REVIEWS OF

MODERN PHYSICS

VOLUME 14 JANUARY, 1942 NUMBER 1

The Operation of Proportional Counters

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INTRODUCTION

IT has been known for many years, indeed since the early work of Geiger and Klemperer,[1] that it was possible to construct counters in which the magnitude of the pulse observed on the collecting electrode was proportional to the size of the initial ionizing event causing the counter to discharge. Pollard and Brubaker[2] worked out a modification of these early counters, suitable for the detection of particles traversing the counter along its axis, and having paths at varying distances from the collecting electrode. This type of detector has been used by many observers.[3] These counters differ from those to be discussed in this paper in that they are essentially point counters, having quite different geometrical properties from those with cylindrical symmetry here described.

It was recognized by Korff and Danforth[4] that it was possible to use the conventional Geiger-Mueller type of non-proportional counter usually consisting of a cylindrical cathode with an axial wire, under certain special conditions, to give proportional counting action. These were first tried in connection with boron trifluoride fillings as counters for slow neutrons, and soon thereafter as recoil counters[5] for the detection of fast neutrons. These counters were used in the study of various problems arising in the cosmic-ray investigations, to measure the amounts of ionization produced by various heavily ionizing particles, such as slow protons,[6] and have been adapted to the balloon technique.[7] The theory of the action of such counters has been studied by Rose and Korff,[8] and recently by Ramsey and Rose.

These counters are to be distinguished from Geiger counters, in that we define a Geiger counter as one in which the magnitude of the pulse observed is not proportional, and indeed is in general independent of the number of ions formed in the initial event initiating the discharge. Geiger counters have been treated in

[1] H. Geiger and O. Klemperer, Zeits. f. Physik **49**, 753 (1928).
[2] G. Brubaker and E. Pollard, Rev. Sci. Inst. **8**, 255 (1937).
[3] For example, G. Ragan, W. Kanne, and R. Taschek, Phys. Rev. **60**, 628 (1941).
[4] S. A. Korff and W. E. Danforth, Phys. Rev. **55**, 980 (1939).
[5] S. A. Korff, Phys. Rev. **56**, 210 (1939).
[6] S. A. Korff, Phys. Rev. **59**, 949 (1941).
[7] S. A. Korff, Rev. Mod. Phys. **11**, 211 (1939); Proc. Am. Phil. Soc. **84**, 589 (1941).
[8] M. E. Rose and S. A. Korff, Phys. Rev. **59**, 850 (1941); W. E. Ramsey and M. E. Rose, Phys. Rev. **61**, 198 and 504 (1942); W. E. Ramsey and E. M. Hudspeth, Phys. Rev. **61**, 95 (1942); W. E. Ramsey, Phys. Rev. **61**, 96 (1942).

detail by other writers,[9] and it is not our purpose to discuss them in what follows.

I. PROPORTIONAL COUNTERS

A. Pulse Size

The problem in using proportional counters is essentially one of obtaining an output pulse produced by some initial ionizing event which it is desired to study, of sufficient size to operate a recording mechanism. It is further necessary that some other ionizing event, smaller than this first one by a known amount, shall not produce a pulse large enough to record. It is evident that any pulse may be amplified to a desired size either in the counter itself or in the attached vacuum-tube circuit. Two variables are in this way provided, and we will discuss below the practical limits on each.

As the potential on a counter is raised, the counter goes through a continuous series of changes, starting at low potentials as an ionization chamber and continuing through the stage of a proportional counter, a Geiger counter, and finally at excessive potentials to the case which has no practical utility in the present discussion, namely a continuous breakdown. As the potential is slowly raised, a voltage is reached at which ions, while being swept to the collecting electrode under the influence of the field, acquire sufficient energy in the last mean free path before reaching the collecting electrode to produce additional ions by collision. This voltage we shall define[8] as the threshold voltage for proportional counter action. As the voltage is further raised, the critical distance moves outward from the wire and the additional ions produce yet other ions by collision, thus forming the familiar Townsend avalanche. At higher voltages, the size of this Townsend avalanche is limited by space charge and other complex considerations, and eventually a maximum avalanche size at any particular counter voltage, is reached. This maximum size is determined by the "overvoltage" of the counter. At these voltages the avalanche is not determined by the amount of the initial ionization but only by the voltage on the counter. Following the Montgomerys[9] we shall define the voltage at which all pulses are of the same size regardless of the size of the initiating event as the starting potential for Geiger counter action. It should be emphasized that this is not necessarily the same voltage as the "threshold" at which a Geiger counter first begins to count with any given circuit. As the voltage is still further raised, the counter characteristic passes along the plateau and eventually to a continuous discharge. The region below the Geiger counter threshold will be that discussed in this paper.

B. The Region of Proportionality

In an ionization chamber, if n ions are formed by an initial ionizing event, then these will be swept into the collecting electrode and, neglecting recombination, will produce a change in the potential of that electrode given by

$$P = ne/c, \tag{1}$$

where P is the size of the pulse in volts on the collecting electrode, c is the distributed capacity of the collecting electrode and the attached electrical parts, and e is the specific charge of the electron in volts. This pulse will appear on the electrode in a time determined by the mobility of the ions involved, which for electrons (since counters are usually operated with the central wire positive) is quite small, and usually lies between 10^{-4} and 10^{-8} sec. At voltages above the proportional counter threshold, the pulse size on the central wire will be given by

$$P = Ane/c, \tag{2}$$

where A is the "gas amplification," or the number of additional ions formed by collision by each initial ion. It is evident that A will range between unity at the threshold to a virtual infinity in the Geiger counter region. The increase of A with voltage is at first uniform, but ceases to be so at higher voltages where the Geiger threshold is approached. Below the Geiger threshold there exists a voltage region of "limited proportionality" in which the larger pulse sizes have had some factor limit their growth, and in which region A is not a constant but depends on n. Ex-

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[9] W. E. Ramsey, Phys. Rev. **57**, 1022 (1940); G. L. Locher, Phys. Rev. **55**, 675 (1939); C. G. and D. D. Montgomery, Phys. Rev. **57**, 1030 (1940); J. Frank. Inst. **231**, 447 (1941); S. Werner, Zeits. f. Physik **92**, 705 (1934); A. N. May, Proc. Phys. Soc. **51**, 26 (1939); H. Geiger and W. Mueller, Physik. Zeits. **29**, 839 (1928); **30**, 489 (1929).

perimentally this has been shown[10] by producing two pulses of known but different sizes, with a ratio of about 12 : 1. This ratio was found to occur both in the ionization chamber phase and throughout the proportional counter region until the Geiger threshold was approached. The proportional threshold was at about 1500 volts, and the pulse size ratio was observed to be maintained up to a voltage of 2600. The ratio progressively decreased at voltages in excess of this and reached unity at the Geiger counter threshold of 3100 volts. It is evident that this counter can be used as a proportional counter only in the region below 2600 volts.

C. Theory of Proportional Counter Action

The theory of the action of proportional counters has been investigated for certain cases.[8] As indicated above, this theory was based on the picture of the Townsend avalanche, three assumptions being made in the calculations. These assumptions are (1) that photons play an unimportant role in the formation of the avalanche, (2) that recombination may be neglected, (3) that fluctuations may be neglected. The validity of the first assumption under certain circumstances has been experimentally established and it has been further shown that it is clearly not valid in certain other types of counters. As to the second assumption, this is evidently justified by the high fields, low gas pressures, and small collecting times. The third assumption is the equivalent of stating that the ionization on the path of any ion is equal to the average ionization along that path. The problem of discussing the effect of fluctuations is at present under way at the Bartol Research Foundation.

The calculations have led to the following general formula for the gas amplification:

$$A = \exp 2(aN_m cr\varphi(0)V_0)^{\frac{1}{2}}[(V_0/V_t)^{\frac{1}{2}}-1], \quad (3)$$

where a is the rate of increase of the ionization cross section with energy, N_m the number of molecules of type m per unit volume, $\frac{1}{2}c$ the capacity per unit length of the counter, r the radius of the wire, $\varphi(0)$ the number of slowest electrons which may be taken as unity numerically, V_0 the voltage on the counter, and V_t the threshold voltage for proportional counter action. By inserting the various quantities for known gases and mixtures thereof, pressures, and geometrical sizes, good agreement has been found between the theory and experiment in certain cases. The formula begins to break down at low gas pressures, at large values of A ($A > 10^5$) and also in the case of mixtures when high percentage concentrations of gases are present in which photons are formed. Subsidiary experiments have shown that photons are important in certain gases. In general, the types of gas to which the above analysis is applicable are those containing complex molecules, and included as a special case are the so-called self-quenching counters. Such gases included methane and boron trifluoride as well as the usual mixtures of argon with alcohol or ether vapor. The analysis does not apply to gases such as argon, hydrogen, neon, or air, or any mixture of these. On this picture the self-quenching action is a manifestation of the absence of photons, since these help to spread the discharge. It will thus be seen that any of the above gases in which photons are absent are especially useful for proportional counters, whereas the other type, because of the rapid variation of A with voltage require much more critical stabilization of the voltage. It is further seen that when these gases are so used the size of the pulse may be computed under known conditions. It should be noted that, when photons are present, the variation of A with V is faster than indicated by Eq. (2). Experimental indications of this effect have been given by Rose and Korff.[8]

Typical starting-potential curves are shown in Fig. 1, for various conditions. Here are shown the curves for various argon-methane mixtures in a counter suitable for the detection of cosmic rays, indicating the advantage of the lowered operating voltage obtainable by such mixtures.

D. Measurements and Calibrations

There are two ways of making measurements with these counters. If the counter is to measure an ionizing event of a given size and to discriminate against a background produced by electrons and gamma-rays, then it may be operated at a single appropriate voltage and the counting rate

[10] S. A. Korff, Rev. Sci. Inst. 12, 94 (1941).

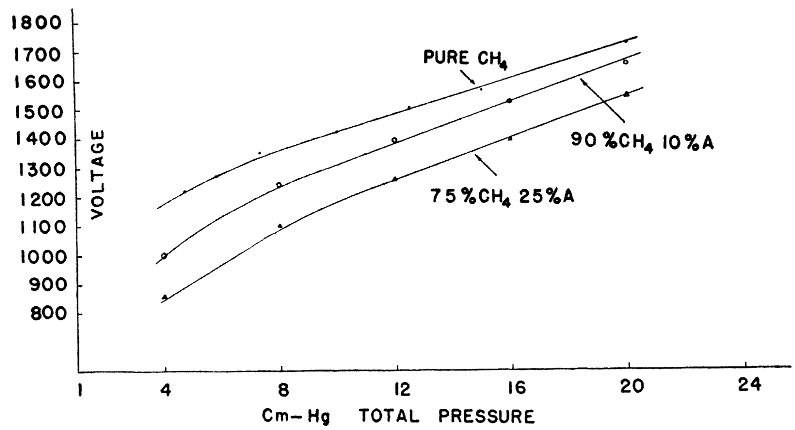

FIG. 1. Starting potential curves for a methane-argon gamma-ray counter. At percentage concentrations of argon, greater than 50 percent, the self-quenching feature disappears and the usefulness of the counter is greatly diminished. Counter 10 cm long, 1.2-cm diameter, 3-mil wire.

recorded. If, on the other hand, it is desired to measure ionizing events which have a distribution in size, such as a group of protons of varying energy might produce, then the following procedure is employed. The counting rate is determined as a function of voltage. It is evident that the curve of counting rate against voltage is an integral curve, since the counter detects all pulses greater than a certain size. The counting rate will be given by

$$n = A \int_{E_1}^{E_2} i(E)dE, \tag{4}$$

where n is the number of counts per second, and A is the cross-sectional area of the counter exposed to the radiation consisting of a flux i of particles of energy E per square cm per second. The limits of integration are the lowest and highest energies detectible in this counter, and will evidently be determined by the amplifier setting, the gas used in the counter, and the nature of the particle detected. The differential of the counting rate curve is the pulse size distribution. Hence to obtain the pulse size distribution it is necessary to differentiate the counting-rate curve with respect to voltage.

Such an integral curve will correspond to a particular setting of amplifier gain determining a fixed minimum pulse size necessary to record. If the gain of the amplifier is increased, the entire curve will be shifted to lower voltages. The desirable pulse size or voltage region in which to operate such a counter is discussed in the last section below. It is clear that there are two variables, the gas and vacuum-tube amplification which may be used alternatively.

The above procedure gives the pulse size distribution as a function of the counter voltage. It is next desirable to know this distribution as a function of the size of the ionizing event, defined as the number of initial ions produced in this event. A calibration in these terms may be achieved by observing the size of the pulse which is produced when an ionizing event of a known size takes place within the counter. Such ionizing events may be produced by projecting alpha-, beta-, and gamma-rays or protons of known energy through the counter, since the amount of energy lost in ionization per counter traversal by such a particle can be found in the range tables for various gases. It is possible in this way to obtain several known pulse sizes. For example, the largest pulse which can be obtained from an electron is one which results when the electron has ended its range along the length of the counter cylinder. An electron of high energy will obviously pass through the counter without giving up all its energy as ionization. Since the ionization of any particle is particularly heavy at the end of its range, this fact may be used in calibration procedure. A simple expedient is to project alpha-particles into the counter through a thin window. Such a construction, used in recent experiments,[11] is shown in Fig. 2. If the thickness of the window is known, the amount of energy expended in ionization by the alpha-particle in the gas of the counter can easily be

[11] S. A. Korff and E. T. Clarke, Phys. Rev. 61, 422 (1942).

computed. The alpha-particle source can then be moved to some slightly further distance from the window and a new point be obtained, since the additional energy loss due to the traversal of the new interval of air between the source and the window can be readily determined.

The above procedure yields the distribution of size of the ionizing events as a function of their number. These data are of direct use if the particles to be studied are those which produce the pulses. Typical curves of this type are shown in Fig. 3. However, in the case of certain other experiments this is not the case. If, for example, it is desired to measure the flux of fast neutrons, then it is evident that these neutrons will produce recoiling nuclei of high specific ionization in the counter. However, since such recoils may take place at any angle it is also evident that a monoenergetic neutron beam will produce a continuous distribution in size of the recoils. In theory, a second differentiation is therefore necessary in order to obtain the energy spectrum of the neutrons involved. Actually a determination of the most energetic recoils usually suffices. For a complex spectrum of neutrons, if the recoil cross section is a function of the energy, it is evident that the counting rate is determined by an integral equation of the general form

$$n=\int I(E)\sigma(E)dE, \qquad (5)$$

where n is the counting rate and counts per second, $I(E)dE$ is the flux per cm^2 per second of neutrons in the energy interval dE, and $\sigma(E)dE$ is the recoil cross section which is in general a function of the energy. An analytical solution in general terms is out of the question. However, in many cases approximate solutions can be made by assuming the cross section to be a constant, which is approximately true in certain cases. This approximate solution, while by no means ideal, is often better than no solution at all.

E. Self-Quenching Counters

In the above discussion it has been assumed that what is measured is the size of the pulse appearing on the wire, that this size is proportional to the number of ions initially formed in the counter, and that therefore a single avalanche mechanism suffices to describe the transient discharge. This is essentially the mechanism which takes place in self-quenching counters when operated at such low voltages that the formation of photons can be neglected. The introduction of the so-called quenching gases such as the organic vapors into a counter filled with argon or other simple gas in which the photons do play an important role in discharge permits the removal of the photons. It is clear, therefore, that an insufficient amount of the organic vapor will result in an incomplete elimination of the photons and in incomplete quenching. A reduction in the amount of the organic vapor present takes place with a fall in the temperature, and hence counters of this type have a temperature coefficient. This difficulty can be remedied[12] by using counters filled with a gas which remains in a gaseous phase at low temperature, such as methane or boron trifluoride.

II. NEUTRON COUNTERS

A. Boron Trifluoride Counters

A counter filled with boron trifluoride gas and operated as a proportional counter will count, when it is exposed to a flux of slow neutrons, due to the alpha-particles which are produced by the

[12] S. A. Korff, W. D. V. Spatz, and N. Hilberry, Rev. Sci. Inst. 13, 127 (1942).

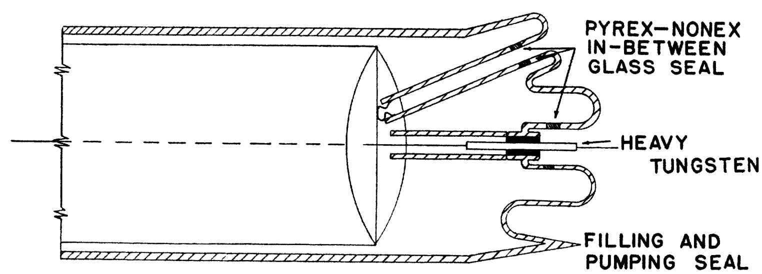

FIG. 2. Construction of thin window on counter to permit alpha-particles for calibration to be projected into the sensitive volume with minimum loss of range. An extremely thin glass bubble is attached to the end of a tube entering the volume of the counter, and a rod with some mesothorium or polonium on one end is lowered through the tube and brought near the window.

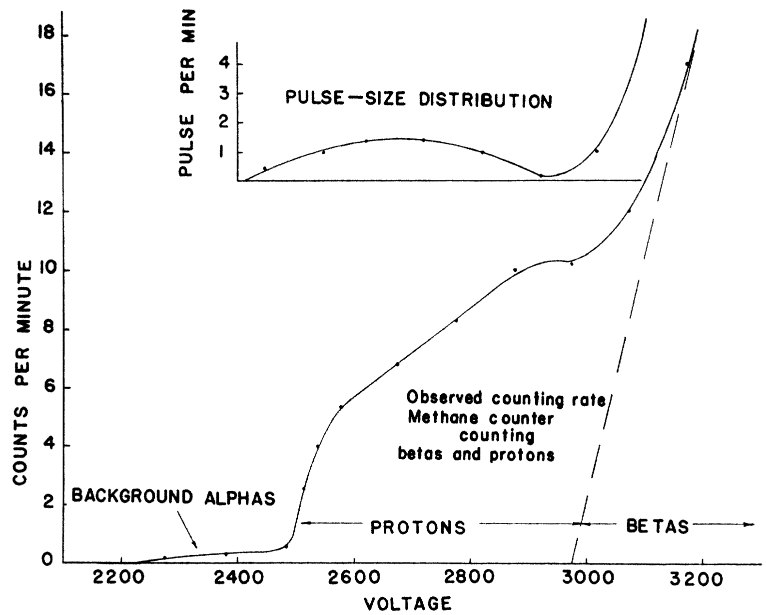

FIG. 3. Example of counting rate curve and pulse-size distribution curve obtained therefrom, while the counter was detecting three different types of particles.

disintegration of the B^{10} nucleus by the neutron. The counting rate of such a counter will evidently depend on the number of such B^{10} nuclei available, the flux of the neutrons, and the cross section for capture. Since the cross section is known to vary inversely with the velocity, and since the flux of neutrons is equal to the velocity multiplied by the neutron density per cc, it is evident that the velocity term will disappear, and that the quantity measured by a neutron counter of this type is the density ρ per cc of all neutrons in the energy range in which the capture probability is governed by the $1/v$ law. For a boron trifluoride counter this is known to cover the energy range between thermal neutrons and those of 10,000 electron volts, and may even extend up to ten times this figure although at these high energies the cross section has become so small as to be comparable with the recoil cross section, and therefore the recoil process will produce a measurable amount of competition.

Typical curves of the starting potentials of a BF_3 counter detecting neutrons are shown in Fig. 4. It will be noted that the operating voltage range, in which it is possible to discriminate between neutrons and gamma-rays, becomes greater at higher gas pressures.

The counting rate n counts per second of such a counter will evidently be given by

$$n = VNp\rho\sigma_B v_B, \tag{6}$$

where V is the volume in cc of the counter, N is the Loschmidt number, p the pressure of the BF_3 in the counter, ρ the density per cc of all neutrons with energies below about 10^5 ev, and σ_B is the capture cross section of B^{10} for neutrons at some known velocity v_B. It is to be noted that v_B is a quantity which has no necessary relationship to the velocities of the neutrons to be measured. The value of σ may be corrected to take account of the $B^{11} : B^{10}$ isotope ratio in commercial BF_3. The quantity which is measured is the neutron density ρ, and the flux cannot be determined by these counters unless the velocity is known.

The efficiency E, defined as the fraction of a flux of neutrons which produces counts, is evidently given by the ratio of the counting rate (e.g., Eq. (5) per unit volume) to the flux, and hence by the relation

$$E = NP\sigma_B L, \tag{7}$$

where L is the average path through the counter of the neutrons to be measured. The calculation of the average path through a cylinder presents certain analytical difficulties in the general cases, although certain special cases have been computed by Swann.[13] To a sufficient degree of approximation we may take L as a diameter. Then, for example, considering a 7-cm diameter counter with one atmosphere BF_3, $P=1$, $L=7$, $N=2.7\times10^{19}$, $\sigma=550\times10^{-24}$, E will be about 10.4 percent. A smaller counter with $p=0.1$ atmos., $L=2$ cm would have an efficiency of 0.29 percent. It is obvious that the counter is not made more efficient by making it longer, although the total counts recorded will increase.

It is also evident that the efficiency depends on the neutron velocities, the above examples assuming the value of σ appropriate for a flux of only thermal neutrons. For higher average energies, σ must be decreased according to the $1/v$ law, i.e., must be multiplied by v_t/v_m where v_m is the velocity of the neutrons measured and v_t the thermal velocity. Thus the efficiency will depend on the arrangement of scattering and slowing down material around the counter.

In computing the number of neutrons to be expected at a given distance from a source, it must be recalled that because of scattering the inverse square law does not apply, and that the processes of the diffusion theory must be used. Since almost any source produces neutrons with relatively high energy and since almost any substance slows them down, it is evident that the energy distribution will be a function of the distance from the source and the geometry. The processes for computing the result for any given arrangement are familiar in diffusion theory.

It is possible to measure the number of neutrons in a given energy range with counters of this type by making measurements with and without certain types of absorbing screens. Thus for example a cadmium shield of $\frac{1}{2}$- to 1-milli-

[13] W. F. G. Swann, J. Frank. Inst. **216**, 559 (1933).

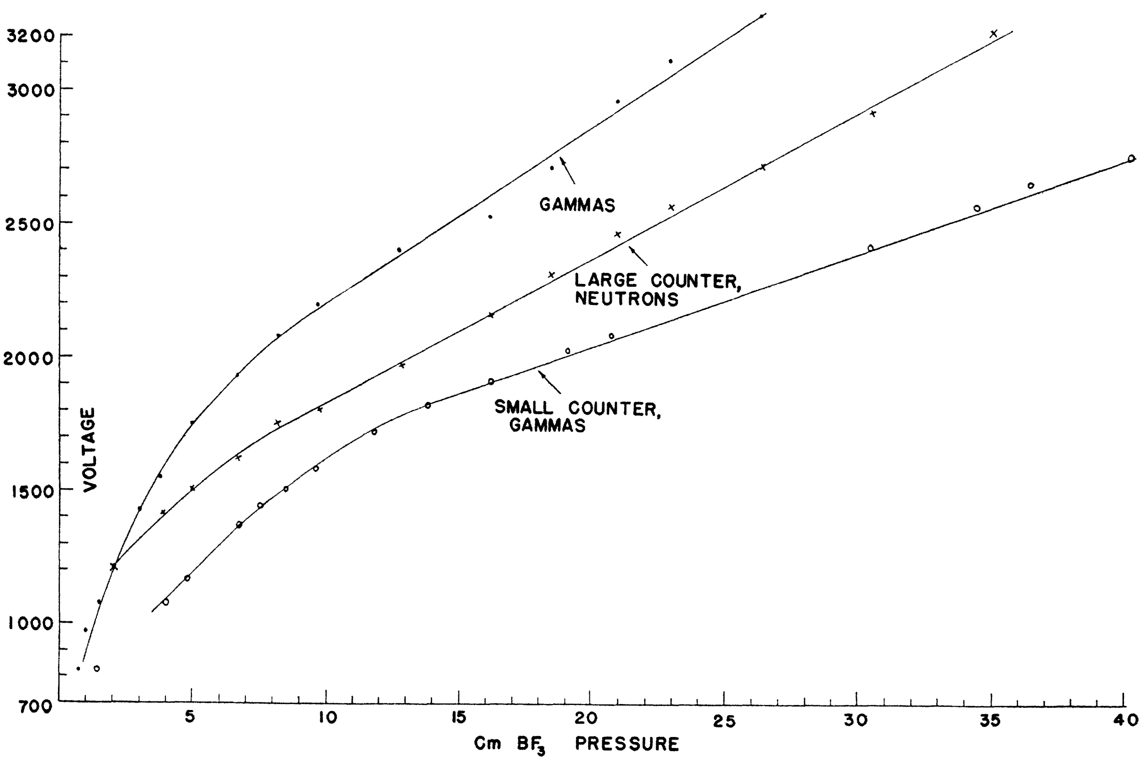

FIG. 4. Curves of starting potentials for neutron BF_3 counters, counting neutrons and gamma-rays. Note that the voltage difference between the neutron and beta-detection potentials increases with the BF_3 pressure. Large counter 5.5 cm-diameter, 22.7 cm long. Small counter 1-cm diameter, 3 cm long, central wire 3 mil. Pulse size constant about 0.1 volt.

meter thickness will be practically opaque to thermal neutrons and practically transparent to neutrons of more than one volt energy. Similarly, borax shields of various thicknesses may be used. In these, the absorption will of course occur inversely with the neutron velocity, and consequently the effect of any given thickness may be computed. In these calculations, account must be taken of the contribution to the slowing down due to the water of crystallization in the borax.

A counter of this type, if subject to a flux of fast neutrons will also count recoils. It is evident that a fast neutron may collide with a nucleus of one of the atoms in the gas of the counter or in the surrounding material and cause that nucleus to recoil through the counter. Such recoiling nuclei often have a high specific ionization and may produce counts. The total number of recoil counts n_r per second produced in the gas of the counter will be given by

$$n_r = VNP\int_{v_{\min}}^{v_{\max}} I(v)\sigma(v)dv, \tag{8}$$

where $I(v)dv$ is the flux of neutrons per sq. cm in the velocity interval dv and the recoil cross section is taken as varying with energy. The experimental evaluation of the limits of integration is discussed below. It will be observed that this is an integral equation of a type discussed previously, and that the simple solution will occur when the cross section may be taken as a constant over the energy range discussed. Because this recoil cross section is small, the efficiency of this counter, defined as the number of recoils produced for each fast neutron passing through it, as computed through Eq. (7), is low. For example, a counter 2 cm in diameter and filled to 28-cm pressure with hydrogen will have an efficiency of about 10^{-5}. The values of the recoil cross section have been measured by various observers for different substances and generally are of the order of 10^{-24} sq. cm. For example, for hydrogen, the neutron-proton scattering cross section is known to vary between 0.5 and 1.5×10^{-24} in the energy range between 400 kev and 4 Mev. For complex molecules, Eq. (8) must be modified to take account of the cross section of each atom of which the molecule is composed; e.g., for BF_3 it would include a term $(\sigma_B+3\sigma_F)$.

A further consideration is that the recoiling nucleus shall have enough energy to produce a count. In terms of Eq. (8), the velocity v of the recoiling nucleus shall be greater than v min. It is well known that a neutron of energy E colliding with a nucleus (other than a proton) of mass M will produce a recoil with an average energy $2E/M$ and a maximum energy of $4E/M$. For protons the maximum energy transfer is E and the average $E/2$. Consequently a counter adjusted not to detect any pulse liberating less than 50 kev as ionization in the counter will, if filled with hydrogen, detect neutrons with average energies in excess of 100 kev, but if filled with argon will on the average not detect neutrons with energies below 1 Mev.

With reference to the recoils ejected from the walls of the cylinder, it is evident that the number of counts will be given by

$$n_{rc} = \frac{N_A\rho A}{2\mu}\int_{v_{\min}}^{v_{\max}} \sigma(v)R(v)i(v)dv, \tag{9}$$

where N_A is Avogadro's number, ρ the density of the material of the cylinder, μ its atomic weight, σ the recoil cross section of the nuclei of this substance for the neutrons to be measured, i the flux of neutrons per cm^2 per sec., A the area of the counter, and R the range in cm of the recoiling nuclei in the material of the wall. The factor $R/2$ evidently arises from an integration to give the average number of recoils actually emerging, assuming a random distribution in angle of the recoils. If from this expression for the total recoils entering the gas from the walls be subtracted those which have insufficient energy after emergence to produce a count, it will be seen that wall recoils are only important if (a) the material of the walls is light, (b) the neutrons are of high energy, and (c) the gas pressure in the counter is small, and hence the recoils produced in the gas are few.

When hydrogen is used as a counter gas, another consideration is of importance. If the recoiling proton has a very high energy, it may pass through the counter without losing enough energy in ionization to produce recorded count. This is indicated by the upper limit of integration in Eq. (9). The upper and lower energy limits are established by the dimensions of the counter, the nature of the gas in the counter, and the energy spectrum of the incident neutrons, as well as by the voltage at which the counter is operated. For a heavy gas such as argon, the neutron energy necessary to produce a recoil too energetic to be counted is so large as to be beyond the range normally encountered and the limit may be considered as virtually infinity. It is evident that increasing the voltage on the counter, other things being equal, is the equivalent of decreasing the lower limit of integration. The upper limit is also raised, in those cases where it is not already effectively infinite.

Such a counter will also count any other event in which a large amount of ionization is liberated. Among such events will be giant showers, nuclear disintegrations produced by the cosmic radiation, and alpha-particles present as natural contamination in the walls of the counter. The number of counts due to these several causes may be regarded as a background if surrounding conditions are not changed and can be determined and subtracted from the counting rate by obvious procedures. The principal problem in the use of these counters lies in separating the disintegrations from the recoils. This may be done by varying the integration limits and by the use of cadmium and borax shields as discussed earlier.

Finally it should be pointed out that other gases in which neutrons may produce disintegrations have a possible usefulness in this connection. An uranium gas may be used since the fission fragments have a high specific ionization and would produce large pulses.

As an alternative to filling the counter with some gas as discussed above, counters are sometimes lined with a solid substance from which the disintegration particles emerge. Such a particle must get out into the volume of the counter in order to be detected. Consequently the number will be governed by an equation of the type of (9) above. It is evident that the maximum efficiency of a counter of this type lined with boron for slow neutrons will be given by the relation

$$E_{\max} = (N_A\rho/\mu)R_B\sigma_B, \qquad (10)$$

where R_B is the range of the alpha-particles in boron and σ_B the capture cross section at the velocity measured. For a boron lined counter and for thermal neutrons, $E_{\max}$ is about 5 percent. The boron lining need be only 0.1 mm thick, and added thickness will only reduce the efficiency. The same considerations would apply to a counter lined with uranium and operating by fission, except that alpha-particles originating in the uranium would have to be taken account of by setting the minimum detectable pulse size at a high value. Any gas may of course be used in such a counter, although those suitable for proportional counting action will be found desirable.

III. CONSTRUCTIONAL TECHNIQUE

A. Construction of Counter

Successful neutron counters have been made by employing the customary Geiger counter procedure of using a glass envelope inside which is a copper cylinder and an axial tungsten wire of 3-mil diameter. These counters have been treated by evacuation and baking, and the wire has been glowed for a brief period at high temperature. Such counters have been found to be still good after a lapse of over two years. The purpose of this technique is to remove any contamination from the containing vessel which might in time react with the boron trifluoride and cause a change either in the amount of the gas or in other properties of the counter.

Such counters have been filled from commercial cylinders of BF_3, some gas from the cylinder being first transferred into a large glass bulb connected to a conventional vacuum system. No special precautions were taken, except to evacuate all connecting tubing previous to transfer. As far as possible, rubber tubing was avoided since this is attacked by BF_3, and in the one place where it was used it was immediately discarded after filling. The pressure of the gas in the glass vessel was measured on a mercury manometer. It was noted that the gas attacked stopcock grease slowly, and once every few months all stopcocks were taken out, cleaned, and regreased.

It should be particularly emphasized that, in constructing a counter of this type, no wax must be allowed to be used on any surface with which the gas comes in contact. Thus, for example, a counter with waxed-in ends cannot be used since the gas not only changes in pressure due to the reaction with the wax, but eventually a film with undesirable electrical properties is formed on the inside of the counter. Some counters have been successfully made in which the gas was contained in a Kovar tube to which were sealed glass ends through which the central wire passed.

B. Gas Pressures

The lower limit on the gas pressure to be used in such a counter is determined by the consideration that, in order to detect disintegration alphas, the range of these particles must not be larger than the average path length through the counter. It will be recalled that such an alpha will have a range of the order of one cm of air equivalent, and hence in a counter of say 1-cm diameter and operating at 0.1 atmosphere will seldom have an opportunity of completing its range in the gas. However, the electron background is also small for such counters, and the difference in specific ionization can be detected even for incomplete ranges.

The upper limit is determined by the fact that as the gas pressure is increased the maximum size of the largest detectable beta-ray pulse also increases. Consequently the fluctuations due to the normal beta-ray background will get larger for bigger counters, and a limit will be reached where these fluctuations have become so large that it is no longer possible to distinguish between these and the alpha-particle pulses. The alpha-particle pulses are a fixed size, and naturally do not increase in size with the gas pressure. Thus, for example, a beta-particle of 250 kev has a range of about 50 cm of air equivalent. A counter 50 cm long and filled to 1 atmos. with BF_3 will permit this beta-particle to lose its full 250 kev as ionization within the counter and hence to produce a pulse whose size is not much smaller than that of the disintegration alpha. Applying this consideration to formula (7) above, it is evident that a practical maximum efficiency of about 50 percent is to be achieved with these counters.

Further increases in efficiency are, of course, possible providing that the gamma- and beta-ray background can be kept small, since it is quite evident that even if the largest beta-ray pulses are large, the neutron pulses can be distinguished by the use of cadmium and other screens providing the background is not so large as to swamp the neutron counts through its statistical fluctuations.

C. Detecting Circuits

The conventional type of the resistance-coupled counter amplifier is suitable for use with these counters. A typical circuit of this type is shown in Fig. 5. As has been pointed out above, a sufficient gain to operate the recording circuit may be achieved either through gas amplification or through vacuum-tube amplification. The upper limit on the sensitivity of such an amplifier, or the largest gain which may be used, is that of the customary linear amplifier. In this case, no gas amplification from the counter is used. However, this technique requires special insulation of the counter wire and first stage of the amplifier, and careful electrical screening is necessary. For other problems, this technique is not suitable due to microphonics to which high gain amplifiers are sensitive. Intermediate values of gain in the amplifier circuit may here be used to advantage, and an amplifier capable of recording a pulse of about 10^{-3} volt can easily be made free of sensitivity to microphonics and at the same time need be less rigidly shielded against electrical noise. With this amount of gain, a certain amount of gas amplification is involved.

As the voltage on the counter is increased and the gas amplification increases, then to produce a constant size output pulse it is possible to use progressively less vacuum-tube amplification. A practical limit is reached however when the vacuum-tube amplifier requires pulses in the order of one volt or more to operate. For pulses of this size and larger, the gas amplification in the counter is so large, that proper proportional counter action is not ordinarily achieved, and the counter is operated in the region of limited proportionality mentioned above. Consequently operation at large pulse sizes is to be avoided.

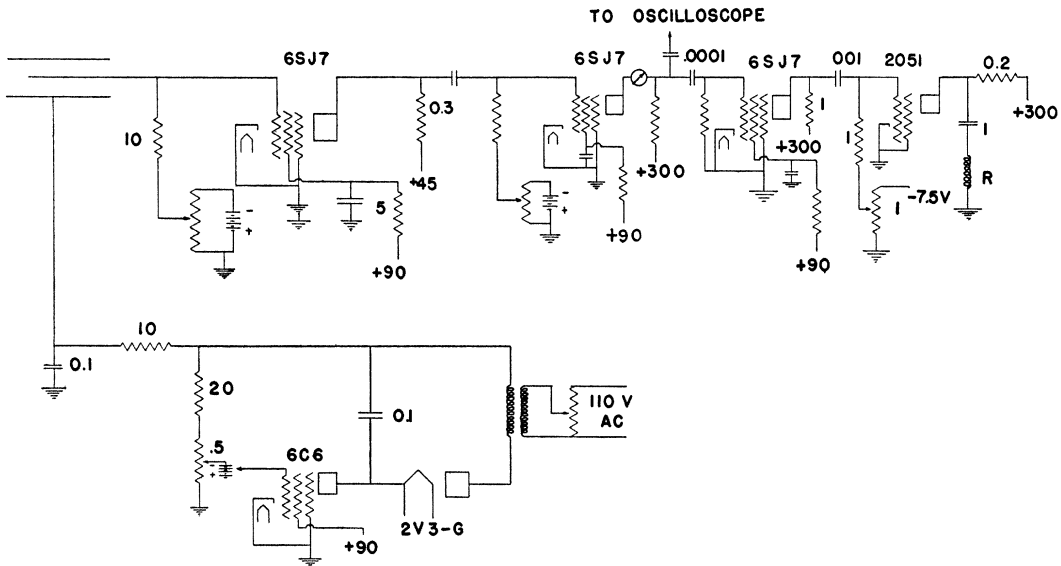

FIG. 5. Circuit for use with proportional counter. Resistances are in megohms, capacities in microfarads, potentials in volts. R is the mechanical recorder. The stabilized voltage supply circuit is shown in the lower part of the figure.

A typical circuit for use with counters of this type is shown in Fig. 5. It will be seen that this is a conventional resistance-coupled amplifier circuit, with controllable gain and of sufficient sensitivity to enable the detection of pulses of the order of 10^{-3} or even 10^{-4} volt in magnitude. The variable grid-bias permits control of the amount of amplification to be obtained in the circuit, and the oscillograph jack permits the size and shape of the pulses to be examined while the circuit is in operation. A stable and adjustable voltage source is desirable. Such sources, and control circuits have been described in detail by Hunt and Hickman.[14] The combination of adjustable voltage and controllable gain permits selection of the pulses to be recorded, and rejection of pulses produced by events other than those it is desired to measure.

The time constants involved are necessarily short. The electron avalanche is over in a very short time, of the order of 10^{-8} second. The migration of the positive ions toward the cylinder, which liberates the charge on the wire produced by the arrival of the electrons, and thus produces the actually observed pulse,[9] requires of the order of $10^{-4 \text{ or } 5}$ second. The subsequent recovery of the counter is determined by the R.C. time of the attached electrical circuits, and for a typical circuit, using a resistance of 10^6 ohms and a distributed capacity of 20 cm in the counter, tube grid, and connections, will be 2×10^{-5} second. If a second ionizing event follows another in shorter time than this, the potential of the counter system has not had time to recover to its full value, and hence will be the equivalent to having V_0 too low in Eq. (3). It is evident that this will result in reducing the value of A, and hence in too small a pulse being observed.

ACKNOWLEDGMENTS

The author wishes to acknowledge the encouragement and assistance received from his colleagues at the Bartol Foundation and at New York University in the preparation of this manuscript. Much of the experimental work reported was carried out at the Bartol Research Foundation of the Franklin Institute at Swarthmore, Pennsylvania. Some of the experiments were aided by grants from the Carnegie Institution of Washington. The counters were constructed by Austin Nester of the Bartol Foundation.

[14] F. V. Hunt and R. W. Hickman, Rev. Sci. Inst. **10**, 6 (1939).