

PARTICLE DETECTORS

Tsipenyuk Yu.M.

Russian Academy of Sciences, Moscow, Russia

Keywords: gaseous counters, ionization chamber, proportional counter, Geiger–Müller counter, semiconductor detector, neutron detection, position-sensitive detectors, time and amplitude measurement techniques

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Summary

In almost every experimental study of nuclear characteristics, nuclear-particle detection forms a major experimental technique. This article presents the main physical principles of the registration of neutral (neutrons) and charged nuclear particles, including ionization chambers, proportional counters, Geiger–Müller counters, semiconductor detectors, and track-etch detectors. Also considered are position-sensitive detectors, and the technique for identifying detected particles by measuring their kinetic energy and specific energy loss. Additionally, the principles of time- and amplitude-measurement techniques are considered, as well as the statistical character of nuclear events.

1. Introduction

The main difficulty in the registration of particles is that, from a macroscopic point of view, the result of a single interaction of particles with matter is negligible. The most noticeable effect is the ionization of matter by charged particles; the operating principle of the majority of existing charged-particle detectors is generally based on this capability. Conversely, neutral particles can only be registered by secondary processes, which is to say that charged particles are created as a result of nuclear reactions. Because of the very small ionization effect of each separate particle it is necessary to use amplifiers of high efficiency; however, conventional radio engineering is not

suitable for the operation of the first stage of amplification. As a rule, a particle detector is used in any unstable state of a physical system for which a detected particle will act as a trigger. Particular examples are supersaturated vapor, superheated liquid, and gas in a state that is just short of breakdown. In this article we consider the main physical principles of the registration of nuclear particles.

2. Gaseous Counters

A charged particle moving through matter loses its energy in collisions with atoms of matter. In each collision atomic electrons are transformed into excited states. If the excitation state belongs to the ionization continuum, then the atom is said to be ionized, producing an ion pair. If ionization is produced in a gas, the ions may be collected by electrodes between which a suitable electric field is established. The amount of charge collected by the electrodes will be proportional to the number of ions produced in the ionization of gaseous atoms. For most gases production of one pair (an electron plus the ionized atom) consumes 32–34 eV of the incident particle's energy.

The motion of ions in a gas is accompanied by many processes—adhesion, diffusion, recombination, collision ionization—whose influence depends on the geometry of the detecting instrument, composition and pressure of the gas, and intensity of the field. Depending on the particular purpose, gaseous counters are divided into:

- ionization chambers, which are current chambers that measure the intensity of radiation and pulsed devices capable of detecting short-range particles;
- proportional counters, in which the electric pulse is proportional to the number of initial ion pairs, and therefore to energy; and
- Geiger–Müller counters, which are instruments for counting separate particles.

2.1. Ionization Chambers

The ionization chamber is an instrument for quantitative measurement of ionization produced by charged particles in their passage through gas. The chamber is a closed gas-filled volume that includes electrodes (see Figure 1). Due to the electrostatic field established between the electrodes, the charge carriers move, inducing a current in the chamber circuit. As the average ionization energy of atoms W is about 30 eV, a 1 MeV-particle can produce in its path some 30 000 electrons, corresponding to a charge of 5×10^{-15} C. In order to create a measurable potential from such a small quantity of charge, the capacity C between electrodes and for electrodes relative to ground has to be small. This capacity, together with the resistor R , which is inserted in series with the electrodes for measurement of potential, forms an RC -network that influences the pulse shape of the voltage. As electron mobility is about a thousand times greater than that of ions, qualitatively the voltage pulse consists of two components (see Figure 1): the fast component, resulting from the greater mobility of the electron; and the slow component, resulting from the less rapid ion component. The existence of the RC -chain leads to a change of shape of the current pulse at the output of the counter. The parameters of the RC -network are usually adjusted to include only the electron component: that is, the time constant is chosen such that $T_e \ll RC \ll T_i$ (T_e, T_i are the collection time of electrons and ions), and hence only the faster component is integrated to give a final pulse shape (see Figure 1) with a height of about $V_e \times T_e$.

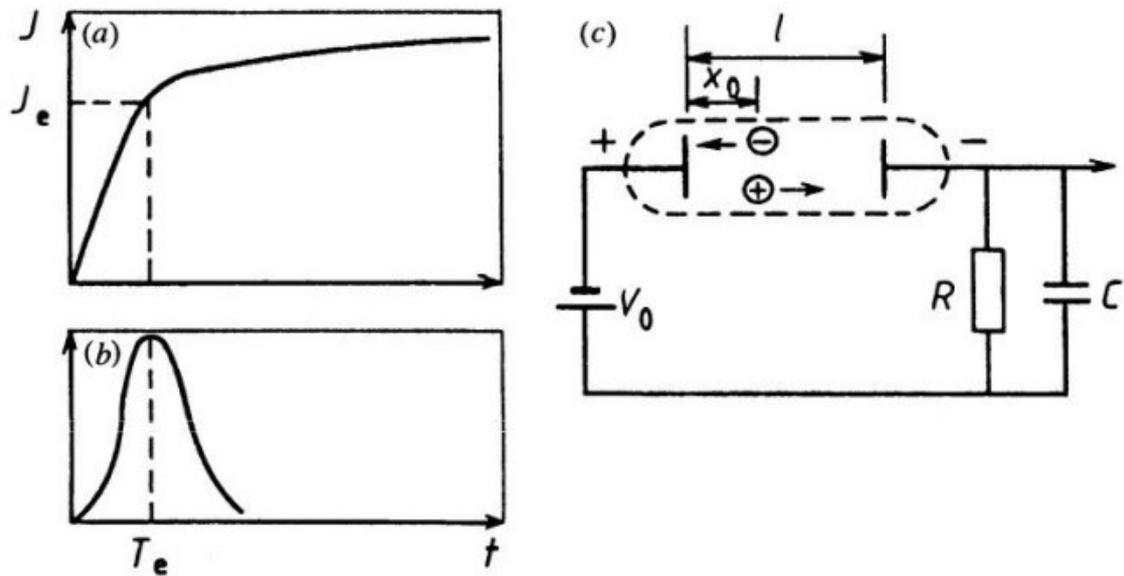


Figure 1. Ionization chamber: (a) shape of the current pulse created as a result of the traversal of an ionizing particle; (b) pulse after RC -network; and (c) electrical scheme

Let us calculate the change in the collecting electrode potential resulting from the traversal of just one particle through the chamber. We assume that the charge produced in gas is small relative to the charges that created the initial electrode potential V_0 . Let the moving particle create during its traversal through the sensitive volume of the chamber an average of \bar{n} ion pairs at a distance x from the anode (see Figure 1c). To move the charge $\bar{n}e$ from a point x_0 to x it is necessary to perform work at the expense of electrostatic energy of the chamber. If the distance between the plates of the chamber is l , the voltage difference after displacement of charge $\bar{n}e = V$, and if the field intensity equals V_0/l , then we obtain, by invoking the law of conservation of energy, that:

$$\frac{1}{2}C(V_0^2 - V^2) = \int_{x_0}^x \frac{\bar{n}eV_0}{l} dx = \bar{n}eV_0 \frac{x - x_0}{l}. \quad (1)$$

Since $\Delta V = V_0 - V \ll V_0$, it is then easy to obtain from (1) that:

$$\Delta V = \frac{\bar{n}e\Delta x}{Cl}. \quad (2)$$

Eq. 2 determines the pulse height due to the displacement Δx of charge carriers. The total pulse height, being equal to the sum of electron and ion components, is determined by particle energy only (i.e., by the number of ion pairs produced). However, in a practical system that only registers the electron component, the pulse height will range from 0 to $\Delta V_{ma} =$ in accord with Eq. 2. This is called the inductive effect.

The electron pulse is practically independent of the point at which free electrons are produced, and therefore a chamber with a cylindrical geometry is used. This independence of the pulse size from the position of registration is due to the fact that the

majority of the voltage drop occurs in the region near the central (anode) wire. If a particle alters a chamber, then the number of ions produced, and hence the pulse height, will be proportional to the particle energy. The least inductive effect is obtained by using a spherical chamber, but such a device is very complicated to manufacture.

Operation of an ionization chamber based on electron collection requires control of the composition of the filling gas. One of the reasons for this is that for some electronegative gases (particularly oxygen and water vapor), electrons have a high probability of adhering to neutral molecules and of forming heavy negative ions—in the examples above these are O_2^- or H_2O^- . Such ions also move to the anode, but with velocities that are approximately equal to those of heavy positive ions, and, as a result, electron collection can be radically inhibited. As such, gas mixtures have to be carefully purified to exclude electronegative gases. Conversely, for chambers based on total ion collection there is no such problem.

If a number of particles traverse the chamber, then an electric current will result in the network, and the current will be proportional to the intensity of particles. In this case the ionization chamber is called a current chamber.

2.2. Proportional Counter

A proportional counter is simply an ionization chamber in which the effect of gas amplification is used. If in the chamber the field strength is increased to an extent that allows the drifting electrons to gain an amount of energy between successive collisions with the gas molecules sufficient to ionize the struck molecule, then the number of charge carriers increases with every collision by a factor of two. The chamber current is thus made higher by the so-called multiplication factor, $M = 2^n$, n being the average number of collisions made by a primary electron during its traversal to the anode.

M remains constant as long as there are no interactions between the avalanches that arise from different primary ionization events. In this situation the total charge Q is obviously equal to $M \Delta E e / W$, and we see, therefore, that Q is proportional to the energy loss ΔE of particles in the gas volume (the so-called conversion medium). Thus, the pulse height is also proportional to the energy of the particle (and hence the name “proportional counter”) with the proportionality constant being much higher than that in the ionization chamber. For low-energy radiation, liberating only a few primary electrons, M can be as high as 10^6 – 10^7 .

The proportional counter is usually constructed in the well-known cylindrical form, which includes a central coaxial wire anode, but can also be constructed in any other geometrical form that gives a nonhomogeneous field. The field intensity in a cylindrical counter is given by $E \propto 1/r$, while the potential difference $U \propto \ln(r/r_0)$. Multiplication mainly takes place in the area of high field strength, and consequently near to the anode wire. Therefore, after termination of the very fast multiplication process, practically the whole charge $\pm Q$ is situated in the immediate proximity of the anode wire. The electrons, therefore, traverse only a very small potential difference during their movement to the anode. In practice the part of the whole potential

difference applied to a proportional counter of cylindrical form with inner and outer radius a and b ($a \ll b$), respectively equals:

$$\frac{\ln\left(\frac{a+\delta}{a}\right)}{\ln\left(\frac{b}{a}\right)} \approx \frac{\delta/a}{\ln(b/a)}, \quad (3)$$

where δ is the distance from the point of ionization to the central anode wire. Therefore, the electron component of the signal current is not significant, and the signal current is predominantly a result of ion movement. The voltage pulse is shown schematically in Figure 2. Note the existence of a delay time (the interval between the time of traversal of a particle and the beginning of an electron avalanche; this depends on the position of the initiating interaction), followed by a sharp increase in pulse size because of the positive ions produced as a result of electron multiplication. For ions moving towards the outer electrode, mobility gradually decreases, with a commensurate slowing down in increase of the associated pulse size. If the electron pulse is used, then the amplitude of the output pulse will be considerably smaller, although its duration will also be shorter ($\approx 10^{-7}$, s).

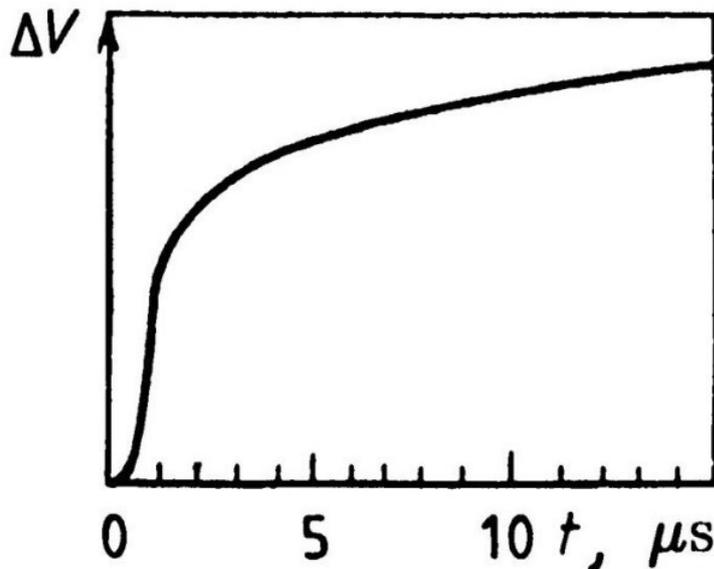


Figure 2. Pulse shape in a proportional counter. In practice the slow component of the pulse is not registered because of the existence of an RC -network or other form of low-frequency filter.

For a fixed expenditure of energy in the proportional counter, fluctuations will arise in the output pulse size. These inherent fluctuations are a result of the number of ion pairs initially released by the effectively monokinetic incident radiation, and the size of the avalanche that each initial electron produces. Additional sources of fluctuation in the pulse height are:

- negative ion formation due to electronegative impurities;
- variations in applied voltage, the multiplication factor varying rapidly with applied voltage;
- variations in multiplication due to variations of wire diameter; and

- imprecise central positioning of the anode, causing extreme difference in the electric field.

For all these reasons it is practically impossible to obtain a proportional counter whose energy resolution is less than 1%, the main cause being fluctuation in the number of initial electrons.

2.3. Geiger–Müller Counters

During the course of electron avalanche formation in the proportional counter, shortwave light photons are also emitted. The emission probability increases rapidly with the increase of voltage. By means of photoemission, these photons may produce new electrons that serve as initiating events for new avalanches. The probability per ion of the first avalanche initiating a second avalanche for an emitted photon is denoted by ε . If the operating voltage is high and the condition $M\varepsilon \gg 1$ is valid, then it is clear that a single primary electron leads to the subsequent initiation of a vast number of avalanches, whose products finally surround the anode with a “host” of positive ions, and these help to reduce the field near the anode and to terminate the discharge. In this case the total charge produced, and therefore the amplitude of the detector voltage pulse, remain constant and independent of the primary ionization. The pulse height depends only on counter dimension and field characteristics. Such counters are known as Geiger–Müller (GM) counters. If the operating voltage is raised greatly beyond the condition $M\varepsilon = 1$, then stable Townsend discharge may take place and the counter may be rendered useless. The admissible operating voltage range is commonly called the counting plateau.

Non-self-quenching counters are usually filled by monoatomic or diatomic (particularly noble) gases, and axial propagation of the discharge results from the cathode material. The light positive ions on their path from anode to cathode gain sufficient energy to extract fresh trigger electrons from the cathode by Townsend’s γ mechanism, as discussed above. Once started, the discharge will continue to produce pulses indefinitely and must be quenched by external means. For quenching, the operating voltage of the tube must be lowered below the starting value for which $M\varepsilon = 1$. It should also be held there until all positive ions are neutralized. Since Geiger pulses of 100 v and more on the anode wire are high enough to quench the discharge, it suffices to make the time constant RC_p of the input network longer than the ion collection time, this being approximately equal to a few milliseconds. Since the parasitic capacity C_p is equal to 10–100 pF, this calls for a very high resistance $R = (10^8 - 10^{10}) \Omega$. The drop of potential across this very high resistance reduces the effective voltage on the counter wire and quenches the discharge.

In self-quenching counters, quenching action is accomplished by the addition to the counting gas of heavy organic molecules in suitable proportion ($\approx 10\%$). These organic vapors dissociate more readily than they ionize. The transfer of charge from positive gas ions to the heavy organic molecules occurs in advance of the positive ions reaching the cathode, thereby preventing the γ mechanism. Thus, no new avalanche opportunities can begin from points on the cathode, and only those from within the gas filling of the counter are possible. These occur in close proximity to the releasing avalanche. The

“hose” of ions, therefore, spreads axially along the anode wire at a constant low velocity. This velocity of axial spread of the avalanche has been measured by various workers, and is commonly found to be of the order of $10 \text{ cm } \mu\text{s}^{-1}$.

As in the proportional counter, the signal pulse in the GM counter is formed by the ion component. Owing to the final propagation velocity v_z of the ions forming along the anode wire, the current pulse consists of an overlap of delayed partial currents of the individual avalanches. With the velocity $10 \text{ cm } \mu\text{s}^{-1}$ and the length of a common GM tube being about 10 cm, the propagation time T_l , needed for the spread of the ions along the length l of the anode wire is of the order of $1 \mu\text{s}$. The characteristic growth time for an individual avalanche is $0.1\text{--}1 \mu\text{s}$. The length of the current pulse—and hence the rise time of the integrated voltage pulse for $RC \gg T_l$ —is given mainly by T_l .

The primary ionization in the above case is assumed to be at $z = 0$ (i.e., at one end of the wire). If instead this takes place at any point ($0 < z < l$) of the anode wire, the ion current is composed of two components: one for each direction of ion propagation $z \rightarrow 0$ and $z \rightarrow l$. Thus, the rise time of the voltage pulse depends on the origin of ionization.

With self-quenching counters, the integrating time constant RC can be chosen to be smaller than the ion-collection time T_{ion} . The maximum count rate is limited only by the intrinsic dead time of the counter. During the spread of the hose of ions towards the cathode, the field is disturbed, and the counter remains effectively dead (insensitive) for an instant and recovers slowly, with the pulse height growing exponentially (this being referred to as recovery time). Externally, the counter exhibits a dead time of about $200 \mu\text{s}$, depending on the level of the voltage discriminator, which selects pulses of certain height.

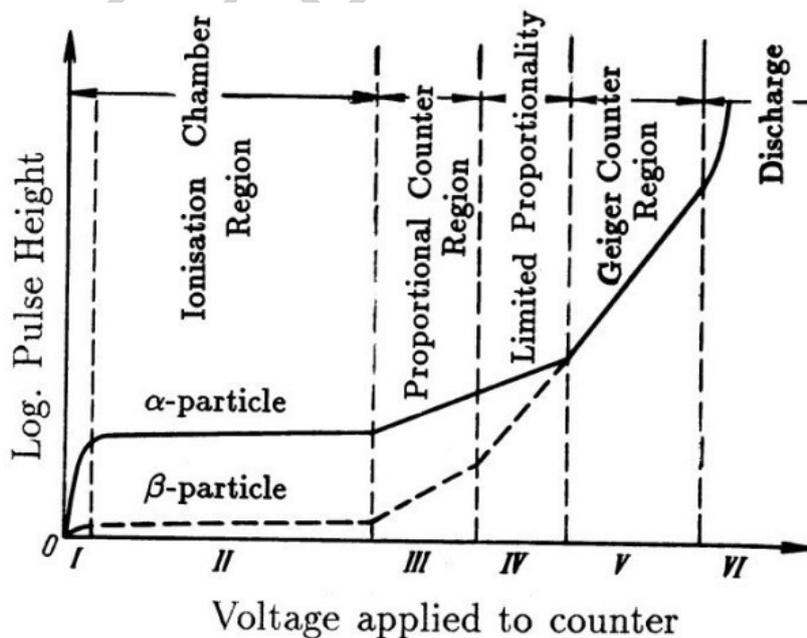


Figure 3. Logarithm dependence of output-pulse amplitude V (in relative units) on gas-counter voltage U : for α -particles ($\approx 10^5$ ion pairs) and for β -particles ($\approx 10^3$ ion pairs).

Notes:

Five operation regions can be picked out:

- I. Region of growing output pulse due to decreasing probability of primary ion recombination.
- II. Ionization-chamber region.
- III. Proportional-counter region
- IV. Limited-proportionality region.
- V. Geiger-counter region.
- VI. Discharge region.

The three types of ionization counter studied so far differ from each other in so far as there is variation of the output voltage pulse height when the applied potential is increased. Figure 3 shows this variation and the applied potential regions in which the ionization chamber, proportional counter, and Geiger counter act (see *Ionization of Gases*).

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Biographical Sketch

Yuri Mikhailovich Tsipenyuk graduated from the Moscow Institute of Physics and Technology (MIPT) in 1961, becoming a Candidate of Sciences in 1969 and a Doctor of Physico-Mathematical Sciences in 1979. From 1961 to 2002 he worked at the P.L. Kapitza Institute for Physical Problems, at the Russian Academy of Sciences, where he is currently the leading scientist of the Institute. In addition he is Professor of Physics of the Moscow Institute of Physics and Technology. His scientific interests include: electron accelerators, fission of atomic nuclei, activation analysis, investigation of the solid state by neutron scattering, and superconductivity. In 1997 he was made Soros Professor and became a Member of the New York Academy of Sciences. Dr. Tsipenyuk has published more than 120 papers in scientific journals, and is the author of three monographs: *Physics of Superconductivity* (in Russian, 1995, MIPT Publishing, Moscow), *Nuclear Methods in Science and Technology* (1997, IOP Publishing), and *The Microtron: Development and Applications* (2001, Taylor & Francis), in addition to being the coauthor of a textbook on general physics for high school: *Basics of Physics* (2001, Fizmatlit, Moscow).

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