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THE MECHANISM OF THE GEIGER COUNTER

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§ 1. INTRODUCTION

The first method of detecting single particles by their ionization was that developed thirty years ago by Rutherford and Geiger[5]. They used the principle of ionization by collision which had then recently been discovered by Townsend[6]. Their apparatus was very similar in principle to the modern form of counter. A fine wire stretched down the axis of a brass tube was insulated from it at the two ends by ebonite stoppers. The pressure of air in the tube was reduced to a few centimetres of mercury and a potential near the break-down potential of the gas was applied to the tube, the outer case being negative. The wire was connected to a quadrant electrometer.

Under these conditions any electrons set free by ionization in the gas were dragged to the wire and in the strong electric field in its neighbourhood gave rise to fresh positive ions and electrons by collision with the molecules of the gas. These electrons ionized the gas by collision in their turn, and in this way an electron avalanche was set up in which each primary electron was multiplied by a factor which was of the order of 1000. With this multiplication the ionization from a single α-particle was easily detected by the quadrant electrometer.

In subsequent experiments in order to reduce the number of natural particles this apparatus was replaced by a ball counter in which the multiplication took place at the surface of a small sphere. As we shall see later these methods of proportional multiplication with changes in detail are still often used for the detection of heavily ionizing particles. They have however been largely replaced by the method introduced by Greinacher[7] in 1927 in which a parallel plate ionization chamber in combination with a sensitive amplifier is used. Wynn-Williams[2] has already given an account of this technique in these reports. It has the advantage of giving a more direct measure of the amount of ionization produced by the particle, since only the primary ionization is collected without any multiplication. This method can only be used when the primary ionization is sufficient to give a change in potential on the electrode larger than the background fluctuations of the amplifier. This makes it inapplicable to measurements on β-rays, and for them some system of multiplication by collision is generally used.

For many purposes the proportional multiplication of ionization is not essential, only the *number* of particles entering the counter being required and not their ionization. For these experiments because of its simplicity the non-proportional counter is most suitable. The first of these was introduced by Geiger[8] in 1913. This consisted of a wire with a fine point at its end which was kept at a high (positive or negative) potential with respect to an outer case. Any ionization in the neighbourhood of the point led to a momentary current in which the charge flowing was independent of the primary ionization. This trigger action made the counter very useful for the detection of β-rays and indeed in any experiments involving the detection of small amounts of ionization. It found many applications and there is an extensive literature concerning its mechanism and methods of preparation. These will not be dealt with here since they will be found summarized in the German Handbuchs[1] and because this type of counter has been almost completely superseded by the tube-counter introduced by Geiger and Müller[9] in 1928.

This was very similar in form to the original proportional counter of Geiger and Rutherford but the potential across the tube was raised. In certain circumstances the counter then responded to ions in the same way as the point counter, by a single abrupt discharge. It had the great advantage of being sensitive over nearly its whole volume instead of just in the neighbourhood of a point. The reasons why the discharge when once started is only momentary and not continuous were and still are rather uncertain. Geiger and Müller held at first that a surface film of oxide on the wire was essential. Other investigators found that provided the surface of the wire was smooth its material did not matter provided the counter was in series with a large resistance. On the other hand the surface of the outer electrode and the purity of the gas were very important. These points will be discussed later.

Because of its much greater sensitive volume and reliability the Geiger-Müller counter immediately found many applications, and special forms were developed for work with x-rays, photometry, etc. This led to the need for elaborate auxiliary circuits for rapid counting, for detecting coincident discharges in several counters, and for maintaining constant potentials across the counter[2, 18, 31]. At the same time in order to obtain reliable counters the mechanism of the discharge was studied with careful purification of the gas and cleaning of the metal surfaces with the technique which had been developed for high vacuum work.

Several summaries of the literature on Geiger-Müller counters have recently been published among which one may mention an excellent article by Moon[3] and a very recent book by Thibaud, Cartan and Comparat[4]. To avoid covering the same ground as these this article will deal mainly with the problem of the mechanism of the counter. Owing to the work of Werner[22] and others it is now possible to give a fairly systematic account of this aspect of the subject.

§ 2. THE PROPORTIONAL COUNTER

Before considering the recent work on the non-proportional discharge we will discuss in some detail the proportional multiplication counter. This has often been used for detecting primary ionization which would be too small to be easily detected directly as in the counting of fast protons, or when the very rapid discharge and consequent short resolving time of the counter is an advantage as when experiments are being carried out in the presence of intense γ-radiation[10, 11, 12]. Quite apart from these applications the processes in the multiplication counter are important for an understanding of the more complicated non-proportional discharge.

The simplest form of apparatus for experiments on multiplication by collision consists of two plane parallel electrodes at a variable distance apart. This is the arrangement which was used in the classical experiments of Townsend[6].

This arrangement has not often been adopted for counting purposes since a higher potential is needed at any given pressure than in the wire counter, and the multiplication is not the same for ions formed at different points in the counter, increasing with the distance from the anode.

However Zipprich[13] has used this method together with a wire grid arranged so that the ions were formed in a nearly field-free space from which they drifted into the multiplication region. It was then found that the charge collected was proportional to the number of primary ions and Townsend's equations for the variation of the multiplication factor were verified. By an ingenious system using two successive stages of multiplication Winkler[14] has extended this method so far as to detect single ions proportionally with a multiplication of 200,000 times.

The most commonly used proportional counters have been the ball and wire types. The first of these was studied in detail by Geiger and Klemperer[10] and the second by Geiger and Zahn[11]. In these the multiplication is confined to the surface of a wire or sphere of small diameter which forms the anode. Using the Townsend theory expressions can be derived for the variation of the multiplication factor with the diameters of the electrodes, pressure of the gas and the voltage. These have been verified experimentally by Müller[15] for air at small multiplication factors. In designing such a counter the working voltage can be deduced from these formulae or more easily from those given by Werner[22] for the non-proportional counting voltage. The potential in the proportional region will not be far short of this counting voltage.

It is important that the multiplication should be independent of the point in the counter at which primary ions are formed and should not be subject to large random fluctuations. In the wire and ball counters the multiplication is confined to a small volume so that ions formed outside this region should all be multiplied to the same extent. Nevertheless multiplication by collision is an essentially random process and must involve statistical fluctuations, which would not be revealed in the classical experiments on steady ionization currents. This point has not been very much studied experimentally. Geiger[16] gives a distribution curve for the size of kick obtained with α-particles entering a wire counter in which the fluctuations appear to be small, of the order of 1/40 of the mean, but Brubaker and Pollard[17] have found fluctuations of the order of 10 per cent in various gases and also find a decrease in the multiplication for ions formed at a distance from the wire. They ascribe this last to the capture of electrons to form negative ions.

There have not been any theoretical papers on this aspect of multiplication. Some calculations by the writer indicate that the fluctuation in the final amount of ionization should be of the order of $M\sqrt{N}$, where N is the number of primary ions, and M the multiplication factor. It would be interesting to compare this prediction with experiments such as the above but the data given are not sufficient.

In the writer's experience the multiplication counter has been very useful, and simplifies the counting of particles very considerably by making it possible to use linear amplifiers of very much less sensitivity than in the direct method. Their only disadvantage is that the multiplication varies rapidly with the voltage applied, so that this must be constant within narrow limits (<1 v. at 1000 v.). Circuits ensuring this have been developed[18], and by frequent calibration with standard sources of ionization the counters can be made quite reliable.

A different kind of proportional counting which has recently come into prominence is that using the electron multiplier devised by Zworykin[19]. This depends on the fact that a fast electron colliding with a surface can cause the emission of a large number of secondary electrons. These can be accelerated and directed on to a similar surface to give a still greater number. By arranging several such stages in series, very high multiplication factors can be attained. Z. Bay[20] and W. H. Rann[21] have shown that this device can be used to detect β-particles which are directed on to the first surface of the multiplier. The great advantage claimed for this type of counter is the small resolving time. The multiplication process takes about 10^{-8} sec. which is much smaller than can be attained with any gas-filled counter.

§ 3. THE NON-PROPORTIONAL COUNTER*

If the potential across a wire counter is raised so that the multiplication factor becomes very large the tube may break down in one of several ways when a multiplication factor of the order 10^4 is reached. It may give a continuous or intermittent discharge which once started does not depend on the presence of any external source of ionization, or it may *count*, i.e. give a single abrupt discharge for each particle entering the tube. There are a number of different ways of securing this behaviour of which the simplest is to place in series with the tube a high resistance, R, of the order of 10^8 to 10^9 Ω. The circuit is then as shown in figure 1.

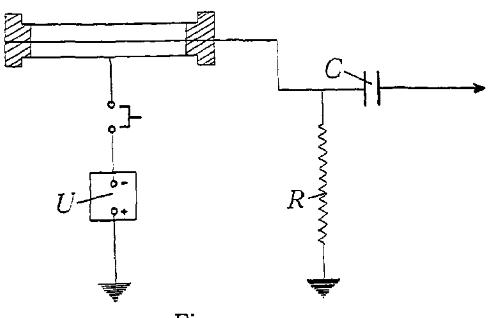

Figure 1.

The discharges are detected by means of the momentary current through R. A small condenser C feeds the potential change due to this current into the recording circuit.

* The following account is mainly founded upon the papers of Werner[22] and Cosyns[23] to which reference should be made for further details.

If with this arrangement and with a constant source of ionization the number of discharges per min. is determined for various values of the applied voltage U, a characteristic curve is obtained, such as figure 2.

This shows a sharp rise from the starting potential V_0 (at which the potential changes on the wire are too small to be recorded) to a constant value giving a plateau BC. This plateau extends to a certain over-voltage $U-V_0$ where the number of discharges begins to rise sharply, along the curve CD.

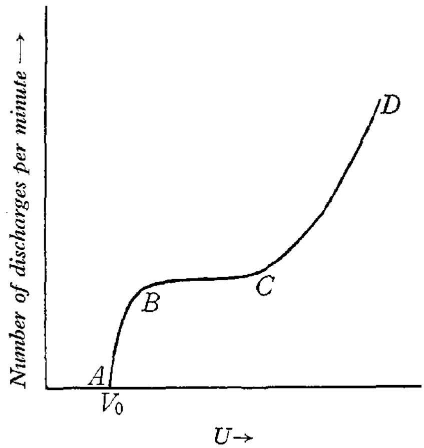

Figure 2.

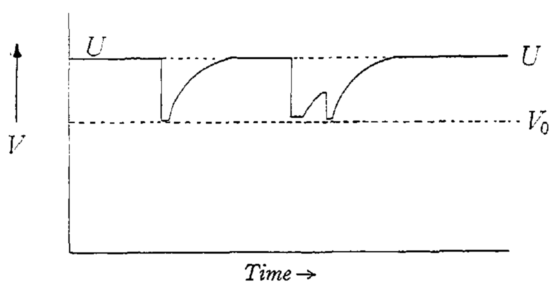

Figure 3.

This plateau is the region of potential in which the counter is normally operated and the reliability of the counter depends on the flatness and extent of this region. It will be shown later that this depends partly on the design of the counter, and partly on the value of R.

A more detailed study of the discharge may be made by means of the cathode ray oscillograph,* the potential V across the counter being applied through a suitable circuit to the Y plates, while a time base circuit is applied to the X plates so that the spot on the fluorescent screen gives a plot of the variation of V with time[22, 24, 25, 26]. The type of result obtained is shown in figure 3.

* Similar results can of course be obtained with any form of rapid oscillograph.

This may be accounted for by the following sequence of events. The potential difference V across the counter is initially U. The onset of the discharge causes the internal resistance of the counter to fall from infinity to a fairly low value (about 1 MΩ.), and the potential V therefore drops sharply. This fall is arrested when V reaches a value V' slightly above the starting potential V_0. The discharge may then burn steadily for a very short time, or stop instantly. As soon as the discharge ceases the potential across the counter returns exponentially to its original value U with a time constant given by the total capacity across the counter, C', and the resistance R. The potential change communicated to the recording system is thus $U-V'$ which is nearly equal to the over-voltage.

The time occupied by a kick is mainly determined by the recovery time, and is therefore of the order RC'. If another discharge occurs before the first has quite disappeared, the potential change will be less than the over-voltage, as shown in figure 3, and such a discharge may fail to be recorded. It is therefore important for accuracy in rapid counting that the recovery time of the counting circuit should be as short as possible.

§4. THEORY OF THE COUNTER DISCHARGE

The proportional discharge consists of only one electron avalanche. If a continuous discharge is to be maintained fresh electrons must be supplied continually from outside the immediate neighbourhood of the wire. Many different mechanisms have been suggested for this: ionization of the gas by the positive ions, ejection of electrons by the positive ions when they reach the outer electrode, and the emission of photo-electrons from the outer electrode by photons from atoms excited in the electron avalanche. The relative importance of these processes in gas discharges in general is discussed in an article by Loeb[27] to which reference should be made. As far as Geiger counters are concerned the evidence is fairly conclusive that the last is the main process.* In Greiner's[28] experiments two counters A and B were used inside the same enclosure. It was found that a discharge in one always spreads to the other. By placing absorption screens between the two counters it was shown that the discharge was propagated by ultra-violet radiation which originating in one counter ejects photo-electrons from the wall of the other. This mechanism is most probably the same as that responsible for maintaining the discharge in one counter. Accepting this we see that each avalanche must produce enough photo-electrons in this way to give a following avalanche of equal size, if the discharge is to be continuous.

If an avalanche starts with N primary electrons each of these is multiplied by a factor m in the discharge so that the final charge arriving at the wire is nm electrons. The number of photo-electrons ejected from the outer wall will be proportional to Nm, say pNm. For the discharge to be continuous we must have

$$m=\frac{1}{p}=M, \qquad \ldots\ldots(1)$$

* Cosyns[23] and Thibaud *et al.*[4] following him assume that electrons are provided by the first process above, *ionization by positive ions*, but the weight of evidence seems to be against this.

where M, which we shall call the normal multiplication, is generally of the order of 10^5. p and therefore M will depend on a number of factors such as the pressure and the work function of the surface of the outer electrode. In particular it will be proportional to the solid angle subtended by the outer electrode at the wire. Christoph and Hanle[29] have shown that if this angle is reduced the counting voltage is increased, as we should expect.

The normal multiplication is attained when the field near the wire reaches a certain value, and this will occur at the starting potential V_0. Werner[22] has calculated the starting potential on the assumption that the potential fall in n electron free paths of length K/p next the wire has to exceed a critical value u. This condition can easily be calculated and gives the following formula for the starting potential:

$$V_0 = \frac{u \log_e r_a/r_i}{\log_e (Kn/pr_i + 1)}. \qquad \ldots\ldots(2)$$

r_a and r_i are here the radii of the outer and inner electrodes.

This formula has been tested by Werner and by Haines[30] for a number of different gases. It gives the variation of V_0 with p and with r_i very well. The values of the constants u and n are determined empirically.

At the starting potential the initial multiplication is equal to the normal. As soon as the discharge has started, however, the positive ions formed near the wire by successive avalanches accumulate, and their space charge modifies the field. Werner has calculated this effect. In order to maintain the same field at the surface of the wire the voltage across the tube has to be raised by an amount $V - V_0$ which to a first approximation is proportional to the density of the space charge and therefore to the positive ion current.

Thus $$V - V_0 = ki, \qquad \ldots\ldots(3)$$

where k is an internal resistance of the order of 1 MΩ. The value of k can be calculated in terms of the other constants.

If the counter is used in the circuit of figure 1 we can calculate the current in the discharge for a given over-voltage. From equation (3) we shall have

$$i = \frac{U - V_0}{R + k}. \qquad \ldots\ldots(4)$$

This brings us to one of the main difficulties in explaining these discharges. Equation (4) is an equilibrium equation and the current i should be perfectly stable. But in fact as we have seen the current in the circuit stops when $U - V_0$ falls below a certain value. The use of the tube as a counter depends on this fact. Werner has investigated this point, and found that the discharge is unstable as long as i is less than a critical value $i_{\min}$ of the order of 1 μA. Above $i_{\min}$ a continuous discharge sets in. From equation (4) we can deduce that the over-voltage must not be allowed to become greater than

$$U_m - V_0 = (R + k)\, i_{\min}. \qquad \ldots\ldots(5)$$

This gives us an upper limit to the working range of the counter: the flat portion of the characteristic is generally considerably smaller than this. We see that in order to obtain a long counting range it is necessary to use a large resistance R, which as we saw above increases the time occupied by each kick, and makes fast counting inaccurate.

This dilemma has recently been overcome by the use of special value circuits. These will not be dealt with here, they will be found summarized in a recent article by Johnson[31]. Briefly the principle of their action is to amplify the kick Ri on the wire by a factor μ and feed it back on to the counter. The condition (5) then becomes

$$U_m - V_0 = \mu\,(Ri_{\min}), \qquad \ldots\ldots(6)$$

so that for the same over-voltage the time of recovery can be μ times as short.

§ 5. INTERMITTENT NATURE OF THE DISCHARGE

Various theories have been put forward to account for the momentary nature of the discharge. The similar discharges in point counters were explained[32] in a similar way to the flashing neon tube discharges by the form of the current-voltage characteristic curve. If this is negative, i.e. if the voltage decreases with increasing current, then the discharge can be intermittent. Similar explanations have been offered[33] for the discharges in wire counters but Werner finds both theoretically and experimentally that except at very low pressures k is always positive, so that the discharge should be stable.

A very similar theory based on the action of space charge has been put forward by von Hippel[34]. This may be correct for the discharges between plane electrodes, but its extension to the wire counter seems to be unsound except in very abnormal circumstances[34a]. Here again Werner's work shows that space-charge effects lead only to the equilibrium condition, equation (4).

The presence of a surface layer on the cathode has been found by some authors to be essential. Very careful outgassing of the electrodes destroys the counting properties of the tubes in some cases[43, 44]. This is probably because of the change produced in the work function of the surface. It seems unlikely that this surface layer actually extinguishes the discharge.

Werner himself suggests that the extinction occurs through random fluctuations in the positive ion space charge. This would occasionally lead to too low a field strength for the maintenance of the discharge. Werner does not give any quantitative estimate of this effect; a rough calculation shows that the fluctuations required would be too large to occur often enough. von Geel and Kerkum and, independently, the writer[35], have put forward the theory that the random fluctuations in the emission of the photo-electrons from the outer wall are responsible. For currents of the order of $i_{\min}$ the average number of photo-electrons generated by each avalanche is only of the order of ten, so that there is a finite chance that at some particular avalanche the number will be zero, when the discharge will stop. This theory gives a good agreement with Werner's data on the mean life time of the discharge at various values of the current i.

The value of $i_{\min}$ for a counter is a most important measure of its reliability. It will be seen from equation (5) that for a given value of R it determines the range of over-voltage in which the discharge is intermittent. It is therefore an advantage to have $i_{\min}$ as large as possible. Unfortunately at the moment none but empirical means can be used to predict its value. Werner gives tables of $i_{\min}$ for various gases from which it appears that it increases with pressure, and is large (1 μA.) for hydrogen, and very small for nitrogen and *pure* inert gases. It is to be hoped that the development of a correct theory of the intermittent discharge will enable values of $i_{\min}$ to be predicted, and these variations understood.

In the type of counter discussed above the discharge is extinguished by the current being brought below $i_{\min}$ by means of the resistance R. This type of discharge always gives a change in potential on the wire nearly equal to the over-voltage.

A quite different type of discharge has been obtained by Trost(36), in counters containing alcohol vapour mixed with the normal gas. These can be used with only a small series resistance, and a large over-voltage. The discharge is no longer extinguished by the external limitation of the current but by some internal mechanism. Trost found that the change in potential on the wire was not equal to the over-voltage, but changed if a condenser were placed in parallel with the counter in such a way as to show that a constant charge was being collected by the wire at each discharge.

Trost suggests that the mechanism of the counter is that the discharge lasts until a sufficient number of positive ions have been accumulated near the wire to bring the electric field throughout the counter below the value at which multiplication occurs. The discharge then ceases and this number of positive ions gives the charge collected by the wire: the magnitude of the charge actually collected agrees with this. It is not immediately clear however why the discharge should be extinguished instead of burning at some steady current i as the counters discussed above. The following suggestion may be offered. If the initial multiplication is very much greater than the normal multiplication, as it will be at high over-voltages, then the first few avalanches may form rather more than the number of positive ions required to reduce the multiplication to normal. The multiplication will then be less than normal until this excess charge has moved across the counter, and in this time the successive avalanches will have been decreasing and may have reached zero.

Because of the low series resistance with which they can be used these counters give a very quick resolving time (10^{-5} sec.) and a very uniform size of kick. Trost found that using argon with 2 per cent of alcohol vapour the counters could be operated at atmospheric pressure.

§ 6. SPURIOUS DISCHARGES AND OTHER DEFECTS

The plateau of the characteristic curve in figure 2 is hardly ever quite flat. The number of counts generally increased slowly with the voltage, an increase of 1 per cent per volt being quite usual. There are several causes for this. Any slight asymmetry of the electrodes leads to variations in the electric field in different parts of the counter, so that the critical value at which counting begins is not attained at the same voltage over the whole tube. The effective counting volume therefore increases continually. Christoph[37] has investigated this effect by deliberately placing the wire at a variable distance from the axis of the outer cylinder. He found that even a small displacement had a marked effect on the plateau of the characteristic curve. On the other hand a local irregularity in the outer cylinder has little effect so that it is possible to use a wire gauze as the outer cylinder.

A similar effect is caused by the variation of the field at the ends of the outer cylinder. This can be avoided by shielding the wire in this region so that it does not count. In this way the counting volume is clearly defined, and has the same length at all voltages. Cosyns[23], by adopting this precaution, was able to obtain a very flat plateau.

Even with these precautions when the over-voltage reaches high values (100 v.) the number of discharges rises rapidly.

When U exceeds the value given by equation (5) the discharge becomes continuous, but well below that point, when the discharge is still intermittent, a large number of spurious discharges occur. These have been studied by various workers[38, 29, 23] whose results are rather complicated and contradictory. It seems to be fairly definite that many, if not all, of the extra discharges are induced discharges in the sense that some previous discharge has left the counter in an excited condition from which it recovers by a series of spurious discharges.

In Medicus' experiments[38] the distribution of the discharges in time was studied, and distribution curves plotted of the number of times the interval between successive discharges had certain values. For low voltages these agreed with the curves expected for a random distribution of discharges, but at high potentials there was a surplus of small intervals showing that one discharge had a tendency to cause another succeeding one. From these results Medicus found that the probability of an induced discharge decreased exponentially with the time after the parent discharge and this decay had a time constant of a few seconds. Other less detailed experiments such as those of Christoph and Hanle[29] and Cosyns[23] led to much the same results. Cosyns found induced discharges with a time delay of the order of minutes.

Medicus found that the presence of traces of water vapour in the counter encouraged these spurious discharges, a carefully outgassed tube did not show them. On the other hand many authors[43, 44] have found that counters with very carefully outgassed electrodes and purified gases fail to show any counting properties. This is cured by allowing a trace of some impurity, usually oxygen, to be present. It seems likely that this forms a surface layer on the cathode which is essential to the working of the counter. Lewis and Burcham[39] found that cleaning the outer tube with abrasives produced a number of spurious discharges which died away in about 10 min. These they ascribed to the emission of electrons in the process of oxidation of the cathode as the surface layer was reformed. It may be that a similar process causes the induced discharges discussed above. The heavy discharge at high voltages might clean part of the layer of the cathode, and during its reformation induced discharges would occur.

The effect of this surface layer is very strikingly shown in some of Trost's experiments in which the cathode surface was coated with a layer of varnish. This greatly extended the flat portion of the characteristic and made it possible to use cathodes of materials such as aluminium which gave very poor counters without it.

All counters, but especially the older types using ebonite insulators, are liable to erratic changes in the counting properties through the emission of gases from their walls. This may occur through a change in temperature or under the influence of the discharge. It can be avoided by connecting the counter to a large reservoir[40] which reduces the effect of a given amount of impurity, or better by using counters sealed in pyrex glass and carefully outgassed. The preparation of these has been described in many papers[23, 41, 42]. This is fairly simple if the counter is for detecting γ-radiation or cosmic rays, but when thin windows have to be used to admit β-rays the technical difficulties are greater but have been overcome.

As was mentioned above too thorough purification of the gas and cleaning of the electrodes destroys the counting properties of the tube. Many authors seem to be able to reach the right degree of impurity by using commercial gases without extra purification, or by accident. It is probably better to use deliberate mixtures of gases, such as those of the inert gases and hydrogen, or those recommended by Trost.

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