I. The Discharge Mechanism of Geiger Counters

II. The Mean Lifetime of the Mesotron from Electroscope Data

Thesis

by

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Throughout the solution of these problems, both of which were suggested and directed by Professor H. V. Neher, the readily available help of Professor Henry Victor Neher and Dr. William Hayward Pickering was often sought. The author is especially grateful to them for that help and for their continued interest in, and enthusiasm for, the problem.

I. The Discharge Mechanism of Geiger Counters

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Summary

The main problem of this research was to determine the discharge mechanism of fast counters and, in so doing, to determine the differences between fast and slow counter action. Numerous small experiments showed that fast counters had an internal quenching mechanism independent of the circuit, whereas slow counters had to drop to threshold voltage to quench. Photoelectric experiments led to the conclusion that the sine qua non of fast counter action was associated with the function of the organic vapor in the gas.

The most important step in the solution of the problem was the discovery of the deadtime phenomenon, and the development of a circuit by which the deadtime and recovery time could be measured. A theory of discharge quenching, by the lowering of the field around the wire by a positive ion space charge, was evolved. The predicted recovery time agreed very well with the measured recovery time.

The deadtime technique was used to investigate the spreading of the discharge in the counter. It was found that the discharge, which spread along the wire throughout the whole length, could be stopped by a small glass bead on the wire. This led to the discovery of a directional Geiger counter. All results agreed with the deadtime theory.

Chapter 1

Historical Introduction and General Characteristics

1.01 Discovery

In 1928, H. Geiger and W. Muller[1] reported the design of a new ion-magnifying device for the detection of ionizing particles, α-rays, β-rays, and cosmic ray particles. In this Geiger-Muller ion counter, henceforth referred to as a G-M counter or simply as a counter, the flow of charge resulting from the passage of an ion-producing particle is independent of the ionization density along the path of the particle. This action is different from that of the proportional counter, which was described[2] by H. Geiger and O. Klemperer earlier in 1928, in which the flow of charge is proportional to the primary ionization of the incident particle. Both the G-M counter and the proportional counter grew as modifications of the original Geiger point counter announced[3] by H. Geiger in 1913. The action of the proportional counter and the point counter is adequately described by H. V. Neher[4] as are also the practical construction details. This last reference -- in the opinion of the author -- is the most complete treatment of Geiger counters from the practical standpoint. It describes not only the construction of the counters but also the construction and design of the amplifying, recording, voltage regulator, and high voltage circuits, that necessarily accompany the counters themselves.

After a great deal of developmental work, G-M counters have proven themselves of extreme usefulness in nuclear physics and cosmic ray work. In the latter field their worth was greatly increased by their use in coincidence circuits. Several counters may be arranged with the proper circuit so that, unless a particle passes through all of them simultaneously, there will be no recorded coincidence. Bothe and Kolhorster[5)] first used this technique and Rossi[6)] developed the first convenient coincidence circuit.

1.02 Elements of G-M Counter; Fundamental Circuit

The original G-M counter consisted of a metal tube with a small wire running coaxially through the tube, held by electrically insulating plugs at the end of the tube. These plugs were waxed in so that the tube could be evacuated and filled with a suitable gas to any pressure. The gas, the wire, and the cylinder make up the primary elements of the G-M counter. In general, in describing the action of the G-M counter it is in reference to the fundamental Geiger Muller counter circuit which is shown in Fig. 1.02. This circuit consists of a high voltage power supply and a series resistance. The positive is connected to the wire and the negative to the cylinder. Neglecting the finer points of the discharge mechanism, the action is as follows. When an ionizing particle passes through the counter the negative ions and electrons are accelerated toward the wire and the positive ions toward the cylinder. In the high field region just around the wire there is cumulative ionization, probably by the electrons. With this surge of current in the counter, there is a current flow through the resistance, R, in the fundamental circuit. The IR voltage drop across this resistance is used to trip the recording circuit. In the original work Geiger and Muller used an electrometer connected to the wire. The kicks of the electrometer were either viewed or photographed. In general, the voltage pulse is fed onto the grid of an amplifier which in turn passes a pulse onto some suitable recording device.

It is of importance to note that in the fundamental circuit the resistance, R, is very large, around 10^9 ohms. In all the early work until the publication[7)] of the Neher-Harper circuit in 1936 the resistance was high. About the same time the discovery of the fast or self-quenching counter also enabled one to lower the resistance to 10^5 or 10^4 ohms. In this historical review before these two advancements, it is important to remember the fact that the resistance is high. Because of a high resistance, it is seen that the RC time constant is very long.

1.03 Counts per Unit Time versus Voltage; Plateau

Perhaps one of the most elementary properties of G-M counters is shown in a plot of the counts per unit time against the voltage applied to the counter. Geiger and Muller[8)] were the first to make such a plot which they reported in 1929 in a further investigation of counters. Figure 1.03 shows the characteristic curve for a typical G.M. counter. The ionizing particles which cause the counts might be from a source

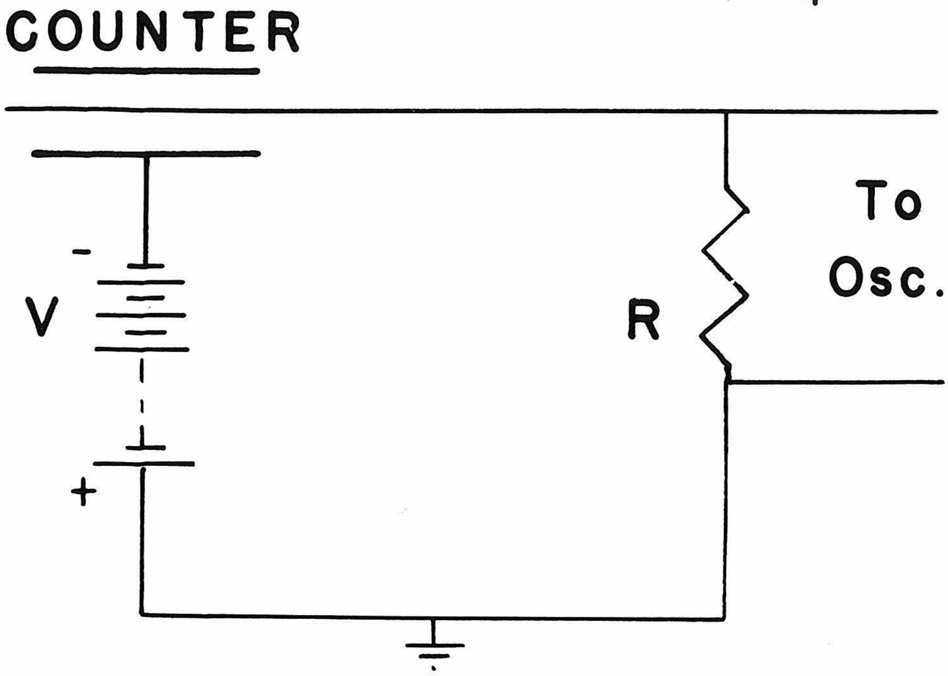


FIG. 1.02

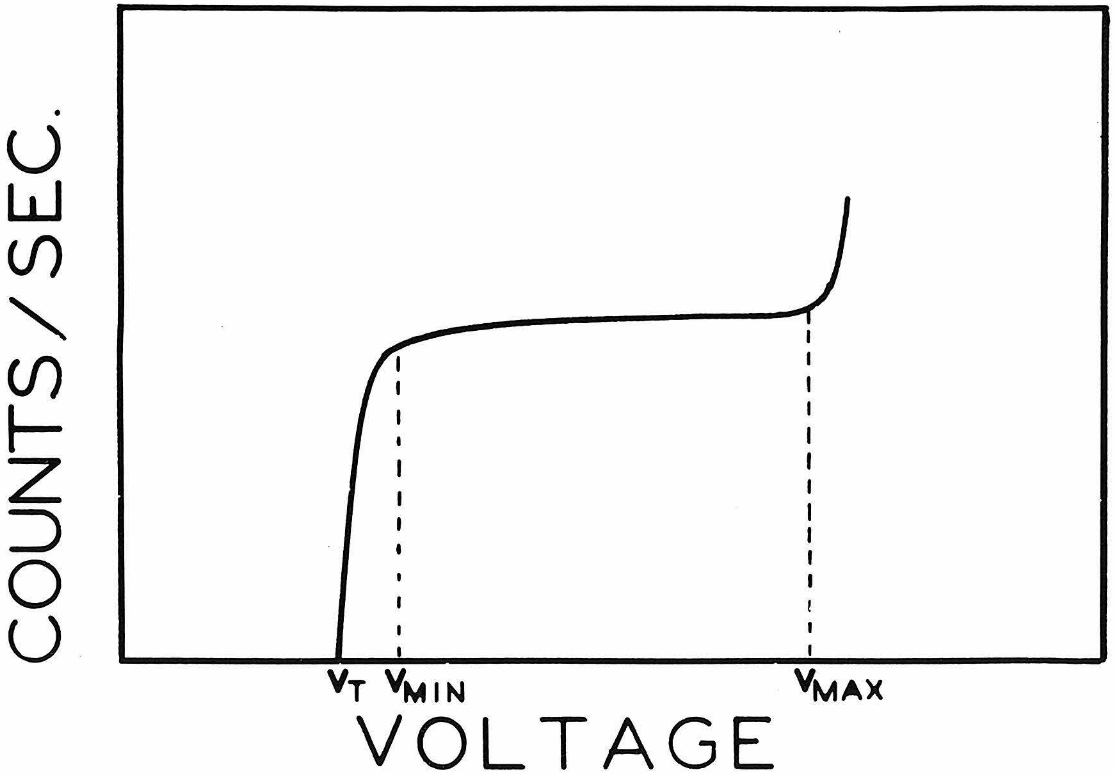


FIG. 1.03

placed near the counter plus background or might be background alone. It is seen from Figure 1.03 that as the voltage across the counter is raised there are no counts until a certain minimum voltage, V_t, is reached. This is known as the threshold voltage. Then the number of counts increases rapidly with increased voltage until the curve levels off for a few hundred volts. Finally, an increase in voltage causes a rapid rise in the number of counts, till the counter breaks into steady discharge. The level portion of the curve is the plateau of the counter, being that region in which the counter is responding approximately to the true number of particles passing through the counter. The counter is operated at some voltage on the plateau. It is seen that it is desirable for the counter to have a long plateau, for then voltage regulation of the high voltage supply is not as essential as if the plateau were short. Moreover, a good counter has a very flat plateau. Since the graph of the number of counts per unit time as a function of voltage furnishes two pieces of information of the counting properties of a counter, it is valuable to plot such a curve for any given counter.

1.04 Original Theory

Very soon in the development of G-M counters the question of their discharge mechanism arose. Why does there exist such a region as the plateau of the counter, in which the counter is not in discharge yet furnishes a pulse of current when there is a triggering ionization spurt? Moreover, why does this current stop after a given time? It is extremely interesting to note the theory which was given by Geiger and Muller in the original paper. Their counter was constructed with a highly resistant coating on the wire. They said that this coating prevented the counter from going into a continual discharge condition. In the following year H. Kniepkamp[9] exploded this theory when he reported the operation of a G-M counter with a bare wire.

The fact that the G-M counter developed as a very useful laboratory instrument,combined with the fact that there was no satisfactory theory to explain its action,precipitated a great number of investigations of its properties.

1.05 Investigation of the Wire

Kniepkamp's work showing that G-M counters worked with clean bare wires was born out by a later investigation by Curtiss.[10] Curtiss used bare copper, bare steel, lacquered steel, oxidized tungsten,and oxidized nichrome,all of which functioned properly. Not only in this paper but throughout the prodigious amount of literature upon the treatment of materials used in G-M counter manufacture there has,in general,been agreement that the wire material did not figure prominently in the action of the G-M counter or if it did, all materials performed the function satisfactorily. Of course it is desirable to have the wire small enough,in order that the voltage applied across the counter need not be excessive in getting sufficiently high field about the wire. Likewise it is necessary that there be no sharp points on the wire for,in that high field region, sparking would result.

1.06 Investigation of the Cylinder

Even a greater amount of literature is concerned with the treatment of the metallic cylinder. Geiger and Muller found that cathode materials of iron, nickel, brass, zinc, lead, paraffin, aluminum,acted approximately the same. Of course it is to be remembered that satisfactory action in early work in G-M counters does not imply satisfactory action in later investigations. In 1930, L. F. Curtiss[11)] pointed out that the inner surface of the cathode was definitely the sensitive,or critical,surface and that its treatment determined to a large extent the quality of the counter.

If the large amount of ionization which takes place in the counter around the wire in a given discharge is taken into consideration, a very large photon emission is expected since many collisions will not fully ionize but merely excite the atoms of the gas. With large photonic emission, the photoelectric properties of the inner surface of the cathode become important so that probably the numerous different treatments of the cylinder are important in that they alter the photoelectric properties of the cathode.

Greiner[12)] investigated the spread of the discharge throughout the tube. He measured the simultaneous voltage pulses from the wires of two G-M counters sharing the same container. He found that both discharged at once,indicating that the discharge spread from one to the other. Moreover,he introduced a piece of celluloid between the two counters and noticed that the discharge still spread, so that he concluded that the spread was caused by photoelectric activity. This photoelectric action has been investigated by numerous other investigators.[13][14][15] Later work will be discussed in the portion of this work on the photoelectric properties of cathodes.

1.07 Investigation of the Gas

Probably the most important of the three primary elements is the gas. Geiger and Muller[8] tried argon, air, hydrogen, and carbon dioxide. Many other gases also work. Curtiss[10] showed that the gases H_2S, SO_2, and H_2O, stopped the action of a counter if admitted with other gases. He believed that the adsorption of oxygen on the wire was necessary and that these gases changed the adsorptive properties. This point of view has had no verification. Werner[16] investigated gaseous discharge phenomena in G-M counters.

As will be seen later, numerous properties of the gas are important. Ionization potential, mobilities, ability to capture electrons, all play important roles.

1.08 Neher-Harper Circuit

Although, in general, the properties of the circuits used with counters will not be considered, it is altogether fitting, in fact necessary, to mention the Neher-Harper circuit developed by H. V. Neher and W. W. Harper in 1935 and reported[7] in 1936. In the author's opinion, next to the actual discovery of the G-M counter, it is the most important step in the development of the G-M counter as a laboratory instrument. It is of importance for two reasons. First, it enables one to lower the series resistance in the fundamental circuit and thus lower the RC time constant. The resistance may be lowered to 10^5 or 10^6 ohms. Second, G-M counters which have very poor behavior in the fundamental circuit operate reasonably well in a Neher-Harper circuit.

In principle the Neher-Harper circuit is very simple. A vacuum tube is placed in the fundamental circuit, across the G-M counter, with the plate connected to the wire and the grid to the cylinder. This vacuum tube is biased to cut off by a grid battery and a grid resistance. When there is a spurt of ionization in the G-M counter, there is a flow of positive charges onto the grid of the tube so that it becomes conducting. This, in effect, shorts the G-M counter out of the circuit so that it has a chance to clear of ions, there being still some voltage drop across it. When the positive charge has leaked off the grid, the tube again is cut off and the high voltage returns to the G-M counter. It is obvious that counters, which tended to go into continuous discharge when an ionizing particle started the flow of current, would be quenched. The pulse may be made considerably shorter than in the fundamental circuit for now the important time constant is the RC constant of the vacuum tube grid. Other circuits have been devised on the same principle. The Neher-Pickering circuit[17)] performs the same operation but avoids putting the high voltage across the vacuum tube, although, practically speaking, there hasn't been too much trouble over that point.

1.09 Fast or Self-Quenching G-M Counters

Sections 1.01 to 1.08 complete the historical introduction of what will be termed slow counters throughout the remainder of this thesis. That the name slow counter,as distinguished from a fast,or self-quenching, counter,is somewhat of a misnomer will be pointed out later. In numerous laboratories around 1935 and 1936 it was discovered that,if alcohol vapor or some other organic vapor is added to the gas in the G-M counter, entirely different properties result. A. Trost[18)] reported on such a counter in 1935. In 1937 he published[19)] an encyclopedic work on this new type G-M counter. This last work is perhaps the most complete experimental investigation of the fast,or self quenching,type counter.

One of the most obvious points in which the fast counter is superior to the slow is that the fast counter may be used in the fundamental circuit with a low resistance without need of the Neher-Harper vacuum tube to quench the pulses. Thus the name self-quenching arises. Another point in favor of the fast counter is that,in general,the plateau in length and flatness is superior to a slow counter. One disadvantage is that many fast counters seem to have a definite counting life. By counting life is meant the total number of counts that a counter will be sensitive to,without going into continuous discharge. In high altitude cosmic ray work and in radioactivity measurements or nuclear physics, where there are high counting rates, this counting life is of great importance.

Since the work of this thesis deals with the discharge mechanism of G-M counters with the object of distinguishing between the action of fast and slow counters, not a great deal about fast counter properties will be mentioned in this introduction.

Chapter 2

Comparison of General Properties of Slow and Fast Counters

2.01 Use of Oscilloscope

Beyond all doubt, an oscilloscope study of the individual pulse shapes of a G-M counter constitutes the most effective means of determining the type and quality of the particular counter. In Chapter 1 the first difference between fast and slow counters was pointed out; namely, the fast counters would function in the fundamental circuit with a considerably lower resistance. In the following sections of this chapter some other differences will be shown. In order to eliminate circuit characteristics as much as possible, oscilloscope studies are made using the fundamental circuit only. Figure 1.02 indicates that the oscilloscope vertical plates are connected across the resistance in the fundamental circuit. Since most commercial oscilloscopes have a resistance of the order of 10^6 ohms across the vertical plates, it is necessary to replace this resistance by a higher one if any experiments with slow counters are made, since the slow counter will not extinguish but go into a continuous discharge with a low resistance. In most of the studies made for this thesis an R.C.A. 155 oscilloscope was used with a switching arrangement which would put either 10^6 or 10^9 ohms across the vertical plates. With the oscilloscope connected as already mentioned and with a linear sweep on the horizontal, the characteristic pulse forms are obtained.

2.02 Slow Counter Voltage Pulse Form

When the experiment of 2.01 is performed with a slow counter, Figures 2.02 a, b, and c, give typical single pulse forms. When the count is initiated, the negative charge builds up on the wire and the IR drop across the resistance causes the voltage across the counter to drop. The current stops building up in the counter when the voltage on the wire has dropped to V_t, at which the counter voltage has dropped to threshold. It is extremely important to note that for a slow counter the voltage drops at least to threshold for every count. When the cumulative ionization in the counter stops, the counter voltage returns to V_o by a leaking off of the charge from the wire through the resistance. The tails of the curves shown are the exponential RC recharging curves.

Rather common for a slow counter is the pulse form shown in Figure 2.02 b. In this case the breakdown portion of the curve is the same as in Figure 2.02 a, but instead of recharging as soon as V_t is reached, the discharge in the counter continues for a time. The length of time of the flat portion varies considerably, occasionally lasting for as long as a second. Figure 2.02 c shows a counter which starts to return to counting voltage but breaks down into another pulse before it returns fully. In general, a good slow counter puts out pulses of form 2.02 a; form 2.02 b and c become more numerous as the quality of the counter gets worse. The worst of slow counters, which will still work in a Neher-Harper circuit, has in general a pulse of form 2.02 b with a very long flat portion.

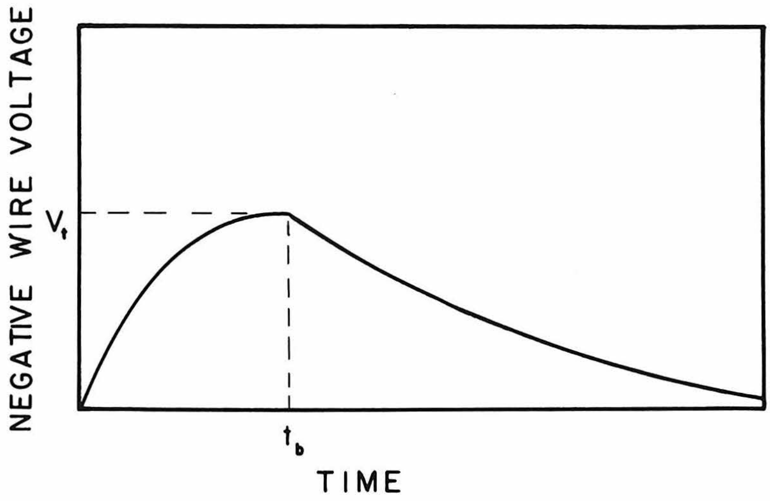


FIG. 2.02 a

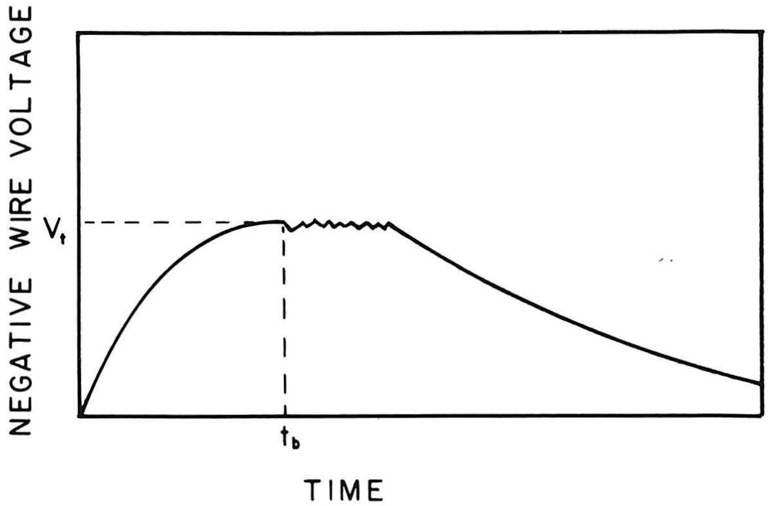


FIG. 2.02 b

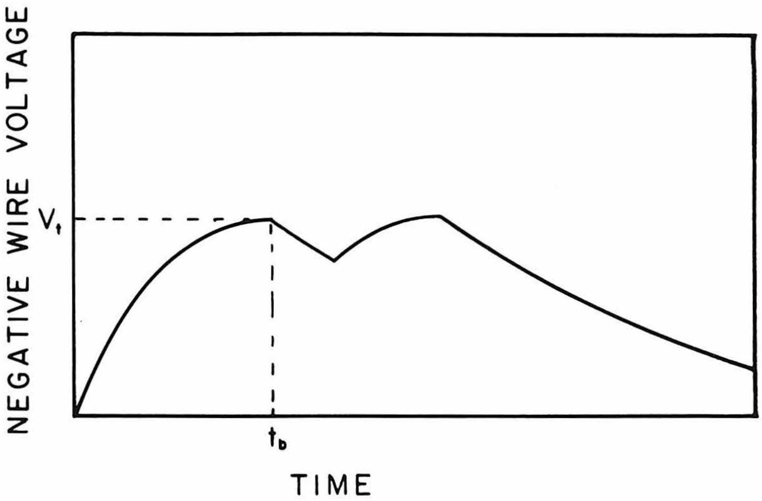


FIG. 2.02 c

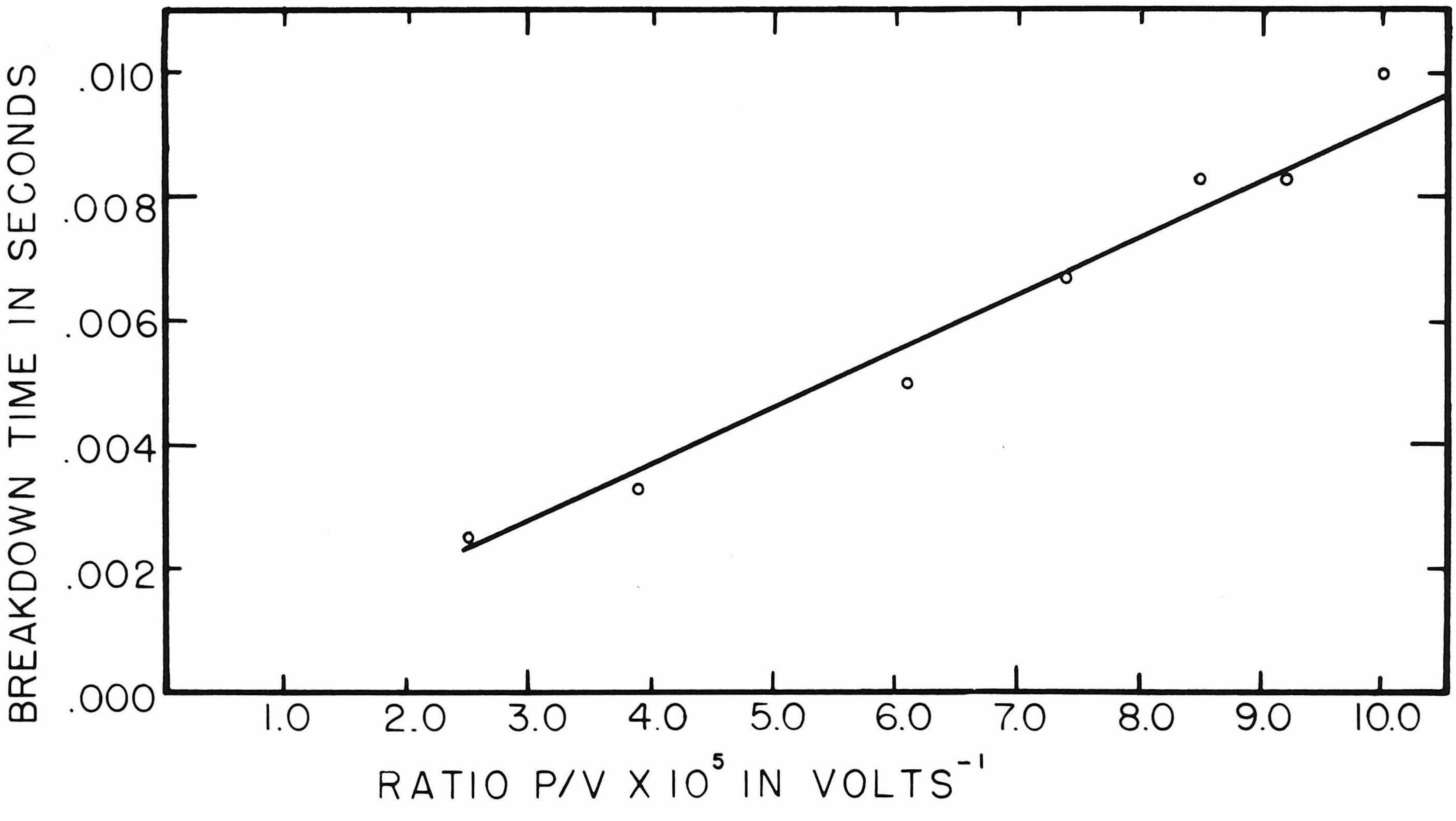

BREAKDOWN TIME IN SECONDS
.010
.008
.006
.004
.002
.000
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
10.0
RATIO P/V X 10^5 IN VOLTS^-1

FIG. 2.02d

Of particular interest in the analysis of the pulse form is the time of breakdown, t_b, which is the time required for the potential to drop to V_t. For a show counter this time is around 10^{-3} secs to 10^{-2} secs. This is, of course, when used in the fundamental circuit. If used in a Neher Harper circuit the current flow is quenched in a shorter time. In Chapter 4 of this work it will be shown that the time for positive ions to migrate from the wire, in the region of which they are formed, to the cylinder is given very approximately by

$$t = \frac{\mathrm{Ln}\,\frac{b}{a}\, b^2\, p}{2\, K\, V_o}\,. \qquad (1)$$

b and a are the radii of the cylinder and wire respectively, p is the ratio of the pressure of the gas to normal pressure, K is the mobility constant, and V_o is the operating voltage. The assumption involved in (1) will be discussed later. From (1) the constant a in

$$t = a\,\frac{p}{V_o} \qquad (2)$$

is 5.3 for a counter with 1.4 cm cylinder and .0075 cm wire with 50% argon and 50% air which gives a mobility of 1.8 cm/sec/volt/cm. This counter was used in an experiment in which the pressure and voltage were varied and the time of breakdown t_b was measured on an oscilloscope. Figure 2.02 d gives a plot of t_b against the ratio p/V_o. The slope is .9 x 10^2 from the figure. This clearly indicates that the positive ion current figures markedly in the breakdown of a slow counter since the breakdown lasts about 18 times as long as it takes for a positive ion to migrate from the wire to the cylinder.

In the light of the above experiment it is possible to see what is necessary for the extinguishing of a slow counter pulse. As space charge is formed by cumulative ionization around the wire, there is no possibility of this space charge increasing the field since the positive ions flow toward the cylinder and the negatives onto the wire. Hence, as the cumulative ionization continues, the field around the wire drops. It drops until it is too low for cumulative ionization at which time the voltage across the counter has dropped to threshold. Although cumulative ionization has stopped, by no means is the counter clear of ions for from the analysis of Figure 2.02 d there must be positive ions throughout the volume. When the cumulative ionization stops, the voltage across the counter starts to return to working voltage. If no electrons are in the counter and if no electrons are produced photoelectrically the discharge stops completely. If, however, there are electrons present or produced, the discharge will be started again before the voltage can return and a pulse of form 2.02 b or c will result. The whole subject of photoelectric action will be investigated in Chapter 3.

2.03 Fast Counter Voltage Pulse Form

If the simple experiment of 2.01 is performed with a fast counter in the fundamental circuit -- and hence a lower resistance -- the pulse form shown in Figure 2.03 a is obtained. Even if the resistance were high, the fast counter pulse would differ from that of the slow counter in the shape of the breakdown. For a fast counter the breakdown time t_b is 10^{-5} seconds or faster. Moreover, the voltage V_m to which the wire drops does not have to be so large that the counter voltage drops to threshold. The fact that the pulse is extinguished in a fast counter without the voltage across the counter dropping to threshold is one of the most important characteristics of fast counters.

In 1.09 the fact was mentioned that the fast, or self quenching, counter could be used in the fundamental circuit with a low resistance. A good fast counter has been operated with as low as 100 ohms in the circuit. In this case a high capacity condenser was put across the high voltage supply to eliminate the effect of the series resistance of the power supply. Of course with such a low resistance in series the voltage pulse was extremely small, too small to be used with a practical recording system. But the fact that the fast counter extinguishes its pulses indicates that the extinguishing action is entirely independent of the resistance in the circuit. If the resistance is completely shorted out, the fast counter doesn't break down into a continuous discharge whereas a slow counter does. Moreover, the plateau of a fast counter doesn't change with resistance.
If a fast counter has the voltage raised above the maximum operating voltage on the plateau, the discharge is not continuous but sporadic, indicating that even then there is an attempt by the counter to extinguish. Proof of this statement and a discussion will be given in a later chapter.

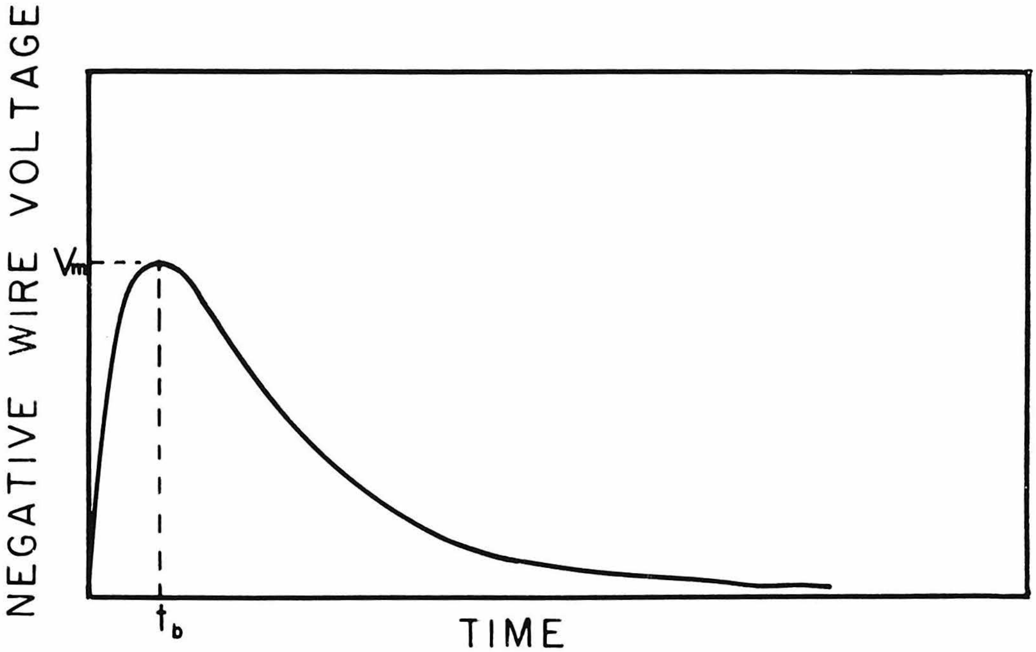


FIG. 2.03a

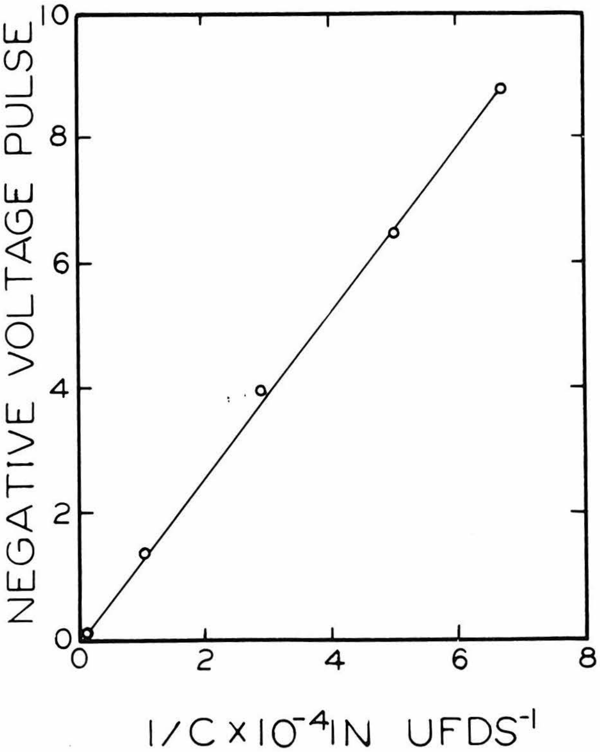


FIG. 2.03b

Another simple experiment, using the fundamental circuit, proving the independence of the internal quenching action was performed. The high voltage supply in the fundamental circuit is replaced by a condenser which has an extremely low leakage loss. If enough commercial paper condensers around .01 μfd are tried, one might be found with a suitable low leakage. These need be new condensers. If none are found satisfactory, a low leakage condenser may be made by evaporating[20] metal onto a thin sheet of mica. The mica is rolled and slipped into a glass tube which is then pumped out in order to dry it. The tube is then filled with dry argon and sealed off. If there remains any electrical leakage, it is in general on the outside of the glass between the two metal leads sealed through the glass. By cleaning the glass with xylol and applying some ceresin wax, this leakage is reduced. The same treatment to prevent leakage on the glass of the G-M counter in the fundamental circuit should be given. The oscilloscope is eliminated from the circuit. Across the condenser, which is charged to the operating voltage of the counter, an electrostatic voltmeter is connected. In this particular experiment the electrostatic voltmeter had a Neher torsion electroscope suspension.[4] Such an electrostatic voltmeter is an extremely valuable piece of laboratory equipment. It has a very convenient voltage sensitivity of about a volt per division, a voltage range of about 800 to 3000 volts and very reproducible readings.

With such an experimental set up it is possible to measure the total charge which flows in a particular count of the G-M counter. This is done by measuring a small drop in voltage, ΔV, which takes place in the time t. Knowing the capacity C and the counting rate s of the counter, measured beforehand, the average charge in a single pulse may be calculated by

$$q = \frac{C\Delta V}{st} . \qquad (1)$$

Although this is the average charge in a count, it is assumed that the deviation from the average charge is negligible. This is born out by the identical nature of the pulses from a fast counter as seen with an oscilloscope. ΔV is kept small in comparison with the overvoltage, or voltage above threshold. Table 2.03 a, b, show the results obtained in this experiment. The charge in a single pulse is given in coulombs in Table 2.03 a and in number of electrons in Table 2.03 b. The counter used was 6 inches long by 1.13 inches radius with a threshold voltage close to 1200 volts. Note that the charge is practically independent of the external resistance. Readings at 1300 volts show that very well. The variation with voltage is also illustrated and it is seen that the charge in a single pulse varies almost linearly with overvoltage. Further proof and use of this fact will be given in Chapter 5. For the higher resistance at 1450 volts the charge is a little higher than at the other resistances. Since 1450 volts is at the extreme top end of the plateau for the counter, the readings in general at 1450 volts might be high due to either nachentladung, spontanentladung, or both. These two phenomena are spurious discharges which will be described in 2.04.

Table 2.03 a

Charge in coulombs

Volts	10^9 ohms	10^6 ohms	10^4 ohms
1450	6×10^{-9}	4×10^{-9}	3.7×10^{-9}
1375		2.8×10^{-9}	
1300	1.6×10^{-9}	1.5×10^{-9}	1.6×10^{-9}
1275		0.9×10^{-9}	

Table 2.03 b

Charge in number of electrons

Volts	10^9 ohms	10^6 ohms	10^4 ohms
1450	3.7×10^{10}	2.5×10^{10}	2.3×10^{10}
1375		1.8×10^{10}	
1300	1.0×10^{10}	$.94 \times 10^{10}$	1.0×10^{10}
1275		$.56 \times 10^{10}$	

Still a third experiment to show that the internal action is independent of the external circuit was performed, again using the fundamental circuit. In this particular experiment a variable condenser or a switching arrangement to change the size of the condenser is put across the resistance in the fundamental circuit. Also it is important to have a condenser across the high voltage supply so that, with respect to the small current which flows in a single counter pulse, there is zero resistance associated with the high voltage supply. With that experimental arrangement the static and dynamic characteristics must be analysed. The static characteristic, which is that prevailing when no count is being registered or has been registered for a time equal to the recovery time of the counter, is very simple. Then the high voltage is entirely across the G-M counter. The dynamic characteristics come into play when an ionizing particle trips the G-M counter. There is cumulative ionization around the wire. The negative ions and electrons flow onto the wire, charged positively, while the positive ions migrate toward the cylinder. The negative charge would be held on the wire by the positive charge in the gas except that the positive charge induces an equal negative charge on the cylinder, this charge flowing from the condenser which is across the high voltage supply. This leaves the negative charge on the wire free to charge up the capacity to ground of the wire system. Of course this capacity includes that of the condenser across the resistance, the wire, and leads, and also the input-to-ground capacity of the oscilloscope. Immediately the charge leaks off through the resistance R with the RC time constant.

With this analysis in mind the function of the counter may be thought of as that of furnishing a negative charge onto the wire. In this whole section it has been assumed that the internal action of the counter was independent of the external circuit constants, so let the hypothesis be made that the charge put on the wire is a function of time only. This charge flows from $t = 0$ to $t = t_b$ and then stops. Include in the hypothesis that the capacity of the wire system is sufficiently large that the voltage across the counter is not greatly changed. In other words, the voltage pulse as measured by the oscilloscope is but a small fraction of the over voltage. Then, when a pulse starts, the charge furnished to the wire is

$$q_f = f(t) \qquad t = 0 \text{ to } t = t_b \tag{2}$$

where $f(t)$ is an unknown function of t only. Immediately the charge begins to leak off at a rate given by

$$\frac{dq}{dt} = -\frac{q}{RC} \tag{3}$$

Let the RC time constant be large compared with t_b which is the time of breakdown. Then the charge on the wire at t_b is

$$q = \int_0^{t_b} f(t)\,dt \tag{4}$$

and the minimum voltage -- minimum since the charge is negative -- on the wire is

$$V_m = \frac{1}{C}\int_0^{t_b} f(t)\ dt \qquad (5)$$

The following experiment was performed. Both R and C were varied such that the product RC remained constant. The RC product was 10^{-3} seconds whereas the breakdown time was 10^{-5} seconds or faster so the one condition was satisfied. The capacity was sufficiently large so that the highest maximum voltage pulse was 10 volts whereas the counter was operated at 1450 volts, 250 volts above threshold. All the postulates of the above theory were satisfied so that, if V is plotted against 1/C, a straight line is expected. Figure 2.03 b gives the results of the experiment. The straight line indicates that the hypothesis of the independence of the internal charging mechanism is correct.

2.04 Spontanentladung and Nachentladung

In section 2.03 the two terms, spontanentladung and nachentladung, were mentioned. These terms were introduced by Trost(19) in order to clarify the nomenclature. Spontanentladung, or spontaneous discharge, is a discharge which occurs occasionally in which the pulse size is much greater than the regular pulse. Trost investigated the occurence of these as a function of gas pressure, treatment of cathode, etc. One interested in such a phenomenon should consult either of Trost's two papers(18),(19) on the discharge phenomenon, in which he has an extended oscillograph study of pulse shapes. This author admits the phenomenon is not well understood but in his experience well constructed and cleaned counters, carefully filled, do not in general put out spontanentladung. Other authors have concluded that it is associated with the storing up of charge on non-conducting greases or other impurities on the cylinder or glass walls. It is an experimental fact that, in counters in which it occurs, the frequency of occurrence increases with voltage above threshold.

Nachentladung also has a descriptive name, for it is applied to discharges which occur directly after a normal discharge. Figure 2.02 c gives a picture of nachentladung for a slow counter. For a fast counter the phenomenon is somewhat similar. Again, good fast counters do not have nachentladung. The frequency of occurrence increases with voltage above threshold just as for spontanentladung.

In the study of the individual characteristics of a particular counter, the usefulness of an oscilloscope is illustrated by the following experience. A 6" by 1 1/8" counter with a copper tube sealed in glass was cleaned with nitric acid and rinsed well. The surface of the copper was given a deep velvety black coat by heating the counter when it was filled with NO_2 gas. With the NO_2 removed the counter was sealed off with 5 cm of Hg pressure of argon-xylol mixture -- xylol 10%. When tested in a recording circuit this counter showed a reasonably flat plateau from 1200 volts to 2300 volts. This was a phenomonally long plateau. Then the shape of the pulses was examined with an oscilloscope to find that the pulses were regular only from 1200 volts to 1800 volts, whereas from 1800 volts to 2300 volts they were given to nachentladung. A recording circuit with a higher resolving time would have recorded many of the nachentladung.

2.05 Shape of Breakdown Curve

Although the work herein reported is not the work of the author, it is best for continuity and completeness to mention an experiment conducted by W. E. Ramsey[21] on the shape of the breakdown curve. This is the only work to analyse the breakdown portion of the curve. Ramsey devised an ingenious circuit which, in principal, began to charge up a condenser at a known rate when the pulse from the G-M counter started. When a predetermined voltage was reached by the wire, the circuit stopped charging the condenser so that by a measurement of the charge on the condenser the time which the wire required to reach the predetermined voltage was calculated. By a series of such measurements the time dependence of the voltage was plotted. Ramsey found that the shape of the curves found for both argon-oxygen and argon-alcohol counters was given quite well by the formula

$$V = -k \log_{10} \left(\frac{t}{t_0} + 1\right)$$

where k and t_0 are constants of the counter and circuit.

There are several points to note about Ramsey's work. The wire capacities which Ramsey used were considerably smaller than those used in the experiment illustrated by Figure 2.03 b. Consequently the voltage drops were greater. Ramsey used a high resistance in series with his counters. The experimental work of Ramsey seems very good although the author disagrees with the theory which was presented to explain Ramsey's results by C. G. and D. D. Montgomery in an accompanying paper.[22] That theory will be discussed in Chapter 4.

Chapter 3

Photoelectric Properties of the Cathode

3.01 The Photoelectric Problem

Throughout Chapter 2 numerous experiments were described to show the differences in the action of fast and slow counters. In order to determine the mechanism of fast counter discharge, it is logical to discover which properties of a particular counter are changed by a treatment sufficient to make a fast counter. In 1.06 some indication was given that there were several treatments of the cylinder metal, which would make the cylinders sufficiently good for counter action. For copper cathodes, which were used for the most part throughout this investigation, H. V. Neher[4] has given a treatment which will produce fast counters. He stated that the various steps, nine in all, were sufficient although perhaps not necessary for fast counter production. Through this investigation the number of steps, sufficient, have been reduced to the following:

1. Starting with a copper-in-glass counter, clean the copper with concentrated nitric acid (6 to 16 normal).
2. Rinse well, first with tap water and then with distilled water. Dry.
3. Evacuate and admit dry NO_2 gas and heat the counter till the copper cylinder obtains a velvety black surface. Pump out NO_2.
4. Admit argon-organic vapor mixture -- 5% to 10% vapor. Petroleum ether, alcohol, xylol, etc. are suitable vapors.

For the various techniques one is referred to H. V. Neher.[4] A simple way of making NO_2 gas is by heating $Pb(NO_3)_2$ till it decomposes into PbO and $2NO_2$. Care is taken that there be no reducing agents such as rubber in the system. The NO_2 is condensed by an alcohol-dry ice mixture at a few degrees below zero centigrade. If the condensed liquid is green instead of brown, there are NO and other nitrogen oxides present. These can be oxidized to NO_2 by running oxygen into the system before condensation.

In 1.06 references to the importance of photoelectric processes in G-M counter discharge were made. The investigation of the change in photoelectric properties of the cathode by the various steps in the treatment producing fast counters might throw light onto the discharge mechanism. If the large ionization which takes place in a single pulse is considered, a very great number of photons must also be given off. As illustrated in Table 2.03, there are of the order of 10^{10} ion pairs produced in a single discharge. Not all collisions in the avalanche of electrons toward the wire will fully ionize the gas atoms. Some molecules will merely be excited. Moreover, some ions produced will recombine. Hence, photons of energy ranging up to the ionization potential of the gas atoms are expected. Loeb[23] has analysed photoelectric action in G-M counters by a study of various experimental results obtained by other authors. He pointed out that various estimates of photoelectric efficiency on counter cylinders have given 10^3 or 10^4 photons needed to produce one electron. His discussion is, to a large part, qualitative.

There exist several mechanisms by which electrons may be produced after the first avalanche of negative ions and electrons toward, and in the neighborhood of, the wire. The most obvious way is by photoelectric emission from the cathode, produced by photons either from excited atoms or from a recombination of ions formed in the neighborhood of the wire. Positive ions migrate toward the wall and upon collision with the wall knock electrons out. Another source of electrons is by diffusion to, and collision with, the cylinder by an atom in a metastable state. Oliphant[24] has estimated that this process is a more efficient electron producer than is positive ion collision. Still another mechanism exists if there is a mixture of gases in the counter, say A and B. If a metastable state of A is higher than the ionization potential of B, atom A in a metastable state may ionize atom B on collision. There also exists the possibility of photoelectric action in the gas.

The time of occurrence of electron emission is of considerable importance in the analysis of G-M counter discharge mechanism. It is seen that electrons produced by photons would be produced early in the discharge when the ionization and excitation was taking place. Electrons produced by positive ions colliding with the cylinder walls would come later when the positive ions had time to migrate to the cylinder. Electrons produced by pilfering collisions with either the cylinder walls or the gas molecules would decrease in number with time. More will be said about this in a later chapter.

3.02 Apparatus and Experimental Set-up

The type counter used in the photoelectric experiments was a photon counter described by H. V. Neher.[4] The important feature of this type counter was the quartz window waxed on the end, through which ultraviolet light could be directed. These photon counters are very useful as detectors for weak ultraviolet radiation.

The source of ultraviolet light was a low-pressure, quartz mercury arc. Strong[20] describes such an arc. Although he makes the statement that the ultraviolet spectrum from such an arc extends down to about 2000 Å, there is sufficient intensity at the 1849 Å and 1942 Å lines of Hg to make readings. The intensities as detected by a photon counter do not have to be as large as those needed for photographic recording. The intensities of these lines are low compared with those of longer wavelength, for both quartz and air absorb quite strongly of the radiation below 2000 Å.

Strong[20] also mentions the necessity of using a double monochromator or two single monochromators in order to sufficiently monochromatize the radiation. By the use of two monochromators, the scattered light which gets through one monochromator is eliminated. That two monochromators were needed was well illustrated by an experiment on a photon counter. The photon counter was sensitive to radiation coming through one monochromator when the monochromator was set on radiation in the visible, but if a piece of glass were inserted in the light beam to cut out ultraviolet the sensitivity stopped. This illustrated the fact that there was scattered ultraviolet from the single monochromator. The monochromators used were Hilger monochromators, described by Strong.[4]

In the experiments to be described the radiation from the second monochromator was directed through the quartz window on the counter onto the inside surface of the metal cylinder. Of course the light had to pass through the gas and it also illuminated the wire. This last point is important in a later portion of the thesis.

3.03 Photoelectric Properties of Copper Cathode Counters

In 3.01, in the treatment described for producing fast counters, the NO_2 treatment and the addition of organic vapor to the gas filling seem to be the important steps which convert a slow counter to a fast counter. It is possible to determine how these two steps effect the photoelectric properties of a copper cathode counter by performing the experiment of 3.02. This was done.

A copper counter 4" x 1" was cleaned and dried. Argon-air mixture (equal amounts) was let into the counter, producing a slow counter, which functioned in the Neher Harper circuit or in the fundamental circuit with a high resistance, with a counting threshold voltage at 1500 volts. The photoelectric experiment was performed at 1700 volts. Table 3.03 a tabulates the results, giving the number of counts per five minute interval for different wavelengths illuminating the cathode. The quartz window was shielded from the radiation in order to get the normal background counting rate. Cases where "stalled" is recorded are those in which the counting rate was so rapid that the resolving time of the mechanical recorder was too long to record the individual counts. In those cases there were several thousands of counts. The results show the counter very sensitive to the 2536 Å line and sensitive to 2652 Å but not sensitive above that. The photoelectric threshold was around 2700 Å.

The same counter was given the NO_2 treatment and again filled with argon air mixture producing again a slow counter with a voltage threshold of 1500 volts. It was operated at 1700 volts. Table 3.03 b gives the results for this case. In this case the counter was slightly sensitive to 1942 Å and more so to 1849 Å. This particular experiment was performed with two monochromators down to 2225 Å and one from there down. This leaves the possibility that the sensitivity recorded at 1942 Å was scattered 1849 Å radiation. It wouldn't be scattered longer wavelength radiation for the counter was not sensitive to that, as proven with two monochromators. Also it wouldn't be much shorter than 1849 Å because absorption by air and quartz is already cutting the intensity down greatly. The 1849 Å sensitivity was definitely 1849 Å radiation for, as the wavelength was varied about 1849 Å, a sharp maximum was detected. Hence, the NO_2 treatment had shifted the photoelectric threshold from 2700 Å to about 1900 Å.

The gas in the counter was then changed to argon-petroleum ether mixture -- 10% petroleum ether -- to a pressure of 6 cm. The counter was then a good fast counter. Table 3.03 c gives the photoelectric data for this counter showing that there is little change from the results in 3.03 b.

The whole experiment was then carried through on the same counter, again yielding the same results. Numerous other experiments on copper cathode counters yielded nothing different. The copper counters were very consistent in their photoelectric action.

Neher[4] mentions that it is possible to make a fast counter without the NO_2 treatment although other properties of the counter are not very good. This was done with the above counter. Its photoelectric properties were, as expected, similar to those given in Table 3.03 a. This counter gave many nachentladung. This is an indication that nachentladung occur in fast counters when the photoelectric threshold potential is low and the photoelectric efficiency high. It is a fact that the author and other workers in this laboratory do not experience numerous fast counters suffering from the malady of nachentladung. The fast counters used here are all given the NO_2 treatment yielding a low photoelectric sensitivity. One point of technique is worth mentioning. The importance of removing all the free NO_2 after the NO_2 treatment was shown by an experiment in which about one cm of NO_2 was left in the counter. The voltage counting threshold was very high and the background counting rate was much too low for the particular size counter. This latter is probably due to electron capture resulting in formation of NO_2^- ion. The negative ions probably do not get enough energy between collision to start cumulative ionization near the wire.

Table 3.03 a

Wavelength (Å)	Counts/5 minutes
Shielded	535 ± 23
2753	497 ± 22
2699	491 ± 22
2652	720 ± 27
2536	Stalled
2400	Stalled
2225	Stalled

Table 3.03 b

Wavelength (Å)	Counts/5 minutes
Shielded	534 ± 23
2225	500 ± 15
1942	635 ± 25
1849	1474 ± 38

Table 3.03 c

Wavelength (Å)	Counts/5 minutes
Shielded	470 ± 15
2225	481 ± 22
1942	885 ± 30
1849	1789 ± 42

3.04 Photoelectric Properties of Aluminum and Brass Cathode Counters

Encouraged by the straightforward reproducible results with copper cathode counters, similar experiments were performed on aluminum and brass counters. Aluminum, because of its low stopping power, is often desirable in counter work in Nuclear Physics. However, compared with copper, it is an erratic performer as the cathode in a G-M counter. It is characterized by a high background counting rate. Often this high counting rate is, in part, due to illumination from the tungsten lights in the room so that in the photoelectric experiments the work was carried out in the dark. Even without illumination the background counting rate is high. Moreover, the plateau is often not flat. An example is that of an aluminum counter with a sensitive voltage range from 1250 to 1500 volts in which the counting rate at the lower voltage was 450 counts per five minutes and at the higher voltage, 1000 counts per five minutes. Aluminum counters are also given to many spurious discharges such as nachentladung.

Table 3.04 gives the results of the photoelectric experiment performed with an aluminum cathode counter.

Table 3.04

Wavelength (Å)	Counts/5 minutes
Shielded	432 ± 21
4046	478 ± 22
3650	3549 ± 60
2536	Stalled

The counter was very sensitive to 3650Å which could easily get through the pyrex glass container since pyrex transmits to about 3300 Å. In this experiment the aluminum had been heated in air. The gas filling was argon and petroleum ether. The same counter, when cleaned with hot concentrated potassium hydroxide and concentrated nitric acid, had a much lower photoelectric emission although it was still sensitive to room lights. NO_2 treatment did not change the photoelectric properties of aluminum materially.

Brass counters were investigated photoelectrically, leading to results quite similar to those for copper counters. The NO_2 treatment had the same effect of increasing the work function. In general, brass was sensitive to slightly longer wavelengths than the copper.

Experience which supports the postulated reasons for spontanentladung was gained in these experiments. In 2.04 the statement was made that some observers believed spontanentladung to be small discharges from nonconducting grease and other impurities on the glass or cylinder walls. Often, when the oxide coating on the metal cylinder began to peel and flake off, or when there were some foreign particles in the counter as a result of careless cleaning, the counters would give a characteristic spontanentladung. For a while the counter would produce normal pulses but the number of nachentladung and irregular pulses would increase until there would occur a very large pulse on the oscilloscope, indicating some discharge in the tube. After the large discharge the pulses would be normal for a time and the whole process would repeat. This action suggests the slow charging up of the non-conducting greases till some form of discharge neutralizes their charges.

3.05 Conclusions from Photoelectric Experiments

Throughout this work the lowering of photoelectric emission by raising the work function of the cathode by the NO_2 treatment consistently improved the action of the counters. However, the presence of organic vapor proved to be the sine qua non for the characteristic self-extinguishing fast counter action. The presence of organic vapor did not materially effect the work function. From this evidence, one concludes that the action of the organic vapor concerns itself with gas discharge properties of the counter, rather than surface phenomena. Other experiments must be brought to bear on the problem of fast counter discharge.

Chapter 4

The Discharge Mechanism from the Deadtime Theory

4.01 The Deadtime Phenomenon

The phenomenon of the deadtime of a Geiger-Muller counter was found in the course of experiments to measure directly the voltage-time characteristics of the breakdown portion of the pulse. For the purposes of Figure 2.03 a the shape of the breakdown portion was estimated from the random pulses viewed on an oscilloscope screen. As described in 2.05, Ramsey[21] had measured the curve indirectly so a more direct method was sought to check his results. Since the writing speeds, on an oscilloscope screen, encountered in this work were in excess of those which could be photographed, it was not possible to photograph the single pulses. However, use was made of the regularity of size and shape of the pulses from good fast counters -- this fact was emphasized in Chapter 2 -- and an electronic circuit was devised so that many pulses could be superimposed on an oscilloscope screen, thus making the pattern brilliant enough to photograph. A discussion of the experimental procedure will be given in Chapter 6.

Again the fundamental circuit is used. In place of the oscilloscope in Figure 1.02, there is placed an electronic circuit which will be described later. The first important property of this circuit is that it passes all voltage pulses from the fundamental circuit onto the vertical deflecting plates of an oscilloscope. Not only does the circuit perform that function but also it is triggered off by the pulse to give a perfect saw-tooth voltage pulse which is fed onto the horizontal plates. For clarity, a pulse from the counter,which triggers off the circuit,is called a trigger pulse although it has no other properties different from G-M pulses. As a result of the above action the time-voltage characteristics of the single pulse are traced on the oscilloscope screen, provided of course that the circuit is triggered fast enough to start the horizontal sweep coincidentally with the start of the vertical deflection due to the pulse. Still another property of the circuit is that at the end of the horizontal sweep the circuit returns the beam to the original position and is ready for another trigger pulse. Then, with a high counting rate due to a suitably placed radioactive source, the pattern of the pulse will be traced over and over. Due to the high intensity of the many superimposed pulses, the pulse shape can be photographed.

At a high counting rate there will be numerous pulses from the G-M counter which arrive after the circuit has started the horizontal sweep but before it has returned the beam to its original position. These pulses register on the vertical plates but in no way effect the horizontal sweep. These pulses are termed follow-pulses. These follow pulses are expected to occur at random all across the horizontal sweep. Experimentally this is not the case. Figure 4.01 a is a diagram of the actual pattern on the oscilloscope screen. It is seen that the G-M counter is insensitive for a time, t_d, the deadtime of the counter. This deadtime, as measured, is of the order of 10^{-4} seconds. Moreover, when the counter does regain its sensitivity to ionizing particles, it isn't capable of registering a full voltage pulse but regains that ability in the time t_r which is the time from t_d to the appearance of full size pulses. This time t_r is also of the order of 10^{-4} seconds.

The single traces occurring in increasing size from t_d to t_r cannot be photographed. However, Figure 4.01 b is a time exposure taken of the oscilloscope screen showing clearly the integrated effect of the follow pulses as they build up in size from t_d to t_r. Note that the RC time constant of the fundamental circuit is small since the counter is recharged to full voltage in less than 10^{-4} seconds.

It is wise to examine what this deadtime implies as to limits of the use of fast counters. It does not imply that fast counters cannot be used in highly resolving coincidence circuits, for that depends on the speed of breakdown. It does however fix the limit on numbers of particles counted per second since the closest together two pulses may occur is of the order of 10^{-4} seconds.

4.02 Postulated Mechanism of Fast Counter Action

The deadtime phenomenon is of importance because of the conclusive evidence it presents for a postulated discharge mechanism of fast counters. With the experimental evidence of 4.01, and the discussion of Chapter 2, this postulated mechanism must account for: (1) the very rapid breakdown time of 10^{-5} seconds or faster; (2) the deadtime or insensitive time; (3) the building up in pulse size from the deadtime to the recovery time.

Consider again a G-M counter in the fundamental circuit and perhaps, for clarity, consider a condenser in parallel with the resistance. This condenser represents the capacity to ground of the wire, oscilloscope and all leads of the wire system. When an ionizing particle passes through the counter, in order to be detected, it must form at least one ion pair consisting of a positive ion and an electron. The electron, or electrons, formed anywhere within the volume of the counter, are accelerated toward the wire. By some process, which isn't specified yet, the discharge spreads along the wire throughout the entire sensitive length of the counter so that in the neighborhood of the wire along its entire length there is an ion sheath consisting of positive ions, electrons, and probably some negative ions formed by electron capture by neutral atoms. This whole action is assumed to take place in a very short time. Since the ionization took place in the immediate neighborhood of the wire, the electrons and negative ions have but a short distance to be moved by the field before they are collected on the wire. This leaves a positive ion space charge sheath around the wire. Of course, this positive space charge would have moved a short distance toward the cylinder while the negatives were being collected on the wire. By this separation of charge the field between the wire and the positive space charge sheath is so reduced that no more ionization can take place. It is interesting and important to note that

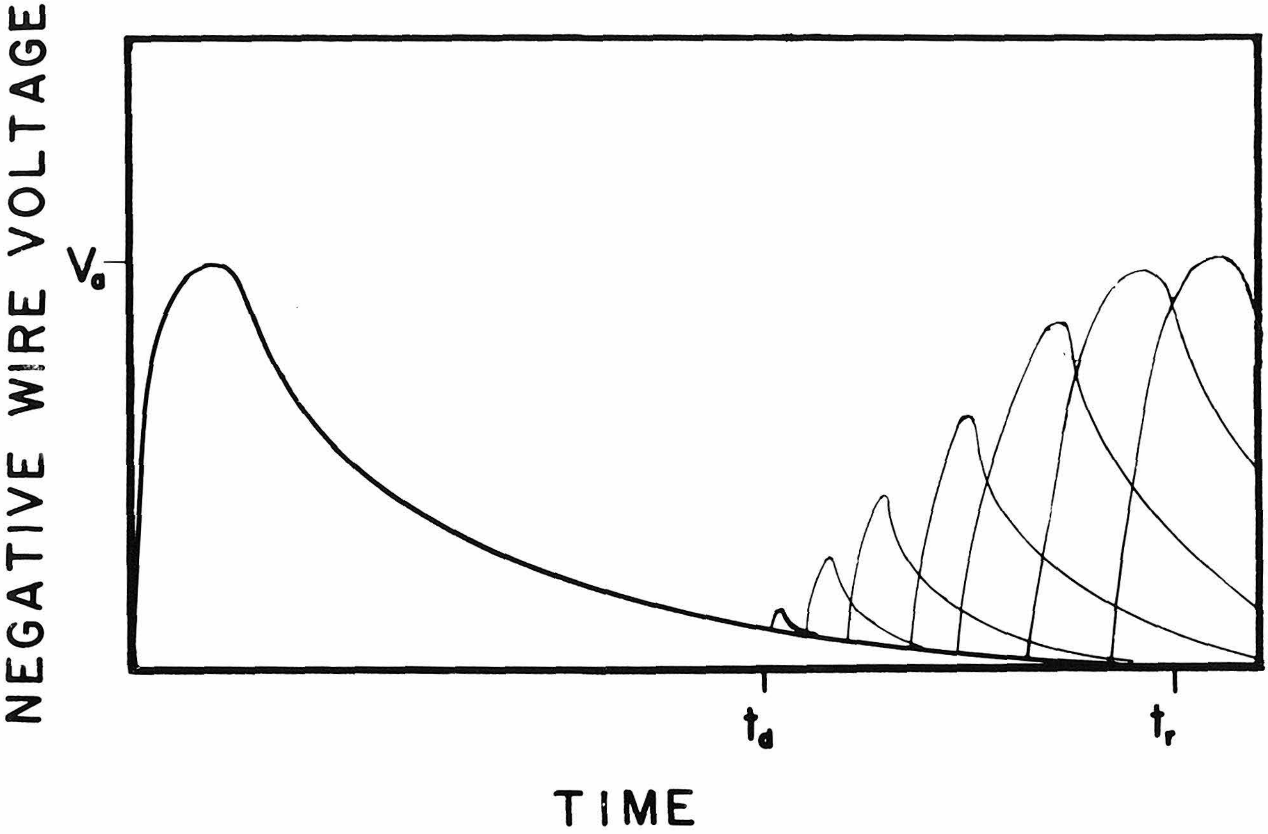


FIG. 4.01a

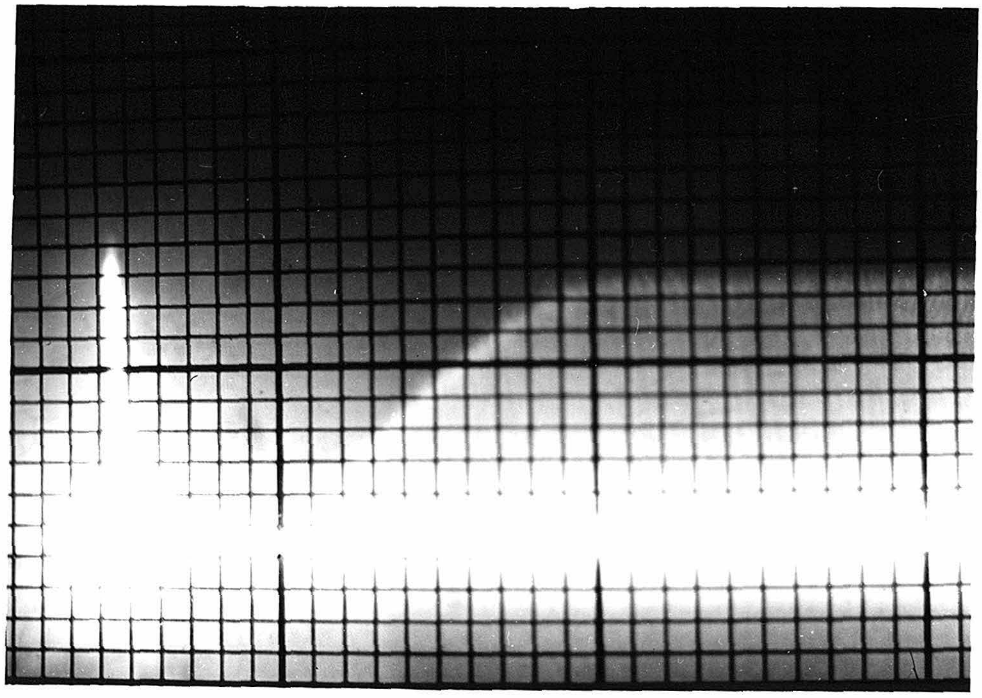


FIG. 4.01b

the charge collected in a single pulse sometimes exceeds that necessary for charging the counter to its operating voltage.

In this analysis the fact that the G-M counter is in the fundamental circuit must not be overlooked. The positive ion sheath immediately induces an equal and opposite charge on the cylinder, this charge being furnished by the high voltage source which is considered to have a condenser across it so that it is of zero resistance with respect to the small current flowing in a single counter pulse. This leaves the negative charge collected on the wire free to charge up the capacity to ground of the wire system, causing a drop in voltage across the resistance. This charge begins to leak off through the resistance to ground. The size of the voltage pulse across the resistance depends on the amount of charge collected, the capacity to ground of the wire system,and the resistance. It may vary, for a fast counter, from a fraction of a volt to several hundred volts. It was shown in Chapter 2 that the amount of charge collected is independent of the circuit constant, depending only on the counter and operating voltage. The fact that the voltage pulse may be as low as a fraction of a volt shows that the potential across the counter does not have to drop to threshold to stop ionization. The positive ion space charge reduces the field below threshold field.

The whole action of the external circuit is to reapply the working voltage across the counter. This may be accomplished in a very short time -- of the order of 10^{-5} -- depending on RC. Superimposed on the current for recharging is the much smaller current which changes the charge on the wire to keep the potential across the counter constant as the positive ion space charge expands cylindrically to the cylinder. The positive charge on the wire increases as the space charge moves out. When the space charge reaches a critical distance R, the field at the wire has just returned to threshold counting field so the counter is again sensitive to particles, although a pulse would be small since the field has not returned to full operating field. As the space charge continues to move out, the field about the wire continues to build up till the space charge reaches the cylinder, at which time the field about the wire has returned to full counting field. The building up of the pulse size is due to the experimental fact that the amount of charge in a given pulse increases with field strength as the field is increased above threshold field.

This theory accounts qualitatively for the observed phenomena. Many observers have postulated the quenching of the ionization by space charge. Some observers[19)25)23)] have credited an insensitive time to the removal of positive ions. All of their methods were indirect and all of their arguments were qualitative, merely indicating that the order of magnitude of the time was that of positive ion migration. It is to be noticed that the formation of a positive ion sheath postulated above is identical with the mechanism postulated by Montgomery and Montgomery.[22)] However, they attribute the drop in potential of the wire to the migration of positive ions to the cylinder, such that the breakdown time, t_b, is reached when the positive ion sheath reaches the cylinder. The migration time for positive ions, obtained from gas ion mobilities, seems to be much too long to have this account for the breakdown time of the order of 10^{-5} seconds.

4.03 Deadtime Theory Developed Electrically

The electrical analysis of the mechanism postulated in 4.02 is to be carried out as a two-dimensional problem, neglecting end effects. Figure 4.03 is a cross sectional diagram showing: the wire, of radius a, with a positive charge, Q per unit length; the positive ion space charge, q per unit length, at a distance r_o from the center; and the cylinder of radius, b, with a negative charge, $-(Q + q)$ per unit length. Assume that there is a potential V across the counter at this time.

The field in region I, between the positive ion space charge and the wire, is

$$E_I = \frac{2Q}{r} \qquad (1)$$

where r is the variable distance. In region II the field is

$$E_{II} = \frac{2(Q + q)}{r} \qquad (2)$$

Since the potential across the counter is V,

$$-V = \int_a^{r_o} E_I \, dr + \int_{r_o}^{b} E_{II} \, dr, \qquad (3)$$

and by (1) and (2)

$$-V = \int_a^{r_o} \frac{2Q}{r} \, dr + \int_{r_o}^{b} \frac{2(Q + q)}{r} \, dr. \qquad (4)$$

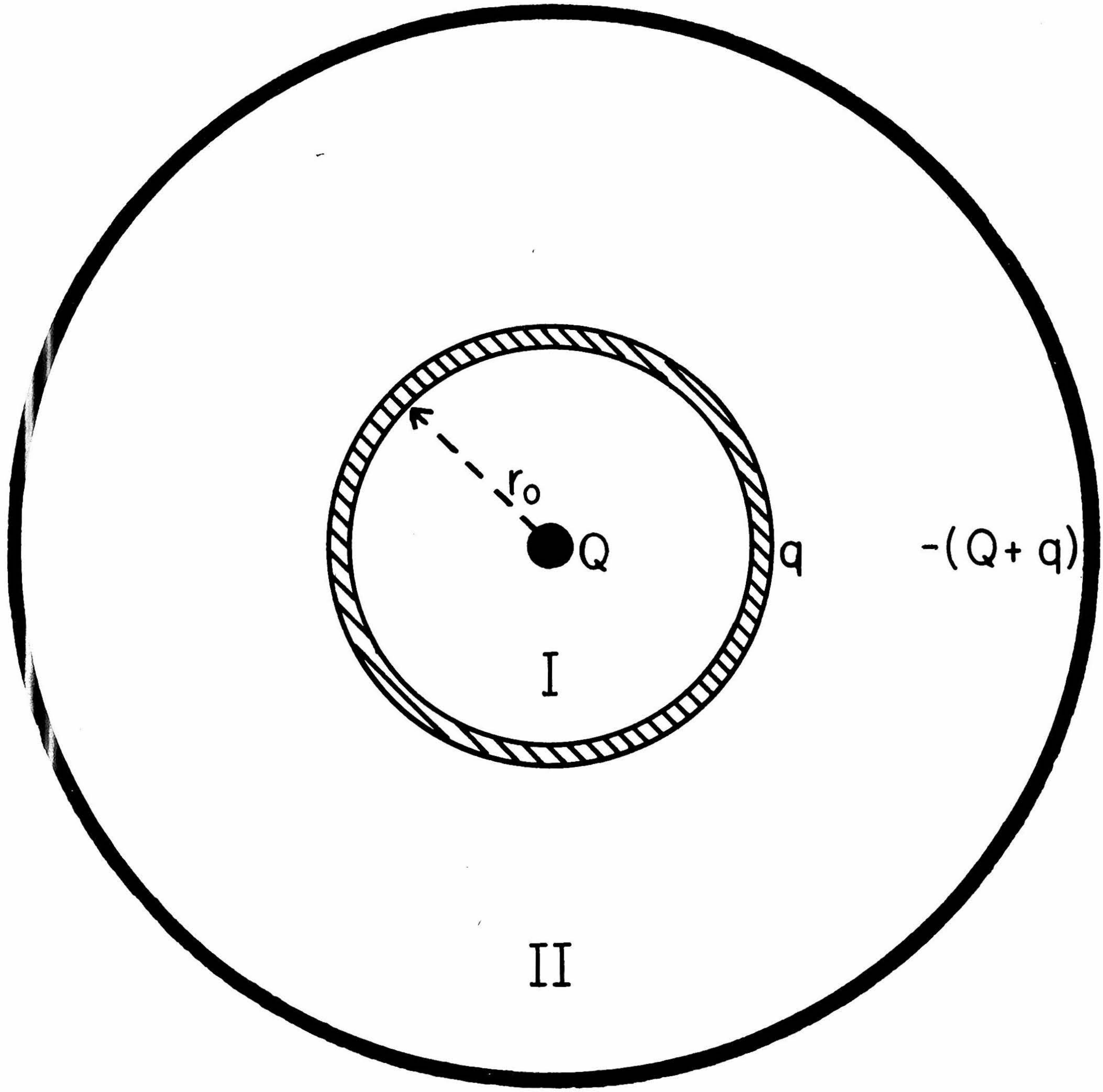


FIG. 4.03

Integrating ,

$$-V = 2Q \operatorname{Ln} \frac{b}{a} + 2q \operatorname{Ln} \frac{b}{r_o} \tag{5}$$

The charge Q which is necessary for a voltage V, with the other conditions as outlined, is

$$Q = \frac{-1}{2 \operatorname{Ln} \frac{b}{a}} \left[V + 2q \operatorname{Ln} \frac{b}{r_o} \right]. \tag{6}$$

The negative integral of E_I across the counter is now defined as an effective voltage. This effective voltage is the apparent voltage across the counter. with reference to counting action, for, when this voltage is above threshold voltage, the counter will count ionizing particles.

$$-V_{\varepsilon} = \int_a^b \frac{2Q}{r} = \frac{-1}{\operatorname{Ln} \frac{b}{a}} \int_a^b \frac{\left[V + 2q \operatorname{Ln} \frac{b}{r_o} \right]}{r} dr. \tag{7}$$

Integrating,

$$V_{\varepsilon} = V + 2q \operatorname{Ln} \frac{b}{r_o} . \tag{8}$$

From the postulated mechanism, when V_{ε} equals the threshold voltage V_t, the counter just begins to count, so that then r_o is the critical distance R. Hence

$$V_t - V = 2q \operatorname{Ln} \frac{b}{R} . \tag{9}$$

Since both V and V_t are high negative voltages, for simplicity, drop the negative sign and consider only the absolute difference. Then

$$R = b\,e^{\frac{-(V - V_t)}{2q}} \tag{10}$$

The critical distance R defining the deadtime is found.

In the experiments to measure deadtime and to check this theory, the wire capacity was relatively high (around 10^{-10} farads), and the resistance relatively low (around 10^5 ohms), so that the voltage pulses were small and the RC recharging time short. Then, throughout the entire pulse, V varied very little from V_o. To a very good approximation

$$R = b\,e^{\frac{-(V_o - V_t)}{2q}} \tag{11}$$

The quantity, $V_o - V_t$, is now termed the overvoltage, or the voltage above threshold at which the counter is operated. Hence, for the experiments to check the theory

$$R = b\,e^{\frac{-V_u}{q}} \tag{12}$$

4.04 Ion Mobilities

The experiment described in 4.01 furnishes a method to measure t_d the deadtime, and t_r the recovery time, directly. In order to check the theory developed in 4.03, an expression for either t_d or t_r in terms of R and other constants of the counter is needed. For this, an understanding of gas ion mobilities is necessary. Loeb[23) 26)] discusses the subject both from a theoretical and experimental point of view. Due to the great complexity of the field of gas ion mobilities, it is possible for the purposes of this work to examine only those factors directly affecting the ion mobilities in a G-M counter.

The mobility constant is the ratio of the velocity of the ion in question to the field strength;

$$k = \frac{dr}{dt} \Big/ E \tag{1}$$

usually expressed in cm/sec/volt/cm. Theoretically, the mobility constant should vary inversely as the number of molecules per unit volume, as measured by the pressure. Loeb[23] states that this law has been verified for pressures from 0.1 mm to 60 atmospheres so that in the G-M counter work, with pressures ranging from several millimeters to 25 or 30 cms, the law will hold.

$$k = K \frac{p}{p_0} \tag{2}$$

where K is the mobility at atmospheric pressure, and p/p_0 is the ratio of the pressure in the G-M counter to normal pressure. The slight temperature dependence of the mobility constant plays no role in the counter experiments for these experiments are carried out at room temperature where most mobility measurements are made.

In self quenching G-M counters the gas filling is a mixture of, say, a noble gas such as argon and an organic vapor such as alcohol, xylol, or petroleum ether. The simple theoretical expression for the mobility constant of a mixture of gases A and B is

$$K = \frac{K_A K_B}{C_A K_B + C_B K_A} \tag{3}$$

where K_A and K_B are the respective mobilities of the pure gases, and the constants C_A and C_B are the partial pressures of the respective components,

$$C_A = \frac{p_A}{p_A + p_B} \qquad C_B = \frac{p_B}{p_A + p_B} \qquad (4)$$

Loeb[26] has pointed out that many mixtures do not follow that law and, from his experiments, gives another law,

$$K = \frac{K_A K_B}{\sqrt{C_A K_B^2 + C_B K_A^2}} \qquad (5)$$

It is safe to say that, unless data is taken on the mobility of the particular gas mixture used, one cannot be certain of the true mobility. However, expressions (3) and (5) are the first approximations.

After a time of the order of 10^{-2} seconds has elapsed following the formation of the positive ions, their mobilities become smaller, probably due to attachment of neutral atoms resulting in a higher effective mass for the ions. Since the ions migrate to the cylinder in a time less than a tenth of that, the values for newly formed positive ions must be used. These values usually are the same as for negative ions.

In the use of mobility constants a very critical matter is their dependence on field strengths. At the surface of the wire there is a field higher than 10^4 volts per cm. At the surface of the cathode the fields are considerably reduced, to around 10^2 volts per cm or less, depending on the radius of the cylinder. Loeb[23] and Druyvesteyn and Penning[27] point out that the ratio E/p, usually expressed in volts/cm/mm, is the essential criterion for the energy which ions acquire between collisions. The variation of K with that ratio is important. For a counter with 10 cms pressure, the E/p ratio is around 100 volts/cm/mm at the wire, and at the cylinder it is about 1 volt/cm/mm. Loeb[23] lists, for various gases, the critical ratio below which the mobility constant does not vary with E/p. These critical ratios vary from about 5 volts/cm/mm to about 80 volts/cm/mm. For argon the value is about 5 volts/cm/mm.

Above the critical ratio the mobility constant is no longer constant with a variation of E/p. As E/p is increased, the mobility increases first and then decreases. The functional relationship of this is not known and, moreover, it varies considerably from gas to gas. Hence, an accurate analysis of the deadtime problem is not possible in the region of the wire. However, the recovery time was indicated as that time which the ions needed to migrate from the critical distance to the cylinder. This region is the low field region. The value of the ratio of E/p is below the critical value so that the expression for the recovery time is calculable using the mobility constant as truly a constant.

4.05 Expression for Recovery Time

The expression for the recovery time is derived rather simply. From 4.04 (1) the element of time taken for the positive ion sheath to move a distance dr is

$$dt = \frac{dr}{kE} \qquad (1)$$

In this expression E is the field acting on the positive ion sheath. This field is

$$E = E_I + q/r \tag{2}$$

The q/r is due to the fact that the force on a surface charge density σ, due to the field of the rest of the surface charge, is $\frac{1}{2} E \sigma$. Hence,

$$E = \frac{2Q_o}{r} + \frac{2q}{r} \left[\frac{1}{2} - \frac{\text{Ln}\,\frac{b}{r_o}}{\text{Ln}\,\frac{b}{a}} \right] \tag{3}$$

where Q_o is the charge on the counter when a potential V_o is across the counter. Note that the second term in the brackets is small compared with $\frac{1}{2}$ for $r_o = R$ so that it may be neglected. R, experimentally, is from $\frac{1}{3}$ to $\frac{2}{3}$ of the radius of the cylinder. With this analysis it is seen that the positive space charge is moving in a field equivalent to that from $Q_o + \frac{1}{2} q$ on the wire. Hence, the effective potential across the counter is

$$V = V_o + q\,\text{Ln}\,\frac{b}{a} \;. \tag{4}$$

The field in (1) is

$$E = \frac{V}{\text{Ln}\,\frac{b}{a}\,r} \;, \tag{5}$$

so that (1) becomes

$$dt = \frac{\text{Ln}\,\frac{b}{a}\,r\,dr}{k\,V} \;. \tag{6}$$

The recovery time, t_r, is obtained by integrating this from R to b.

$$t_r = \frac{\mathrm{Ln}\,\frac{b}{a}\,(b^2 - R^2)}{2\,k\,V} \quad . \qquad (8)$$

With the pressure dependence of k substituted in,

$$t_r = \frac{\mathrm{Ln}\,\frac{b}{a}\,(b^2 - R^2)\,\frac{p}{p_o}}{2\,K\,V} \quad . \qquad (9)$$

If the mobility constant could be correctly assumed constant,or if an expression of its variation with field strength were known,the deadtime could also be calculated by integration of (6) from a to R. Assuming the former,

$$t_d = \frac{\frac{p}{p_o}\,\mathrm{Ln}\,\frac{b}{a}\,(R^2 - a^2)}{2\,K\,V} \quad . \qquad (10)$$

This will be shown to give erroneous results.

Chapter 5

Experimental Verification of the Deadtime Theory

5.01 Measured Quantities

From the postulated mechanism of G-M counter discharge presented in 4.02, there was derived the expression for the recovery time

$$t_r = \frac{\text{Ln}\,\frac{b}{a}\,(b^2 - R^2)\,\frac{p}{p_o}}{2\,K\,V} \qquad (1)$$

where

$$R = b\,e^{-V_u/2q} \qquad (2)$$

and

$$V = V_o + q\,\text{Ln}\,\frac{b}{a} \quad . \qquad (3)$$

In order to verify the postulated theory, the recovery time is measured and compared to the recovery time as calculated by (1). That t_r may be calculated from (1) is seen in an examination of the quantities which appear in the expression. The radii of the wire and cylinder, the pressure, the operating voltage, and the voltage above threshold, are all directly measurable. If the composition of the gas is known, the mobility constant is calculable in a very good first approximation from the expressions given in 4.04. This leaves only the charge per unit length in the positive ion space charge sheath. In 2.03 an experiment to measure the total charge in a single pulse was described. Since it is assumed that the counter breaks down along its whole length, so that the charge in the space charge sheath is uniform along the length of the counter, it is possible to get q by dividing the total charge by the length of the counter.

Experimentally, it was found that q varied approximately linearly with overvoltage, for a given counter and a particular gas mixture. This fact was mentioned in 2.03. This linear relationship held for different pressures and different threshold voltages, if the same mixture were kept in the counter. From (2) this linear relationship fixes the critical distance R as a constant for a given counter. There is no theoretical significance placed on this linear relationship. In fact, since there was some indication that it broke down for high values of V_u, it might be assumed that it doesn't hold in all cases. Nevertheless, when it does hold it simplifies calculation and enables one to speak of a particular critical distance, characteristic of a given counter. In the calculation of V for different conditions, each separate value of q must be substituted.

5.02 Experimental Measurement of the Recovery Time

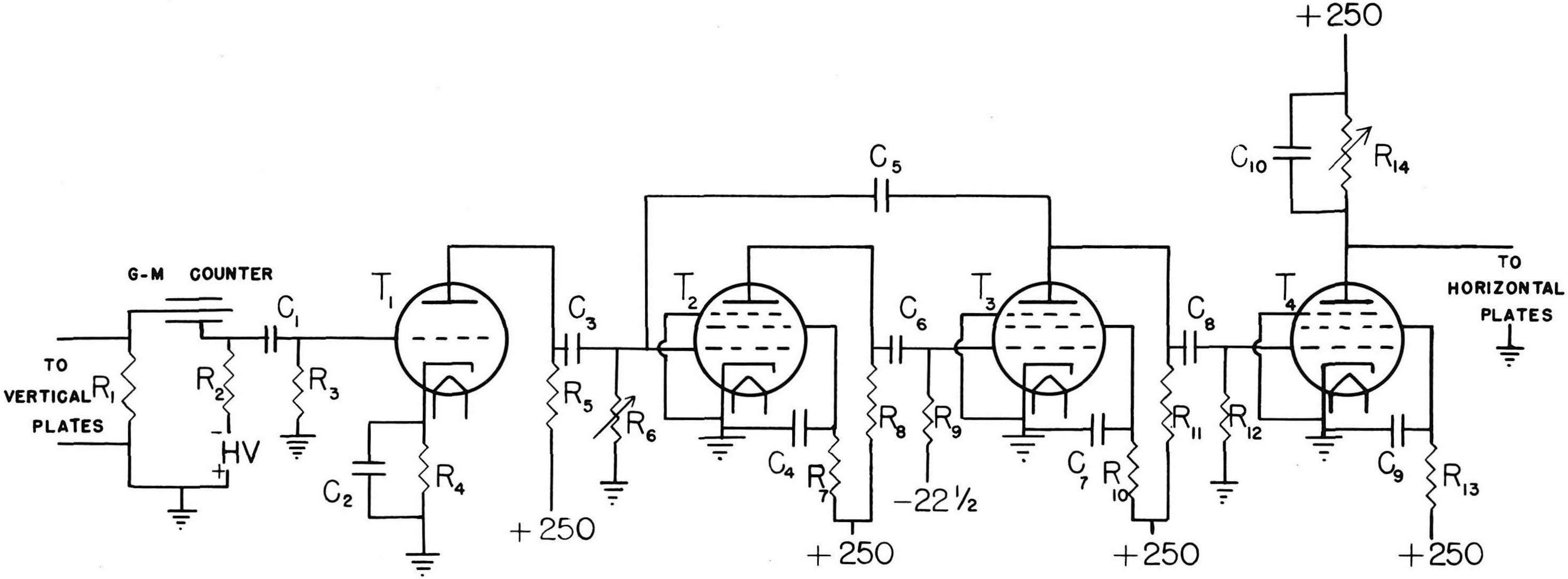
In 4.01 it was pointed out that the deadtime phenomenon was discovered in the course of experiments to measure the voltage-time characteristics of the G-M counter pulse. A writing speed of about 10^5 inches per second on the oscilloscope screen is needed to get a pattern of the fast breakdown of the G-M counter. From data given in a commercial cathode ray tube catalogue[28], this is about 10 times as fast as is possible to photograph in a single trace. For that reason a superimposition of pulses was required. Several methods were tried. Since two of the methods can be used in the deadtime work, they will be discussed.

In most oscilloscopes the linear sweep on the horizontal is furnished by the sawtooth voltage pulses from a gas discharge, relaxation oscillator which employs a type 885 gas triode tube. Single sweeps are obtained by biasing the gas tube sufficiently high that the ratio of plate voltage to negative grid voltage does not exceed the firing ratio which is in general about 10. To trigger the single sweep, a positive pulse is fed onto the grid. When fired, the tube discharges a condenser in the plate circuit till the plate voltage drops sufficiently for the grid to take control again. Then the first part of the RC exponential recharging of the condenser is used as the linear sweep. Since the time of firing the gas tube is about 10^{-5} seconds, it is impossible to get the breakdown portion of the G-M counter pulse on the linear sweep. However, it is possible to measure the deadtime and recovery time since they are of the order of 10^{-4} seconds. For the work here reported, an RCA 155 oscilloscope was made to work as a single sweep instrument by increasing the bias on the 884 relaxation oscillator tube. This circuit satisfies the other conditions which were listed in 4.01 as necessary for observation of the deadtime phenomenon. It is ready for another trigger pulse as soon as the single sweep is completed. A follow pulse does not effect the horizontal sweeping characteristics.

In practice it was not possible to get away from a non linear return sweep but the return sweep was calibrated with a sine wave oscillator so the difficulty was surmounted.

A more convenient method of getting the deadtime pattern also originated in attempts to measure the breakdown characteristics. It has several advantages over the method described above. In it, a different circuit is used to obtain the single horizontal sweep. When triggered, the circuit starts the electron beam of the oscilloscope across the screen in a linear sweep at the end of which it returns it rapidly. This is a decided advantage over the relaxation oscillator which first swings the beam across the screen and returns it in a linear sweep,for,in the latter case,part of the pulse to be measured is over before the linear sweep starts.

The circuit is diagramed in Figure 5.02. A positive pulse is fed onto the grid of T_1 from the cylinder of the G-M tube. T_1 is an isolation stage to prevent feed back from the rest of the circuit to the fundamental circuit. This feed back would distort the characteristics of the negative pulse which is fed onto the vertical plates of the oscilloscope from the wire of the G-M counter. A negative pulse is then passed onto the grid of T_2 which,together with T_3,acts as a multivibrator. The circuit characteristics of multivibrators are discussed adequately by Neher[4)] or in many electronics textbooks. Briefly its action is described here. A negative pulse fed onto the grid of T_2 starts to cut off the current, for normally T_2 is conducting. This action passes a positive pulse through the large condenser C_6 to the grid of T_3, which normally is biased to cut



R_3, R_{12}, R_{14} = 10^6 OHMS
$R_4 = 5 \times 10^3$
R_5, R_{13} = 10^5
$R_6 = 2 \times 10^6$

R_7, R_{10} = 10^4 OHMS
$R_8 = 2 \times 10^3$
$R_9 = 10^7$
$R_{11} = 1.5 \times 10^4$

C_1 = .001 MFD.
C_2 = 10
C_3, C_5 = .0001
C_4, C_7 = 8

C_6, C_8 = .01 MFD.
C_9 = .1
C_{10} = .0025

T_1 -- 37
T_2, T_3 -- 6AG7
T_4 -- 6SJ7

FIG. 5.02

off. The negative pulse which T_3 puts out is fed back onto the grid of T_2 through the condenser C_5. This causes T_2 to become even less conducting. The result of this action is that the plate of T_3 drops in voltage very rapidly. When the charge on the grid of T_2 has leaked off, the whole action is reversed. The result is a square wave output from the plate of T_3. The natural length of this square wave is determined by the RC discharge rate of the grid of T_2. The resistance R_6 is variable so that the length of the square wave can be changed. The square wave output from T_3 is fed onto the grid of T_4 which is normally in a conducting state. The plate is nearly at ground potential, most of the voltage drop being across the resistance R_{14}. The condenser C_{10} is charged to a voltage i_pR_{14}, where i_p is the plate current of T_4 in the conducting state. Since the plate voltage swing of T_3 is nearly the full 250 volts, T_4 becomes non-conducting immediately. C_{10} begins to discharge through R_{14} and continues until T_4 again becomes conducting. If the natural length of the multivibrator pulse is shorter than the $R_{14}C_{10}$ time constant, the voltage pulse from the plate of T_4 is a nearly perfect saw tooth. This voltage pulse is fed onto the horizontal plates of the oscilloscope. The linear sweep which it causes starts with a time delay of around 10^{-6} seconds from the time T_1 received the trigger pulse.

The circuit described above was used in obtaining the picture of the deadtime and the recovery time shown in Figure 4.01 b. The circuit also fulfills the requirements of 4.01. With it, measurements of the recovery time and the deadtime may be made. It is not necessary to photograph the pattern on the oscilloscope screen,for visual measurements on a ruled screen are sufficiently accurate.

5.03 Comparison of Calculated and Observed Recovery Times

In 5.01 and 5.02,a description of the methods of measurement for the various quantities was given. In this section,results of those measurements are to be presented.

In 5.01 (1) the quantities a, b, R, K,and p_o,are constants for a particular counter. One can get a variety of different conditions by varying the pressure in the counter containing a given gas mixture. The threshold potential does vary directly with pressure. It is possible to vary the pressure of an argon-xylol, 9 to 1,mixture from about 16 cm to about 1 cm pressure and still have a good fast counter. Argon-xylol counters will work as fast counters at much higher pressures but the percentage of xylol must be lower since the vapor pressure at room temperature of xylol is around 16 mm.

A permanent glass system with provision for changing cylinder, wire,and gas,was used in these experiments. It was far more convenient than making a new sealed off counter for every change in parameters.

The first counter used to test the theory was a copper cylinder counter which had been given the NO_2 treatment. It was 15.3 cms long by 1.11 cms radius with an 0.010 cms tungsten wire. The gas filling was a 9 to 1, argon-xylol,mixture. The critical distance R was calculated to be

0.65 cms. Table 5.03 a gives the data taken with that counter. The pressure was varied from 13.2 cms to 5.0 cms. The threshold voltage changed from 1410 to 985 volts. The threshold voltage is given in parenthesis for each different pressure. The calculated and observed values of t_r are listed for each different set of conditions. Note the good agreement. Note also that the variation of the observed t_r follows closely that of the calculated t_r.

The value of 0.8 for the mobility constant is the average of the values obtained from the two formulae in 4.04. The two values are 0.6 and 1.0. These are obtained using 1.8 as the mobility constant of newly formed positive argon ions and 0.2 for the mobility of xylol ions. This last value is obtained as an estimate from tables[29)] listing mobilities of close relatives of xylol. The value of 0.8 may be in error by 30% but the agreement with all predictions of the theory still would be very good.

As a check on the above, and as further verification of the theory, a counter of different dimensions was investigated. The radius was 1.43 cms. The gas in this counter was an argon-xylol mixture but this time it was 5% xylol and 95% argon. Although the radius b was larger, the value of q was so much smaller than in the previous case that R, the critical distance, was only 0.47 cms. With the different gas mixture, the value of K was 1.0, obtained as before. In this particular experiment, a better condenser was used in the measurement of q so that the final data is expected to be more accurate. The results are given in Table 5.03 b. Even though

Table 5.03 a

b = 1.11 cm   a = 0.010 cm   K = 0.8   R = .65 cm

Pressure (cms)		Voltage (V_o)	t_r (calc) (secs)	t_r (obs) (secs)
13.2	(1410)	1470	2.4×10^{-4}	2.2×10^{-4}
		1540	1.6	2.1
		1620	1.6	2.0
		1680	1.5	1.9
11.0	(1290)	1380	1.9	2.0
		1450	1.6	1.9
		1515	1.4	1.8
		1612	1.2	1.7
9.0	(1200)	1270	1.7	1.7
		1330	1.5	1.7
		1375	1.3	1.6
		1500	1.0	1.5
7.0	(1115)	1235	1.3	1.4
		1445	0.8	1.2
5.0	(985)	1045	1.1	1.2
		1140	0.9	1.1
		1215	0.8	1.0

Table 5.03 b

b = 1.43 cms   a = 0.010 cms   K = 1.0   R = .47 cm

Pressure (cm)		Voltage V_o	t_r (calc) (sec)	t_r (obs) (sec)
13.4	(1320)	1370	4.5×10^{-4}	4.3×10^{-4}
		1480	4.5	4.3
11.0	(1185)	1235	4.2	4.3
		1360	4.3	4.2
9.0	(1080)	1145	3.7	3.7
		1230	3.6	3.1
7.0	(985)	1035	3.3	3.6
		1170	3.0	3.1

the conditions are such to give calculated recovery times more than twice those of the other counter, there is still excellent agreement between calculated and observed recovery times.

The data herein presented, along with other data on less complete runs with different counters, seems to give sufficient verification of the theory of counter discharge.

5.04 Comparison of Calculated and Observed Deadtimes

The deadtime may be measured by the same method as used for the recovery time. As discussed in 4.04, the simple expression for the deadtime, derived in 4.05, is not accurate. To show the discrepancies between the observed deadtime and the calculated deadtime, Table 5.04 tabulates the results for the counter to which Table 5.03 b refers. The observed deadtime is 4 or 5 times as long as the calculated deadtime. Not only for this counter but for other counters, this fact was observed. Either the mobilities are much lower in the high field region or else the ions do not reach their equilibrium velocity. There is still however a dependence of the deadtime on the pressure/voltage ratio.

Although the deadtime can be used only in a semi-qualitative way to prove the theory, it is still an important quantity to measure. It is the quantity which determines the maximum counting rate of fast counters. In a particular experimental set-up, the size of the voltage pulse necessary to trip the recording circuit must be known. Then the insensitive time of the set-up may be measured experimentally as that time from the

Table 5.04

b = 1.43 cm	a = 0.010 cm	K = 1	B = 0.47 cm
Pressure (cm)	Voltage	t_d (obs) (secs)	t_d (calc) (secs)
13.4	1370	2.6×10^{-4}	$.65 \times 10^{-4}$
	1480	2.5	.52
11.0	1235	2.4	.60
	1360	2.3	.46
9.0	1145	2.1	.52
	1230	2.1	.41
7.0	1035	1.8	.43
	1170	1.7	.32

beginning of a trigger pulse to the time when the follow pulses have built up to the required size. The experiment employing the RCA 155 oscilloscope takes but a short time to perform. After it is set up the insensitive times can be measured for a large number of counters in a short time.

Chapter 6

Deadtime Technique Applied to Discharge Spread

6.01 The Spread of the Discharge

In the postulated mechanism of discharge of 4.02, it was assumed that the discharge spread throughout the full length of the counter in a time, short compared with the 10^{-5} second breakdown time. The excellent agreement with experiment of the predicted action from that theory seems to justify the assumption. In fact, in view of the identical nature of the pulses in size and shape, it is hardly possible to assume anything but complete spreading of the discharge. With the deadtime theory so convincingly supported by experiment, an examination of the spreading of the discharge was undertaken. Many of the experiments herein reported were performed before the complete theory was worked out; they contributed immeasurably to the formulation of the theory. However, logically they belong in this chapter dealing with the spread of discharge.

Some time before the deadtime technique was discovered, Professor Brode of the University of California described to the author an unpublished experiment on the spread of discharge in counters. This experiment, referred to as the Brode experiment, was performed with a double counter, i.e., a single glass tube container with two cylinders and two wires. The cylinders, end to end, were separated by a fraction of an inch. The wires were supported in the middle by an insulating glass bead. The pulse from either counter could be taken from its wire or its cylinder. Brode connected one wire to the vertical plates of an oscilloscope and the other wire to the horizontal. If one counter fired without the other, the electron beam of the oscilloscope would undergo a horizontal or a vertical displacement. If both fired coincidentally, either from a true coincidence or from the spread of the discharge from one to the other, there would be a 45° deflection of the beam. This assumes equal pulses from each counter. Brode found that, if both counters were slow counters, the discharge did spread. For fast counters the discharge did not spread; most pulses were either vertical or horizontal, very few 45° deflections being observed.

In repeating the Brode experiment, the author found similar results. There is, of course, the possibility that some of the occasional coincidences observed were from discharge spreading but the number was so small that it didn't indicate a uniform spreading of the discharge along the counter. This experiment was interpreted by assuming the discharge to be localized. It definitely eliminated photoelectric action on cathodes and in the gas as a mechanism for discharge spread. When the deadtime technique was discovered and supported so well, this whole question of discharge spread was reexamined, for the deadtime theory demands that the discharge spread along the unobstructed wire.

6.02 Divided Cylinder, Divided Wire Counter

In order to see if the deadtime, as well as the discharge, spreads in the type counter described in 6.01, a similar counter was built. This is diagrammed in Figure 6.02. The over all length was about 8 inches, the two cylinders being separated by about 1/4 inch. The two wires were held together mechanically, but separated electrically, by a glass bead about 1/8 inch in diameter. All gas fillings considered in this chapter are 9 to 1, argon-xylol, mixture. Each counter exhibited the deadtime and, due to equal dimensions, the two deadtimes were the same.

The particular deadtime experiment to be performed on this and other multiple counters needs some explanation. If two counters, say A and B, are connected in parallel, then a count from either of them may act as a trigger pulse. Moreover, a count from either of them may act as a follow pulse. If the two counters are independent, as far as deadtime is concerned, there will be no definite deadtime for the combination. This is because, although the one which gave the trigger pulse, say A, is dead for a short period thereafter, the other, B, is still sensitive. The same holds true if B furnishes the trigger pulse, for then A is still sensitive. On the oscilloscope screen this shows as the customary deadtime pattern, as illustrated by Fig. 4.01 b, except there are additional pulses filling in the open space from $t = 0$ to $t = t_d$.

If the two counters are not independent with respect to deadtime, then the customary deadtime picture with no modifications is expected.

DIVIDED CYLINDER, DIVIDED WIRE

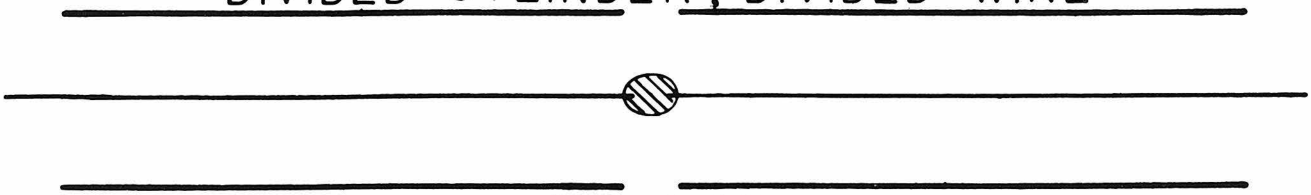


FIG. 6.02

DIVIDED CYLINDER

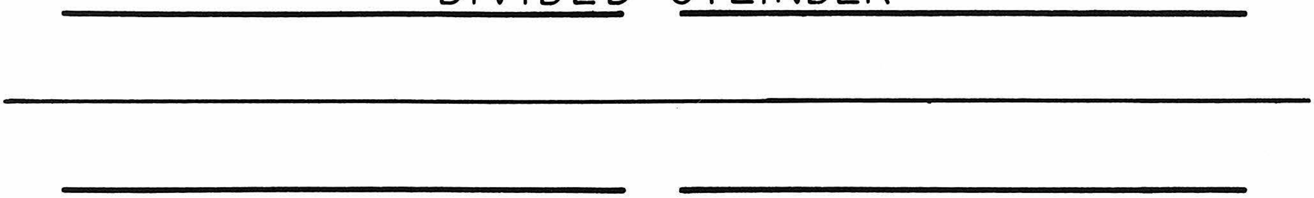


FIG. 6.03

DIVIDED WIRE

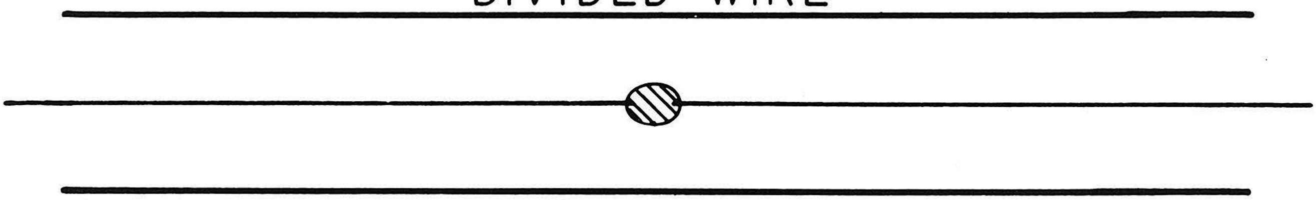


FIG. 6.04

BEAD ON WIRE

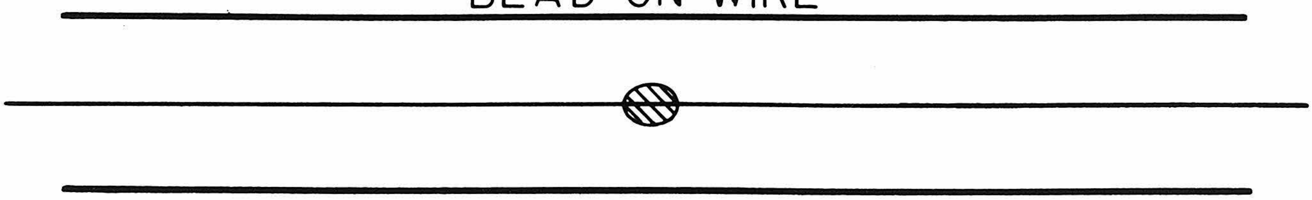


FIG. 6.05

Also, when the discharge spreads from one counter to the other, the resulting voltage pulse is the sum of the individual voltage pulses.

In order to test the spread of the deadtime in the divided wire, divided cylinder counter, the two separate counters were connected in parallel. The deadtime did not spread. There were, of course, a few double pulses from either true coincidences or occasional discharge spread.

6.03 Divided Cylinder Counter

The next step was to test to see if the deadtime and discharge would spread in a counter with a divided cylinder but a single wire. Again the counter, diagrammed in Figure 6.03, was 8 inches over all. Taking the pulses from the cylinders individually, each of the counters exhibited the same deadtime. When the cylinders were paralleled externally, it was found that the deadtime did spread. Moreover, the discharge spread too, for the voltage pulses were the sum of the voltage pulses of the individual counters. The counters acted together as a single counter. In other words, it was not the divided cylinder but the wire divided by the glass bead which prevented the spread of discharge and deadtime in the experiment of 6.02.

One very interesting and important fact was observed in the performance of Brode's experiment on the divided cylinder counter, taking the pulses from the two cylinders. As expected from the results of the deadtime experiment, all the deflections were at 45°. However, when these deflections were examined closely, it was found that the counter which received the ionizing particle did start slightly ahead of the other. To test this, a radioactive source was moved from one end to the other. This indicates definitely that the spread of discharge does take a finite time. This time was estimated to be but a fraction of the breakdown time or around 10^{-6} seconds or less. This spreading of the discharge down the length of the counter in a time, short compared with the breakdown time, was assumed in the postulated theory of discharge. It is comforting to note that it is verified experimentally.

6.04 Divided Wire Counter

Merely as a check on the experiments of 6.03, a divided wire counter was made as diagramed in Figure 6.04. The overall length of the single cylinder was 8 inches. As was expected, neither the deadtime nor the discharge spread. These experiments were sufficient to indicate that a spread of the discharge implied a spread of the deadtime. All the experiments have agreed with the theory of the deadtime.

6.05 Bead on Wire Counter

In the deadtime experiment, performed with the divided wire counter, the two wires were externally connected electrically. Hence, it was concluded that the spread of the discharge was a surface phenomenon on the wire or some phenomenon occurring in the gas very close to the wire. To test that conclusion, a counter was constructed with a single cylinder and single wire but with a glass bead about 1/8 inch in diameter and 1/4 inch long on the wire in the center of the counter. This counter is diagramed in Figure 6.05.

Although Brode's experiment could not be performed with this counter, there still remained two methods with which the spread of the discharge could be investigated. The spread of the deadtime and the size of the voltage pulses were still applicable to the problem. When tested with the deadtime experiment, the counter was found to behave as two. The discharge did not spread. This was corroborated by the pulse size experiment. A glass bead on the wire is sufficient to prevent the spread of the discharge. In the previous experiments, it was not the fact that either the cylinder or the wire was divided but the fact that there was a glass bead on the wire that prevented the discharge from spreading. No longer does one conclude from Brode's experiment that the discharge is localized. It spreads along the unobstructed wire; but a small glass bead is sufficient to stop it. This experiment shows that a new mechanism must be used to account for the spread of discharge, for, previous to Brode's experiments, it was thought to be photoelectric action on the cylinder and, from the time of Brode's experiment to very recently, it was considered to be localized.

6.06 Small Bead on Wire Counter

The next step in the investigation of the discharge spread was to find the minimum size of the bead which would stop the spread of discharge. For that purpose an 0.022 inch diameter bead was put on an 0.008 inch diameter wire. Instead of sealing off the counter constructed with this wire, the deadtime experiment was performed at several pressures. At 10 cm pressure with an operating voltage of 1300 volts, the deadtime didn't spread; the counter acted as two counters. The same held true at 6.5 cms pressure with an operating voltage of 1100 volts. However, at 3.5 cms pressure the action changed. From the threshold voltage of 790 volts to 840 volts, the deadtime didn't spread. As the voltage was increased above 840 volts, more and more double sized counts appeared until all counts were double sized. Then there was a unique deadtime. The counter had changed in action from that of two apparently separate counters to that of a single counter.

A possible explanation of this phenomenon is obtained if a fact mentioned in 4.04 is examined. It was there indicated that the quantity which determines the energy which an electron gains between collisions is the ratio E/p. This is obvious since E is a measure of the energy gained per unit path and $1/p$ determines the mean free path. For a particular gas or gas mixture, there is a critical value of E/p for which the electrons gain sufficient energy between collisions for cumulative ionization to take place. As the voltage across a G-M counter is raised, the threshold voltage is reached when the critical value of E/p is obtained near the wire. As the voltage is raised above threshold, the point at which the critical value of E/p is obtained is pushed out from the wire so that the volume which is sensitive to cumulative ionization is increased. This increase in the sensitive volume probably accounts for the observed increase with overvoltage of charge flowing in a single pulse. Although this ratio of E/p has a critical value, cumulative ionization isn't obtained in a limited space, such as the region of the wire, if the pressure is too low, for then there are not enough collisions for very rapid multiplication.

With this in mind the explanation of the change in action of the small beaded counter is clear. As the pressure was lowered, the operating voltage decreased but not as rapidly as the pressure. Since

$$E = \frac{V}{r \, \mathrm{Ln} \frac{b}{a}}$$

the value of E/p then increased. At the pressure 3.5 cms, with an operating voltage of 840 volts, the sensitive region had been pushed out from the wire till its radius exceeded that of the bead. Then if the spreading action were photoelectric, the discharge could spread.

This experiment indicates that the spreading action is due to a photoelectric phenomenon in the immediate vicinity of the wire. There are two possibilities: a gas photoelectric effect preferential to that portion of the gas around the wire, and photoelectric action on the wire. The latter is somewhat doubtful for a simple calculation shows that a photoelectron from the wire would travel only 2 or 3 mean free paths before the high field pulled it back to the wire.

6.07 The Directional Geiger Counter[30)]

Two experimental facts from this work on the spread of the discharge in G-M counters led to the discovery of a directional counter. Firstly, the discharge of a counter spreads along the unobstructed wire such that the charge collected on the wire in a given pulse is proportional to the length of the counter. Secondly, a small glass bead on the wire, of diameter a few times the diameter of the wire, is sufficient to stop the spread of this discharge.

The directional Geiger counter consists of an ordinary Geiger counter with beads of glass on the wire, dividing the counter into sections, preferably equal. Such a counter with two beads is diagramed in Figure 6.07 a. It is to be noted that this is an argon-organic vapor filled counter with treatment of the copper walls of the cylinder to give very low photoelectric emission efficiency and high work function. From the work reported in Chapter 3, it is known that the NO_2 treatment will give such a surface.

If an ionizing particle passes through one section of the counter, this section by normal counter action furnishes a charge q on the wire, this charge depending on the length. The other sections do not enter into the discharge. If an ionizing particle passes through 2 sections, then the charge furnished to the wire is 2q, for equal length sections, and for 3 sections, 3q, and so on. Hence, for a given wire capacity C, the voltage pulse is nq/C, where n is the number of sections through which the particle

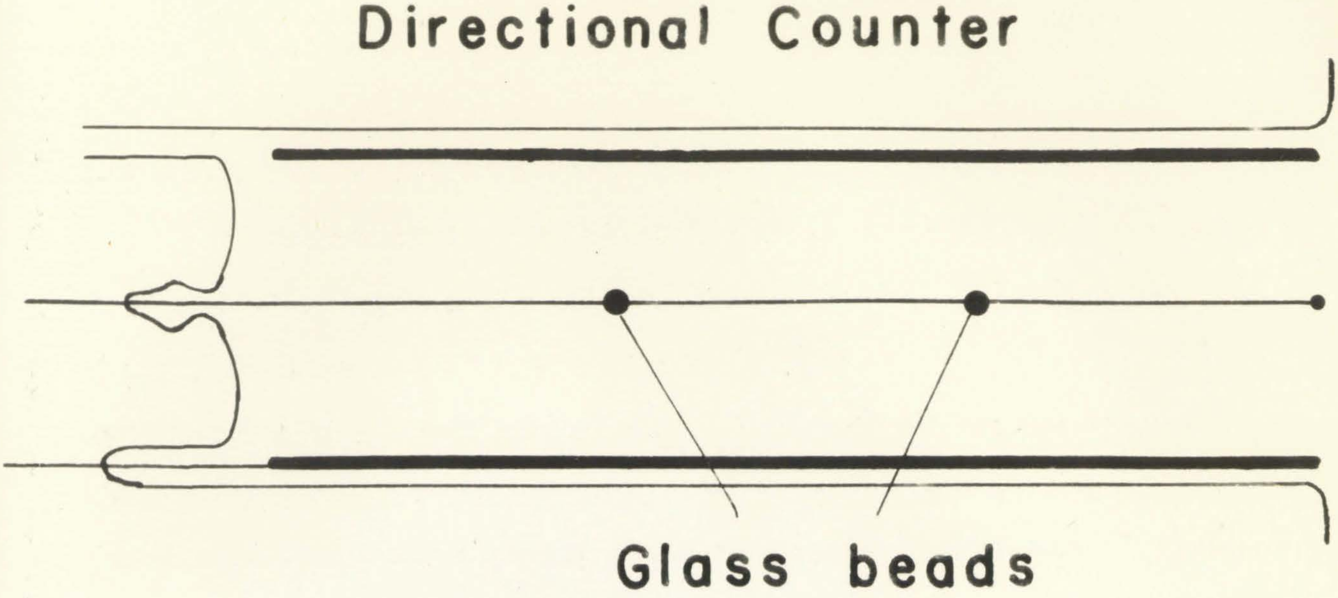


FIG. 6.07 a

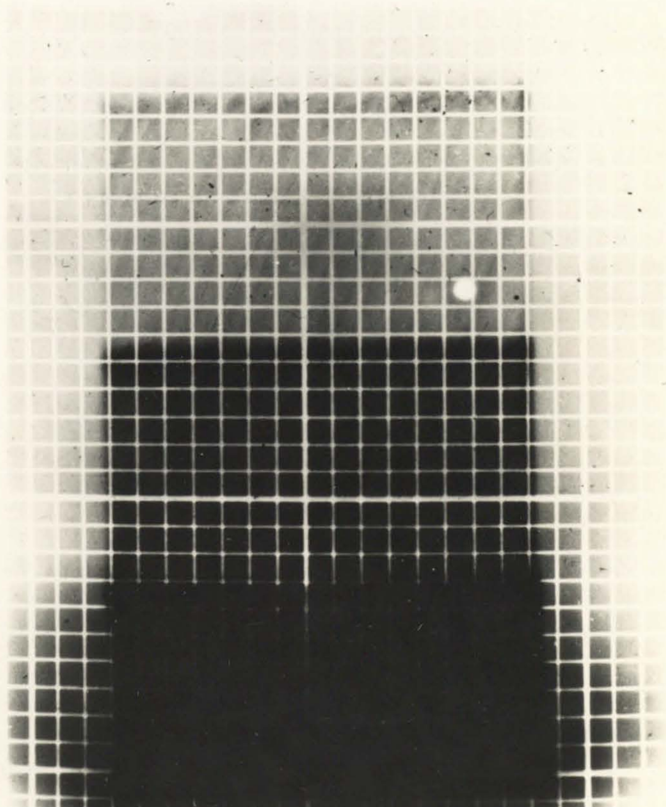


FIG. 6.07b

passed. From this the directional effect is immediately obvious for if, in the recording circuit, the first amplifier is biased so that it passes on only pulses of certain minimum voltage, $n_0 q/C$, where n_0 is the total number of sections, then only ionizing particles which have passed along the tube through all sections will be recorded. This is a true G-M counter telescope.

To show this directional effect, an electron source was placed at the end of a two beaded counter, so that singles, doubles, and triples were expected. The voltage pulse from the wire was put on the vertical plates of an oscilloscope and a linear sweep on the horizontal. Figure 6.07 b is a one minute exposure of the oscilloscope screen showing the three heights of pulses. The individual pulses are not distinguishable since it is a time exposure. It is important to note the sharp dividing line between single, double, and triple, counts.

Table 6.07 gives results of a simple experiment to show that this counter may be used to count a directional, ionizing, ray where there is a large general background radiation, with no hindrance from the background. With the electron source at the end of the tube, the number of triples was recorded for a five minute interval. Then, on the perpendicular bisector of the axis of the tube, a γ-ray source was placed such that the increase in single counts was 20,000 counts per five minute interval and again the triples were recorded. There were 22 ± 4 triples from the γ-ray source when the electron source was removed.

Table 6.07

Triple Counts per Five Minutes

	Without γ-ray background	With 20,000 γ-ray singles
	1140	1145
	1131	1144
	1139	1117
	1145	1150
	1143	1202
Av	1140 ± 15	1152 ± 15

Practically speaking, probably the optimum number of sections is three. Two sections would give too large a solid angle and,moreover, would have some stray photon coincidences. These stray photon coincidences would be sufficiently rediced in a three section counter to be neglected. By varying the length of the sections, any reasonable solid angle can be obtained with a three section counter.

The action of this directional counter well illustrates the phenomenon discussed in this chapter. It might prove of some value,not only in pure research,but in geophysical prospecting and well logging.

6.08 Conclusion

The discharge mechanism of G-M counters,as postulated in 4.02,is in excellent agreement with all the known facts of fast counter discharge. There are,however,two points which should be cleared up. One of these is the function of the organic vapor, or rather how the organic vapor performs its function. The presence of organic vapor leads to a very rapid and very efficient ionization in the neighborhood of the wire such that the positive ion space charge, left when the negatives flow onto the wire, is sufficient to lower the field to prevent further cumulative ionization. Perhaps this efficient ionization is due to pilfering collisions between organic vapor molecules and argon atoms, in which the metastable states of argon undergo a transition to ground state by giving their energy to the organic vapor molecule. Since the ionization potential of the organic vapor is lower than some metastable states of argon, ionization takes place. Loeb[23)26)] and Druyvesteyn and Penning[27)] discuss this process.

The other point, which should be cleared up, concerns itself with the mechanism of discharge spread. Some progress was made on that problem. Perhaps the deadtime technique would help in the solution of both problems. It makes possible the study of discharge spread over obstacles on the wire. A systematic study of the sensitive ionization region, similar to the analysis given in 6.06, might clear up the problem.

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II. The Mean Lifetime of the Mesotron

from Electroscope Data

Table of Contents

Summary

In order to detect the postulated decay of the mesotron and to secure data for the calculation for a mean rest lifetime, τ_o, an experiment, which consisted of the measurement of cosmic ray intensity at various depths in two lakes of widely differing altitude but of the same geomagnetic latitude, was performed, using one of our self recording electroscopes which has been used in other cosmic ray work. In the higher lake, about 12,000 ft above the lower, readings were taken at depths of 4.9, 5.9 and 6.9 meters and in the lower lake at 1.3, 2.3 and 3.3 meters, the difference in depth in the two lakes being about equal in mass to the air between the lakes. On the basis of the most recent theory, air and water were assumed to be gram for gram equivalent absorbers for the mesotron involved. The ratio of intensities at equivalent points in the two lakes was theoretically calculated by finding the probability that a mesotron of mean lifetime τ and of energy E would reach the lower station, and integrating this probability over the energy distribution curves of Blackett from a minimum energy, E_0, just necessary to penetrate to the instrument in the lower lake. Matching observed and calculated ratios, a mean rest lifetime of 2.8×10^{-6} secs. was found.

I. Introduction

At the Cosmic-Ray Symposium during the summer of 1939, B. Rossi[1] summarized the then existing evidence for the postulated decay of the mesotron. He pointed out that the temperature effect and the greater absorption of air compared with more dense materials resulted in a mean rest life of the order of 3.0×10^{-6} sec. Other experimental facts gave no evidence for mesotron disintegration although they were not contrary to such a theory. At that time no experiments showed that the mesotron was beta-radioactive. It was concluded that the disintegration evidence was incomplete.

Since the Symposium a number of experiments have been designed specifically to detect the mesotron decay and to measure its mean rest life. As the first direct evidence that the mesotron was beta-radioactive, Williams and Roberts[2] published a cloud-chamber photograph of a positive mesotron at the end of its range emitting a positron with energy approximately half the rest energy of the mesotron. The mesotron lifetime obtained from the temperature effect is in the same range as the value from other experiments although the effect is not as clear. Blackett[3] first explained the negative temperature effect by assuming the formation level of the mesotrons is extended upwards for a warmer atmosphere so that there was a greater time for decay before reaching sea level. This view has been furthered by other observers although recently Hess[4] in analyzing five years of electroscope data concluded that the normal negative temperature effect was not completely explainable on the mesotron disintegration hypothesis.

The anomalous absorption of cosmic rays reported by Ehmert[5] and others, which was explained by Euler and Heisenberg[6] by the mesotron decay hypothesis, has been considerably investigated. Most results of this method lead to a mean lifetime of 2.6 x 10^{-6} sec. or higher. Rossi, Hilberry and Hoag[7] reported a lower value of 2.0 x 10^{-6} sec. for a mesotron rest mass of 160 times the electron rest mass. Fermi, in a prepublication letter,[8] thought that the anomalous absorption could be explained by a correction in the absorption theory rather than by mesotron decay. When the effect of the field of the ionizing particle on surrounding electrons was taken into account, the energy loss in dense materials was lessened. The order of magnitude of that correction was the same as that used to indicate mesotron decay. However, when the complete analysis[9] was published, Fermi indicated that only half or less of the anomalous absorption could be accounted for by this polarization effect.

All previous experiments to obtain the mesotron lifetime employed the Geiger counter cosmic-ray telescope as recording mechanism to compare the absorption of mesotrons in more dense materials such as lead, carbon, earth, to the absorption in air. In order to eliminate some of the corrections and inherent difficulties in Geiger counter measurements, such as the correction for showers produced in the more dense absorber and the increased shower production in the air at higher altitudes, Professor

J. R. Oppenheimer suggested the present experiment. The object was to compare the mesotron absorption in air and water by highly accurate electroscope data. For all points of measurement, the electroscope was surrounded by the same medium, water. Care was taken at all times to preserve the symmetry of the surroundings of the instrument.

Examining past experiments which compared the cosmic-ray absorption of air and water, those of Millikan and Cameron[10)11)] stand out. In the first of these experiments, in 1926, these experimenters compared absorption curves in Arrowhead and Muir lakes with an altitude difference of about 2040 meters. The slight discrepancies from the mass absorption law for air and water were within the experimental error. In 1928, using more accurate pressure electroscopes, Millikan and Cameron performed a similar experiment in Arrowhead and Gem lakes, with an altitude difference of only 1200 meters. In this latter experiment the mass absorption law was found to hold.

II. Experimental Work

The experiment herein reported consisted in measurement of cosmic-ray intensities at various depths in two lakes of widely differing altitude. The intensities were measured by an accurate recording electroscope of the type used and described by Millikan and Neher.[12)] Lake Tulainyo at 3921 meters above sea level was the higher lake and Kerchkoff Reservoir at 305 meters was the lower lake. These were chosen for their low horizon which was about 82° from the vertical in both cases. Since the intensity falls off approximately as $\cos^2 \theta$, it is clear that not more than a small fraction of a percent of the total intensity was lost in either lake. Both lakes were at approximately 43° north geomagnetic latitude, well above the equatorial dip, and within 70 miles of each other longitudinally so that no difference of intensity due to the earth's magnetism entered. The instrument was placed well away from shore and from the bottom of the lakes. In Kerchkoff, measurements were made at depths 1.31, 2.31, and 3.31 meters below the surface; in Tulainyo at 4.88, 5.88, and 6.88 meters. The readings were taken first in Kerchkoff and then in Tulainyo, after which the Kerchkoff readings were repeated. Table I gives a summary of the results. N, the number of ions per cubic centimeter per second, has been corrected for barometric pressure variation and for residual radioactivity of the instrument. The instrument had a negligible temperature coefficient for the range of temperatures encountered. Each N is an average of about 14 discharges of the electroscope which corresponds to 24 hours of measurement. The probable error of each reading was computed from the deviation from the mean of these 14 discharges. The 3.57 meters of water difference in depth of reading in the lakes corresponds approximately in stopping power to the 3.62×10^5 cm column of air at an average density 0.00094 g/cm^3.

In Figure 1 the logarithm of N, the number of ions per cubic centimeter per second, is plotted against the total absorbing matter from the

Table I: Corrected readings for both lakes

Date	Lake Altitude in meters	Depth in Lake in meters	Total Absorber in meters of water	Ions/cc/sec N
Sept. 1	Kerchkoff	1.31	11.29	2.209 ± .014
2	305	2.31	12.29	1.938 ± .007
3		3.31	13.29	1.736 ± .009
9	Tulainyo	4.88	11.38	2.501 ± .007
10	3921	5.88	12.38	2.217 ± .007
11		6.88	13.38	1.982 ± .002
17	Kerchkoff	1.32	11.30	2.242 ± .007
18	305	2.32	12.30	1.936 ± .007
19		3.32	13.30	1.747 ± .007

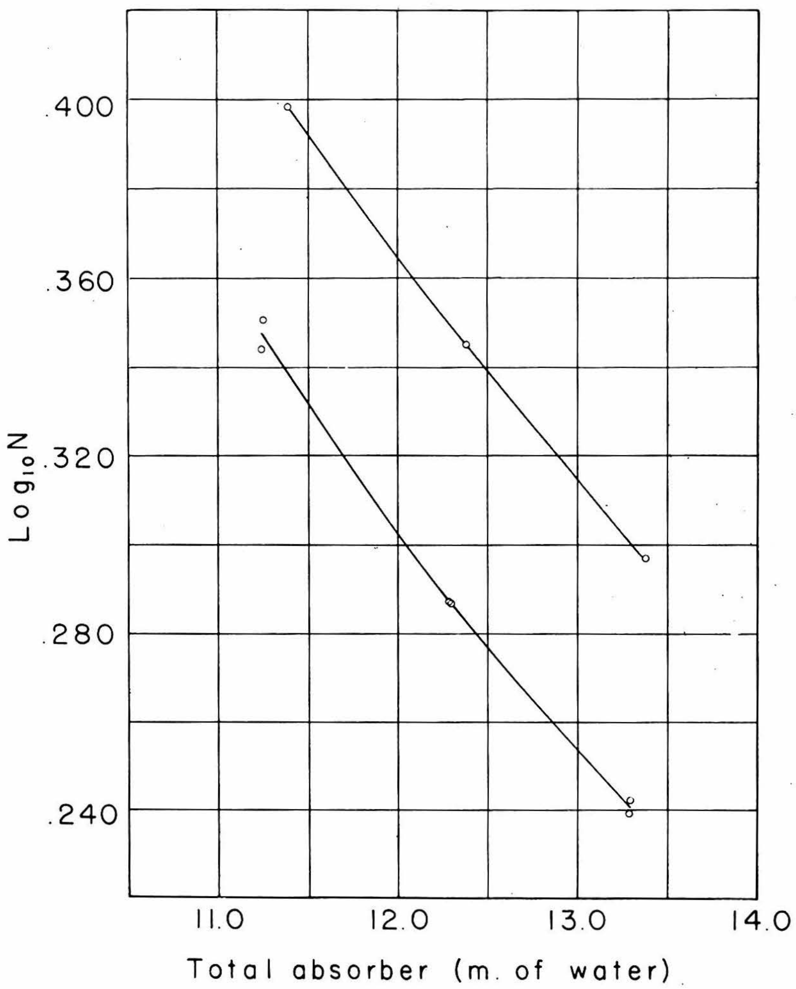

FIG. 1

top of the atmosphere to the electroscope, expressed in meters of water equivalent. The upper curve represents the absorption in the upper lake (elevation 3921 meters); the lower curve is the curve for the lower lake (elevation 305 meters). Air and water are taken as gram for gram equivalent in stopping power.

III. Relative Mesotron Stopping Power of Air and Water

Previous to the recent modification of the absorption theory by Fermi,[9] the energy loss per unit path in an absorber of n electrons per cubic centimeter by a high energy mesotron of energy E and velocity $v = \beta \cdot c$ was given by the Bethe-Bloch formula,[13][14]

$$-\frac{dE}{dy} = \frac{2\pi n e^4}{m_e c^2 \beta^2} \text{Log} \frac{m_e c^2 \beta^2 W}{(13.5Z)^2 (1 - \beta^2)} , \qquad (1)$$

where m_e is the rest mass of the electron and e is the electronic charge. W is the maximum energy which may be imparted to an electron in a direct collision with a mesotron of mass m.

$$W = \frac{E + 2mc^2}{1 + m_e c^2 (1 + m/m_e)^2 / 2E}$$

Fermi subtracts from (1)

$$\frac{2\pi n e^4}{m_e c^2 \beta^2} \text{Log}\, \epsilon \quad \text{for } \beta < \frac{1}{\sqrt{\epsilon}} \qquad (2)$$

or

$$\frac{2\pi n e^4}{m_e c^2 \beta^2} \left[\text{Log} \frac{\epsilon - 1}{1 - \beta^2} + \frac{1 - \epsilon\beta^2}{\epsilon - 1} \right] \quad \text{for } \beta > \frac{1}{\sqrt{\epsilon}} \qquad (3)$$

where ϵ is the effective dielectric constant for the polarization effect.

From the Bethe-Bloch formula, the ratio of the energy loss in one gram of air per square centimeter to the loss in a similar amount of water is about 0.9. When, however, the Fermi correction is applied to the case of water, the ratio of energy losses is just 1.0 if an average mesotron energy of a few Bev and the value given by Fermi for ϵ are used. From these considerations it is concluded that points in the two lakes under equal masses of absorbing materials may be compared in intensity, the difference of intensity being just due to the mesotrons which have decayed in the 3.62×10^5 cm air column.

IV. Theory of Mean Lifetime Determination and Application to Experimental Results

Consider high energy mesotrons of velocity, $v = \beta c$, where $\beta \approx 1$. In the coordinate system stationary with respect to the earth, the energy is given by $E = kmc^2$ where $k = 1/(1 - \beta^2)^{1/2}$ and the mean lifetime is $\tau = k\tau_0$ where τ_0 is the mean rest lifetime of the mesotron. Let P be the probability that a particle will survive for a time t so that the probability for disintegration in the time interval t to t + dt is

$$-dP = Pdt/\tau. \tag{4}$$

For a mesotron incident at any angle θ from the vertical and having an energy, $E = kmc^2$, at $y = 0$, where y is the vertical distance measured downward, with a uniform loss of energy, imc^2, per unit path, (4) may be written

$$-dP = \frac{Pdt}{\tau_0(k - iy \sec\theta)} = \frac{Pdy}{\beta c\tau_0(k/\sec\theta - iy)} \ . \qquad (5)$$

Integrating (5) from $y = 0$ to $y = y_0$, the probability, $P(E,\theta)$, that the mesotron will reach a vertical distance y_0 below $y = 0$ is

$$P(E,\theta) = \left[\frac{E - imc^2 y_0 \sec\theta}{E}\right]^{1/i\beta c\tau_0} \qquad (6)$$

It is important to note that $P(E,\theta) = P(E',0)$ where $E' = E/\sec\theta$ or, in words, the probability that a particle of energy, E, traveling at an angle θ will reach a vertical distance, y_0, downward is the same as the probability that a particle of energy, $E/\sec\theta$, traveling vertically will reach y_0.

Assume that the energy distribution, $f(E)$, is of the form B/E^{γ} for mesotrons above some minimum energy. This is a valid assumption for Blackett's[15)] energy distribution curve at sea level is of that form with γ between 2 and 3. The total intensity incident at an angle θ at y_0 is

$$J_{y_0}(\theta) = \int_{E_0}^{\infty} P(E,\theta)\frac{B}{E^{\gamma}}\,dE, \qquad (7)$$

where E_0 is the energy just sufficient to penetrate the air column and the layer of water above the instrument in the lower lake. By inserting a new variable $E' = E/\sec\theta$ in (7) it is seen that

$$J_{yo}(\theta) = (\cos\theta)^{\gamma-1} J_{yo}(0). \qquad (8)$$

This last result shows that the total intensity, N_{y_o}, which is the integral of (8) over the hemispherical solid angle, is just proportional to the vertical intensity, the constant of proportionality being the same for all y_o. With that in mind, the ratio of intensities at points in the two lakes under equal total absorber may be written

$$N_u/N_L = \int_{E_o}^{\infty} f(E)\,dE \Big/ \int_{E_o}^{\infty} P(E,0)f(E)\,dE. \qquad (9)$$

Since the energy distribution, f(E), for the upper lake is not known, it is necessary to write an expression similar to (9) for the lower lake where Blackett's sea level energy curves hold to very good approximation, the lower lake being only 305 meters above sea level. It is to be remembered that the energy E in $P(E,\theta)$ in expression (6) is the energy at the upper lake. In terms of E', the energy at the lower lake, letting $f'(E')$ represent the lower lake energy distribution,

$$\frac{N_u}{N_L} = \int_{E_o'}^{\infty} \frac{f'(E')\,dE'}{P(E' + iy_o mc^2, 0)} \Big/ \int_{E_o'}^{\infty} f'(E')\,dE'. \qquad (10)$$

E_o' is the energy necessary to penetrate to the instrument through the water in the lower lake. Expression (10) is integrated graphically for various values of m/τ_o using Blackett's energy distribution at sea level for $f'(E')$ and expression (6) for $P(E' + iy_o mc^2, 0)$. For the point at 3.3 meters under the surface of the lower lake E_o' has a value 0.75×10^9 ev. A value of 78 ion pairs per cm with 32 ev per ion pair in atmospheric air was used for the energy loss per unit path. The value of the ratio of mesotron intensities N_u/N_L from (10) is plotted against m/τ_o and then the experimental value of N_u/N_L is used to find the experimental value of m/τ_o from the plot. From Fig. 1 the experimental N_u/N_L is 1.15 which gives a value for m/τ_o of 58 in m_e/microsecond units where m_e is the electron mass. Thus for a mass 160 times the electronic mass, the value of the mean rest lifetime is $\tau_o = 2.8 \times 10^{-6}$ sec.

V. Discussion of Results and Sources of Errors

Experimentally the intensity, N, is made up of mesotrons, knock-on electrons, soft primary component and decay electrons. In the above determination of m/τ_o, it was assumed that the intensity measured by the electroscope was made up of mesotrons or a component proportional to the mesotron. Of the three soft components, the knock-on electrons are proportional to the mesotrons so they introduce no error. The soft primary component which is only 4 percent or 5 percent of the total intensity at sea level is negligible at the point in question 3 meters below sea level. In an associated work, Mr. Nelson[16)] finds, using cascade theory, that at the lowest depth in the lower lake, the decay electrons are of negligible intensity. From these considerations it may be concluded that $N_u/N_L = 1.15$ is the correct ratio of mesotron intensities.

It should be pointed out that, for the points at 1.3 and 2.3 meters below the surface of the lower lake and their corresponding points in the upper lake, the experimental ratios N_u/N_L are about the same as for the point at 3.3 meters. From expression (10), since E_o' is lower with a greater probability of decay, it might be expected that the ratio would be greater. However, the decay electron intensity is greater for the shallower depths in the lower lake so that the two effects approximately cancel. Nelson's quantitative results taking into account the decay electrons are in excellent agreement with the experimental intensities found. This is good evidence that the mesotron decay, detected in this and other experiments, is a beta-decay with the decay electron producing cascades.

The data herein presented were taken with well-tested dependable apparatus and the method used eliminated many errors inherent in other experiments. The chief error in the ratio m/τ_o found here is not due to the experimental data but rather to the inaccuracies in the energy distribution and other approximations used in the derivation of expression (10). Naturally the value of τ_o depends on an accurate mesotron mass determination, and until such is made the ratio m/τ_o is the only constant determined by this experiment.

In conclusion appreciation for the funds used for this work is extended to the Carnegie Corporation of New York. Mr. T. Smith, Mr. H Bradner and Mr. R. Hoy generously assisted on location. Especially we thank both Professor Oppenheimer for pointing out several finer points in the results and Mr. Nelson for his theoretical treatment of the problem.

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