Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

DSE2T (Nuclear and Particle Physics)

Topic – Detector for Nuclear Radiations (Part – 1)

Introduction:

In their basic principles of operation, most detectors of nuclear radiations follow similar characteristics. The radiation enters the detector, interacts with the atoms of the detector material (losing part or all of its energy), and releases a large number of relatively low-energy electrons from their atomic orbits. These electrons are then collected and formed into a voltage or current pulse for analysis by electronic circuitry. Thus the investigation of nuclear and particle collisions or disintegrations relies upon detectors for measuring the products of such interactions. Although subatomic particles are certainly too small to be observed through purely visual means, we can use the mechanisms for energy deposition to detect such particles. Although we will describe only the very simplest prototype detectors, the principles underlying their performance are similar to those used in even the most sophisticated devices.

To measure the energy of the radiation, we should select a detector in which the output pulse amplitude is proportional to the energy of the radiation. Here we must choose a material in which the number of released electrons is large, so that if we experience statistical fluctuations or fail to count a few, it does not substantially affect our ability to determine the energy of the radiation. To determine the time at which the radiation was emitted, we must choose a material in which the electrons can be gathered quickly into the pulse (the device needs to be fast enough), the number of electrons gathered is of considerably less importance. To determine the type of particle (such as in a nuclear reaction, in which many varieties of particles may be produced), we must choose a material in which the mass or charge of the particle gives a distinctive signature. To measure the spin or polarization of the radiation, we must choose a detector that can resolve or separate different spin or polarization states. If we expect unusually high counting rates, we must choose a detector

Dr. Avradip Pradhan,
Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

that can recover quickly from one radiation before counting the next, for very low counting rates, we must be concerned about detecting every event and about reducing the influence of background radiations. Finally, if we are interested in reconstructing the trajectory of the detected radiations, we must have a detector that is sensitive to the location at which the radiation enters the detector.

Gas Filled Detectors:

The function of many detectors of nuclear radiation is to use an electric field to separate and count the ions (or electrons) formed as a result of the passage of radiation through the detector. The simplest type of detector that accomplishes this is the *ionization detector*, in which the region inside is filled with a gas, often air. This device is designed to measure the ionization produced when an incident particle traverses some medium. If the number of detected electrons and positive ions is to reflect the energy deposited in the material, then any produced electron-ion pairs must be kept from immediately recombining into atoms. This can be done by applying a sufficiently high electric field across the gaseous medium. This field will separate the charges, start their drift towards their respective electrodes, and thereby keep them from recombining.

The basic ionization detector consists of a chamber that is filled with a suitable gaseous medium that can be easily ionized. The chamber has a cathode and an anode that are held at some large relative voltage, and the device is characterized by a standard parallel-plate capacitance (C) that is determined by the geometry of the electrodes. The operating medium should be chemically stable (or inert) so that the moving ionization electrons are not easily captured by the molecules of that medium. The medium should not be very sensitive to radiation damage so that its response to incident particles does not change markedly with use. In addition, the medium should have a low value of ionization potential ($\bar{I}$) in order to maximize the amount of ionization produced per energy deposited by any incident particle.

As we have mentioned, when a charged particle traverses a sensitive region of a detector, it ionizes the medium and produces electron-ion pairs. These start drifting immediately along the electric field lines: electrons to the anode and the

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

positive ions to the cathode. As the charges drift, they induce signals on the electrodes, which provide small currents that flow through some resistor R (as shown in Fig. 1). This, in turn, produces a voltage drop that can be sensed with an amplifier. The amplifier signal can be analyzed to obtain a pulse height that can be related to the amount of produced ionization. The amount of produced ionization depends primarily on the density and atomic structure of the ionizable medium and of course, on the charge of and energy deposited by the incident particle. However, the amount of ionization that is detected is determined by many technical factors, foremost among which is the nature and size of the applied electric field or the applied voltage.

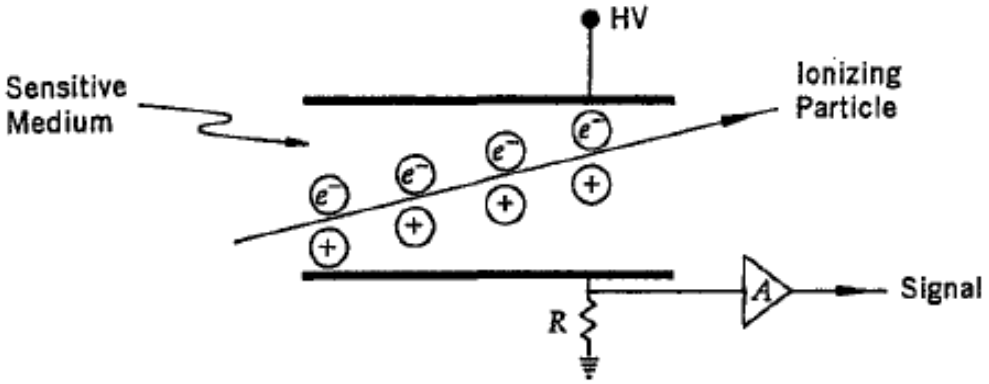

Fig. 1

Here, we will take an example. In air, the average energy needed to produce an ion is about 34 eV. Thus a maximum number of ions and electrons produced from a 10 MeV radiation would be

$$n = \frac{10\times10^{6}}{34} \approx 3 \times 10^{5}.$$

For a medium-sized chamber, with a cross section of $A = 100$ cm^2 with a plate separation of $d = 1$ cm, the capacitance (C) is

$$C = \frac{\varepsilon_0 A}{d} = \frac{8.854\times10^{-12}\times100\times10^{-4}}{1\times10^{-2}} = 8.854 \times 10^{-12} \text{ F}.$$

Thus the resulting signal voltage pulse is about

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

$$V_{sig} = \frac{Q}{C} = \frac{ne}{C} = \frac{3\times10^{5}\times1.6\times10^{-19}}{8.854\times10^{-12}} \approx 5 \text{ mV}.$$

This is a rather small signal, which must be considerably amplified (by a factor of roughly $\sim 10^3$) before we can analyze it using standard electronics. The amplitude of the signal is proportional to the number of ions formed (and thus to the energy deposited by the radiation), and is independent of the voltage between the plates. The applied voltage determines the speed at which the electron and ion clouds drift to their respective electrodes by the usage of the charge carrier's mobility (μ). Drift velocity (v) and mobility are related by the relation

$$v = \mu E = \mu \frac{V}{d}$$

where E and V are the electric field and voltage between the plates. The transit time (τ) can be calculated as $\tau = \frac{d}{v} = \frac{d^2}{\mu V}$. For a typical voltage of roughly $V = 100$ V, the ions move at a typical mobility about $\mu = 1$ $cm^2V^{-1}s^{-1}$ and will take roughly $\tau = 0.01$ s to travel across the 1 cm chamber, using the previous relation. Although electrons are more mobile and they travel about 1000 times faster. This is an exceedingly long time by standards of nuclear counting and thus the ion chamber is of no use in counting individual pulses.

Various Regions of Ionization Detector. According to Fig. 2, when the voltage difference between electrodes is small, the electrons and ions can recombine soon after they are produced, and only a small fraction of the produced electrons and ions reach their respective electrodes. This provides an output signal that corresponds to fewer electron-ion pairs than are produced in the gaseous medium. The range of operating voltage where this occurs is referred to as the *recombination region.* As the voltage difference is increased beyond the point where dissociated electron-ion pairs can recombine, we obtain a signal that reflects the total amount of produced ionization. This operating range is called the *ionization region.* Increasing the voltage further, provides the initially freed electrons with sufficient acceleration and energy so that they can ionize additional atoms of the medium. This increased ionization is often referred to as *signal amplification* or *signal multiplication.* The output signal in

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

this operating region of voltages is larger than, but proportional to, the initially produced ionization and for this reason, this operating range is referred to as the *proportional region.* (It should be noted that proportional does not necessarily imply that the signal increases linearly with voltage.) Increasing the voltage even further, yields an avalanche of electron-ion pairs. In this mode, referred to as the *Geiger-Müller region* (or *G-M region*) the energy of the original ionization electrons increases sufficiently rapidly so that they can excite or ionize more atoms, thereby providing more freed electrons or photons from relaxation of atoms. This, in turn, produces more electron-ion pairs, and eventually leads to a discharge, that is, to a highly amplified output signal whose size is independent of the amount of original ionization. Finally, increasing the voltage beyond the *Geiger range,* leads to a breakdown that generates a continuous discharge of the medium, with the chamber no longer being sensitive to any incident ionization. Depending on the circumstances, most detectors are operated as ionization, proportional or Geiger counters.

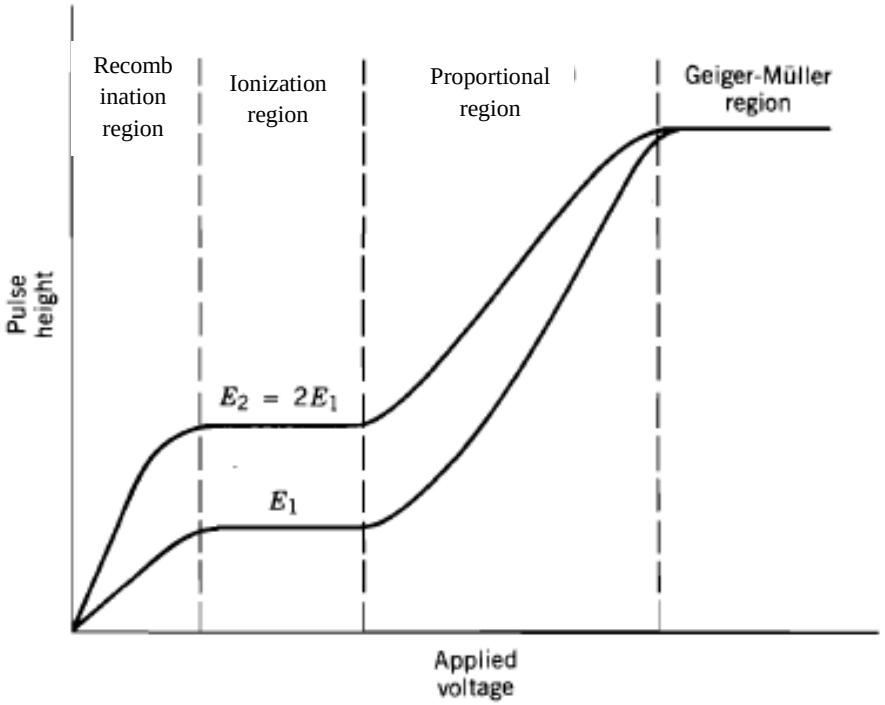

Fig. 2

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Ionization Counters:

Ionization chambers or *ionization counters*, operate at relatively low voltages, and therefore provide no amplification of the original signal. Consequently, the output pulses for single minimum-ionizing particles tend to be quite small and usually require special low-noise amplifiers for attaining efficient operating performance. For heavily ionizing nuclear fragments, however, or for a flux of many particles, the fully integrated signals can be substantial and easy to detect. Ionization chambers are not very sensitive to voltage variations, and provide very linear output response for a wide range of input signals. Because there is no inherent amplification of signal, or discharge in the operating medium, these types of counters do not require much time to recover from large currents, and can therefore be used in environments with high interaction rates. In addition, because there is no amplification, they provide excellent energy resolution, which is limited primarily by electronic noise and by the inherent fluctuations in the production of the initial ionization. Liquid-argon ionization chambers have been used with great success as sampling detectors in high-energy calorimetric measurements of energy deposition. Solid-state devices, pioneered in nuclear physics, are now used commonly as ionization counters in high energy experiments. Gaseous ionization chambers are useful for monitoring high levels of radiation; they were also used in the past to measure, for example, ranges of alpha-particles from radioactive decays of nuclei.

Proportional Counters:

Gaseous *proportional counters* usually operate in high electric fields of the order of 10^4 Vcm^{-1} and achieve typical amplification factors of about 10^5. Such fields can be obtained using thin (diameters of 10 – 50 μm) metallic wires as anode field electrodes in a cylindrical chamber geometry (shown in Fig. 3). The electric field in this geometry at a radius r is given by

$$E(r) = \frac{V}{r \ln\left(\frac{b}{a}\right)}$$

where b is the inner radius of the cathode and a is the outer radius of the anode wire.

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Assistant Professor,
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Because the fields are most intense near the axial anode wires, this is where the multiplication of charge, that is, *secondary ionization*, also takes place. For a large variety of gases, the output signals, even for minimum-ionizing particles, are quite large. Also, these detectors can operate over a relatively wide range of high voltage settings. Although proportional chambers can be used for measuring absolute energy deposition (pulse heights), their reliance on the multiplication of ionization in the medium makes them quite sensitive to the dependence of the output signal on the magnitude of the operating voltage.

Because the output signal of a proportional counter comes mainly from the avalanche process, which occurs very rapidly, the timing is determined by the drift time of the primary electrons from the point of the original ion formation to the vicinity of the anode wire where the avalanche occurs. This time is of the order of microseconds and thus the counter can be operated in a pulse mode at counting rates of the order of 1 MHz.

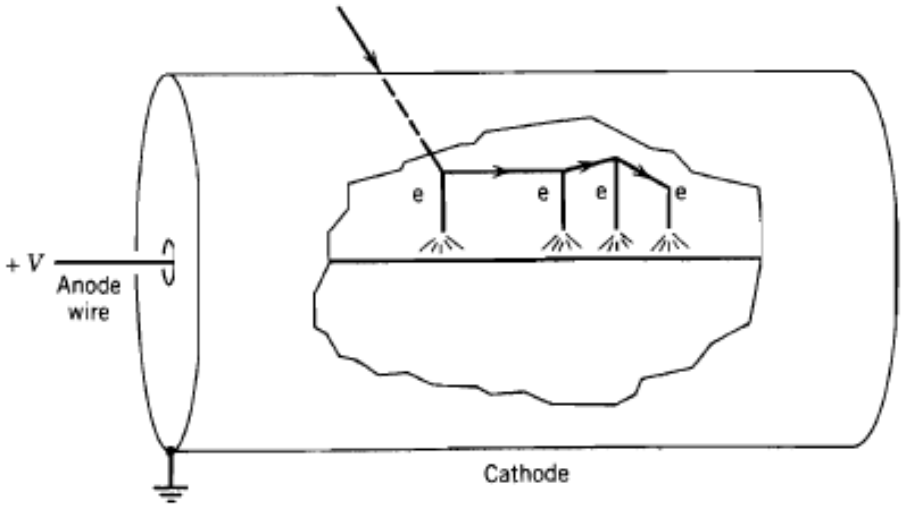

Fig. 3

Geiger-Müller Counters:

A *Geiger-Müller counter* or simply *Geiger counter* is an ionization detector that operates in the Geiger range of voltages, namely at a voltage high enough so that any produced ionization causes a gaseous discharge. Here the amplification

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Assistant Professor,
Department of Physics,
Narajole Raj College, Narajole.

factor is perhaps as large as 10^{10}. Because the entire tube participates for every incident event, there is no information at all on the energy of the original radiation-all incident radiations produce identical output pulses.

The output signal from a Geiger counter consists of the collected electrons from the many avalanche processes. The signal is of the order of 1 V, so no further amplification is usually required. The collection time is of the order of 10^{-6} s, during which time the positive ions do not move far from the avalanche region. There is thus surrounding the anode wire a positively charged ion cloud that reduces the electric field intensity and eventually terminates the avalanche process.

Quenching. The cycle would then be completed after the positive ions have drifted to the cathode and become neutralized (which takes 10^{-4}-10^{-3} s), but during their travel they can be accelerated and strike the cathode with enough energy to release electrons (from the cathode) and to begin the process again (and because of the nature of the multiple avalanche process in the Geiger tube, all it takes is one electron to create an output pulse). To prevent this from occurring, a second type of gas, called the *quenching gas*, is added to the tube. The quenching gas is usually one with complex organic molecules such as ethanol, the primary gas is generally one with simple molecules, such as argon, and a typical mixture might be 90% argon and 10% ethanol. As the space charge, consisting mostly of argon ions, begins to drift toward the cathode, collisions will occur with the quenching gas in which there is a high probability of the transfer of an electron, so that the argon is neutralized and the ionized ethanol begins to drift toward the cathode. When it arrives there and is neutralized, the energy that formerly went into releasing a free electron can now be absorbed in the dissociation of the molecule (a process not possible for a simple argon atom). The quenching gas is thus gradually used up, and the Geiger tube must periodically be replaced. Other Geiger tube designs use halogens as the quenching gas; the subsequent recombination of the dissociated molecule eliminates the need to replace the tube.

The technical advantage of a Geiger counter is its simplicity of construction and its insensitivity to small voltage fluctuations. It is very useful for general

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Department of Physics,
Narajole Raj College, Narajole.

measurement of nuclear radiation, but it has two important disadvantages. First, there is no information whatsoever on the nature of the ionization that caused the pulse. Second, because of the large avalanche induced by any ionization, a Geiger counter takes a long time (about 1 ms) to recover between successive pulses, and so it has a substantial dead-time, which means that it cannot be used for high counting rates.

This concludes part 1 of this e-report.

The discussion will be continuing in the part 2 of this e-report.

Reference(s):

Introduction to Nuclear and Particle Physics, A. Das & T. Ferbel, World Scientific

Introductory Nuclear Physics, Kenneth S. Krane, John Wiley & Sons

(All the figures have been collected from the above mentioned references)