors, but only at very low pressures. Since at these pressures some of the electrons move outside of the sensitive volume and cannot be collected. But at higher pressures all electrons move in the sensitive volume and are collected. We have shown that there is also another effect in which pressure changes the drift velocity.

In this case curve (a) of Fig. 13 is almost a straight line and curve (b) does not change. This is shown in Fig. 16. Curve (c), the product of these two shows that for large size collectors at the higher pressures the pulse height decreases.

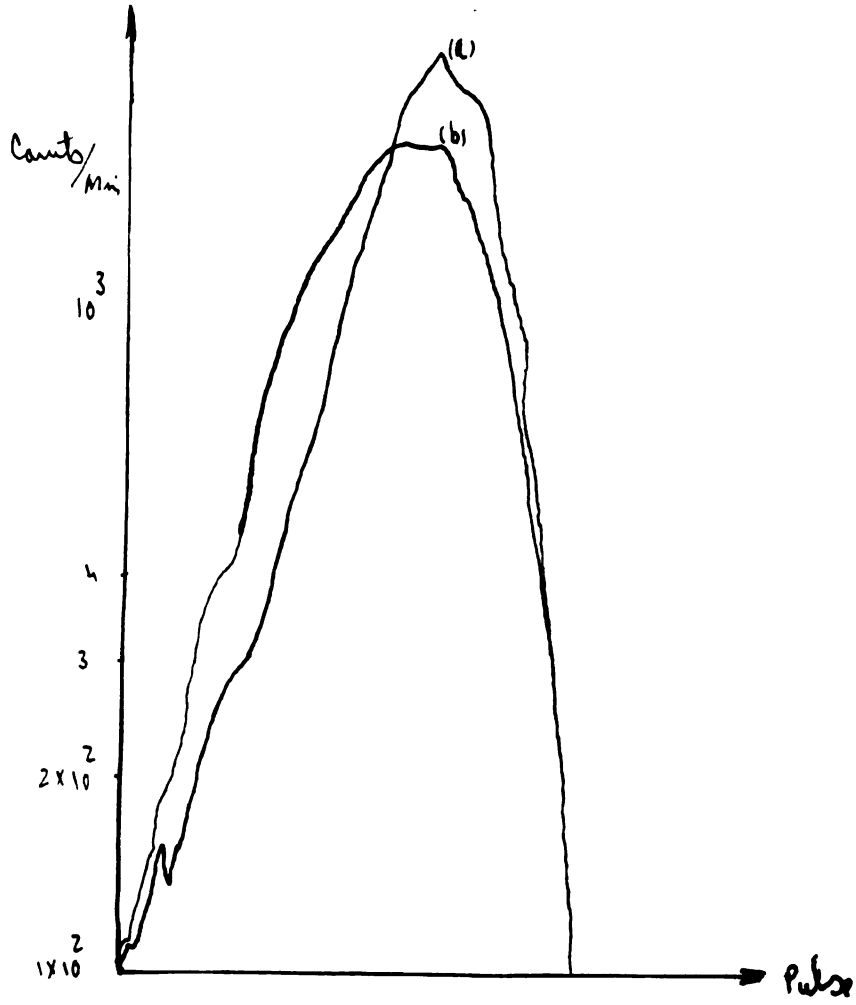

Fig. 14 - No. of counts per minute vs. pulse height.

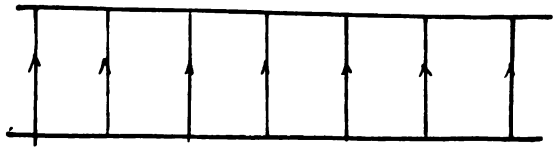

Fig. 15 - The field lines in large size collectors.

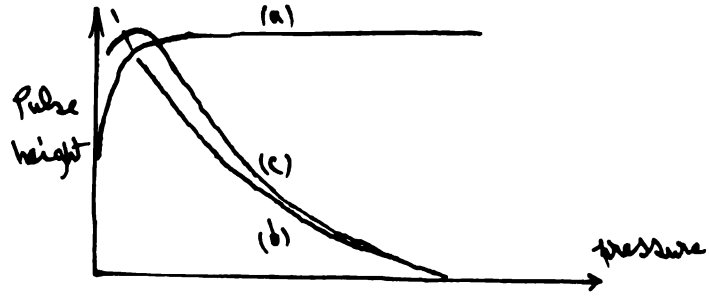

Fig. 16 - Pulse height as a function of pressure.

In Figs. 17 & 18 some variation of pulse height as a function of voltage for two different pressures is apparent.

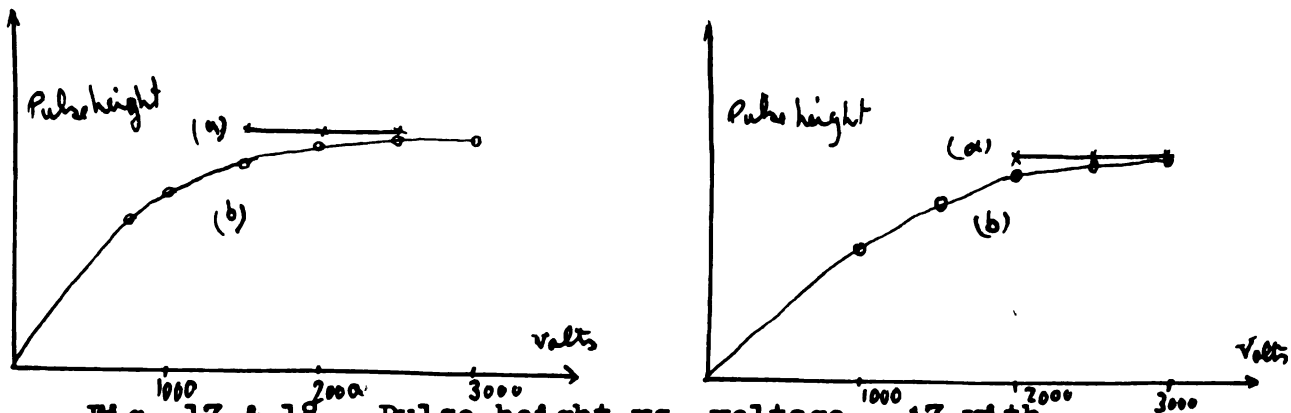

Fig. 17 & 18 - Pulse height vs. voltage. 17 without guard ring, 18 with guard ring.
(a) pressure about atmosphere.
(b) 30 p.s.i. plus atmosphere.

c) Collector with guard ring:

We compare here the operation of the counter with a guard ring and without the guard ring. The field line patterns are shown in Fig. 19. The field for the collector without guard ring focusses in the region close to the collector.

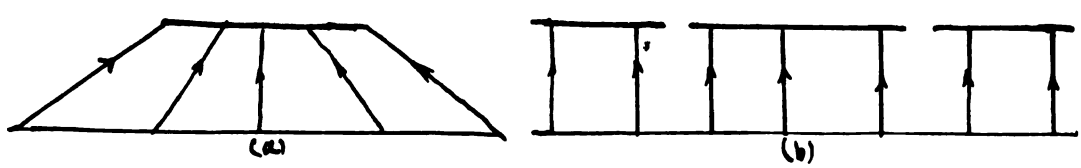

Fig. 19 - Field line pattern.
(a) without guard ring. (b) with guard ring.

The electrons move rapidly in the focussing region and there are no recombination effects. The pulse height increases as we increase the voltage up to 2000 volts, approximately. Then it remains constant. This region is by definition, the

ionization region since the pulse height does not change with the potential. Fig. 20 curve (a) and (b) show the change of pulse height with voltage in this region. The pulse height for a collector with a guard ring is smaller than without the guard ring, since some of the electrons are captured by the guard ring and some by ions. In the ionization chamber with guard ring, if we increase the voltage we eliminate the effect of recombination. Therefore, the two curves approach each other at still higher voltages.

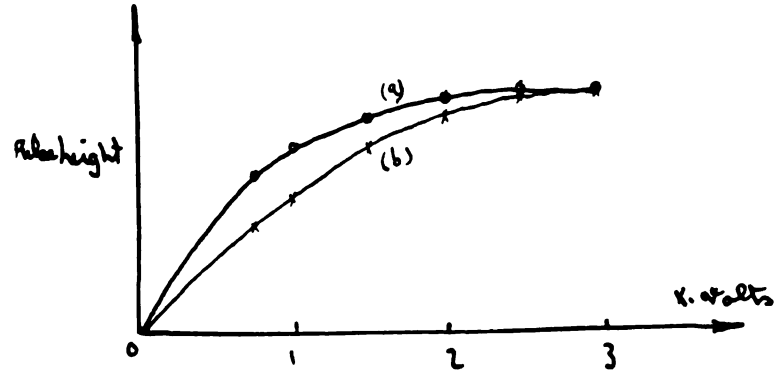

Fig. 20 - Pulse height as a function of voltage.
(a) no guard ring.
(b) guard ring.

d) Comparison of Fig. 17 (a) and (b) shows that at lower pressures the chamber starts to be in the ionization condition at a lower voltage. The difference is much more pronounced for the collector with guard ring, Fig. 18, (a) and (b), since here some of the electrons will be collected by the guard ring. The difference between the pulse height for high and low pressure here is greater than the difference of pulse height for the collector without the guard ring.

e) Resolution

Again using diagram 14, it is seen that the majority of the electrons in (a) are in the same form. For each pulse the number of electrons are approximately equal. This is not, however, true for curve (b), since as we mentioned previously some of the electrons are created closer and some farther away from the collector. Therefore only some of the electrons which are ejected by an alpha particle will be captured by the collector and the remaining electrons will recombine. Thus the pulse height due to this ionization is small, and also resolution is low. This effect can be seen from Fig. 14 curve (a) and (b). In these two curves, the areas under the curves (which correspond to the total number of all electrons) are equal.

VI. DISCUSSION

The original problem for our research was to find the branching ratio of thorium 232. The preparation of the source is difficult since thorium compounds $ThCl_4$ and $Th(NO_3)_4$ are hydroscopic. The difficulty arises in evaporating these compounds; also preparing a very thin layer of source is difficult with these materials, since after a short time they absorb water from the air and are no longer smooth layers. The evaporation of thorium compounds must be done in vacuum aparatus at very low pressures. In gentle heating, the water of hydration is removed. The pressure guage shows the increase of pressure which is due to the water. Then we stop heating the source until very low pressure is reached again. We repeat this several times till there was no more water in the source. Then we heated up to very high temperatures and therefore the compound evaporated and deposited on the holder. But as we mentioned before it is very difficult to protect these compounds from the air.

It seems that it is best to evaporate pure thorium metal since it is not hydroscopic. But the melting point for thorium is 1840^0, and the boiling point is 4500^0. Therefore it is difficult (but possible) to deposit thorium on the holder.

We deposited a very thin thorium 232 metal source on the mylar holder and we obtained only about 10 counts per minute

for alpha decays. This number is due to wholy different decays of thorium 232 and its daughters. The size of pulse after the amplification was about 15 to 20 volts and the noise was about 12 to 15 volts and sometimes more. The thorium spectrum did not have good resolution for different peaks, therefore we could not continue this problem.

Leakage Problem:

Usually a small amount of electro-negative atoms will capture all electrons which are emitted by ionization. If the air leaks through the chamber or through the rubber hole connecting the chamber to the vacuum pump, no pulses are produced.

The question that arises is: Can this chamber work as a proportional counter? To answer this question, we use the equation on page 17,

$$M = e^{AV^{\frac{1}{2}}}\left[\sqrt{\frac{V}{V_t}} - 1\right]$$

for proportional counter $M > 1$ or $V > V_t$. The experiment showed that V_t is greater than 4000 volts. To increase the field intensity between the plate we decreased the distance of the electrode to 8 millimeter for 4000 volts, but the chamber was still in the ionization region. However, using high voltages, 4000 volts or greater, brings forth a new problem. This problem is arcing between the electrodes. Furthermore, it is not practical to make a proportional counter with such high voltage across the electrode. Therefore this apparatus is an ionization counter and cannot be operated as a proportional counter for the above reason.

VII. BIBLIOGRAPHY

1. Walske, M.C., Physics Review, 1952, 88, 1283
2. Rossi & Staub, Ionization Chamber & Counters , Page 40
3. Bumemann, O., N.R.C.Report , P.D. 285
4. Smith, P.T., Physics Review, 1930, 36, 1293
5. Farley, T.A., Canadian Journal of Physics, Aug. 1960, 8, 1059
6. Sergre, E., Experimental Nuclear Physics, Vol.1, 177