

Serial: Ionizing Radiation Detectors

Introduction

Ionizing radiation, as the name suggests, has the ability to ionize matter. Ionization means the removal of an electron from the electron shell of an atom or molecule. This creates a free electron and a positive ion, or the molecule may dissociate into a negative ion and a positive ion. It is precisely ionization that is the reason for the danger of ionizing radiation to living organisms, but also the principle of most ionizing radiation detectors. We will learn more about both later in the text.

Although ionizing radiation is dangerous, it also has many useful applications in medicine (X-ray imaging, cancer treatment, positron emission tomography, ...), imaging (imaging the internal structure of objects, defect detection, investigation of crystal structure, ...), dating (detecting art forgeries, dating archaeological finds or rocks, ...), energetics (nuclear power plants, ...), security (X-ray scanners at airports, ...), and in other fields of human activity. In the first half of the text, we will look at the individual types of ionizing radiation, and in the second half, we will see what various detectors are used to detect ionizing radiation.

Energy Scales

In the microworld, we operate at energies orders of magnitude lower than in everyday life. The basic SI unit of energy, the “joule”, is impractical. Therefore, in nuclear and particle physics, we use the energy unit “electronvolt” (eV) and its multiples. 1 electronvolt is the energy that a particle with an elementary charge of $1.602 \cdot 10^{-19} \text{ C}$ would gain when accelerated by an electric potential of 1 V

$$1 \text{ eV} = 1.602 \cdot 10^{-19} \text{ J.}$$

In the text, we will more likely encounter higher energies and multiples of electronvolts – kiloelectronvolts ($1 \text{ keV} = 10^3 \text{ eV}$), megaelectronvolts ($1 \text{ MeV} = 10^6 \text{ eV}$), and gigaelectronvolts ($1 \text{ GeV} = 10^9 \text{ eV}$). Also, it is common for particles to move at relativistic speeds. Therefore, be careful when solving problems for this part of the series; you may need to use relations from the special theory of relativity. Thanks to Einstein’s relation between mass m and rest energy $E = mc^2$, we can express particle masses in units of “electronvolt per speed of light squared” (eV/c^2) and its multiples. Similarly, particle momentum can be expressed in the unit “electronvolt per speed of light” (eV/c) and its multiples. Particle and nuclear physicists often choose a simplification by introducing a unit speed of light $c = 1$. Consequently, mass, momentum, and energy are expressed in the same units – in electronvolts. Although it seems unintuitive, introducing a unit speed of light is just a rescaling of the unit of distance and a realization that distance and time are linked through the fundamental physical constant of the speed of light. Distance and time can thus be expressed in the same unit, e.g., in seconds, or in light-seconds.

Radioactive Decay

A widespread natural source of radioactive radiation is radioactive isotopes. Elements in the periodic table are ordered by the number of protons. A neutral atom of an element always has the same number of electrons as protons, and this determines the chemical properties of the element. However, atoms of an element can have different numbers of neutrons without affecting their chemical properties. The arrangement of protons and neutrons in the atomic nucleus has a defined binding energy, which can be complexly calculated from quantum physics. It may happen that an atomic nucleus is unstable and has the possibility to jump to a state with lower energy. One or more particles fly out of the nucleus, carrying away the released energy in the form of kinetic energy. This is called radioactive decay, and it is one of the ways ionizing radiation is generated.

Radioactive decay is a random (stochastic) process. We cannot predict exactly when a specific nucleus will decay; we can only determine the probability of decay, which follows an exponential distribution. The probability of a nucleus decaying sooner than time t is

$$P(t) = 1 - e^{-\lambda t},$$

where λ is the decay constant of the given isotope. If we observe a large number of radioactive atoms $N_0 \gg 1$, then after time t , the remaining number of these atoms will be

$$N = N_0 \cdot 2^{-\frac{t}{T_{1/2}}},$$

where $T_{1/2}$ is the half-life. The relationship between the decay constant and the half-life of an isotope is

$$T_{1/2} = \frac{\ln 2}{\lambda}.$$

The energy states of the nucleus are discrete, and therefore the total energy released during the same decay of the same isotope is always the same. If only one particle and the recoiling nucleus arise from the decay, it is a two-body decay. Using the laws of conservation of momentum and energy, you can verify that in such a case, the emitted particle will always have the same energy, and it will be a source of monoenergetic radiation.

Types of Ionizing Radiation

From the perspective of particle detection, the most important factor is whether the particle is electrically charged or not. Charged particles interact electrostatically with electrons in the matter through which they pass. During their flight, they tear electrons from electron shells, ionize matter, and gradually lose energy. At high speeds, $v \approx c$, radiative energy losses are added to ionization losses, where the particle emits photons. In contrast, electrically neutral particles (photons, neutrons, ...) can travel a long distance before any interaction with matter occurs. Therefore, electrically neutral radiation is more penetrating, harder to shield, and larger detector volumes are needed for reliable detection.

Electrically Charged Particles

Alpha radiation consists of helium nuclei ${}^4_2\text{He}$. A radioactive isotope undergoing alpha decay changes into an isotope of an element with two fewer protons and two fewer neutrons. Alpha decays occur predominantly only in heavy elements such as lead and heavier. It is a two-body

decay, and therefore alpha particles from a single isotope have the same initial energy or several possible discrete energies. The daughter nucleus may not be formed in the ground state with the lowest energy but may find itself in an excited state, from which it additionally releases energy, for example, via gamma radiation (a photon). The initial energies of alpha particles range from 3 MeV to 10 MeV. Isotopes with a shorter half-life emit alpha particles with higher energy. Also, of two different isotopes with similar half-lives, the isotope with the higher proton number will produce alpha particles with higher energy. This dependence is described by the *Geiger-Nuttall law*, which can be derived from quantum mechanics

$$\log T_{1/2} = a_1 \frac{Z}{\sqrt{E}} - a_2,$$

where a_1, a_2 are constants, Z is the proton number of the isotope, and E is the energy of the alpha decay.

Electrons and positrons can be created in several ways. A positron is the antiparticle of the electron with the same rest mass 511 keV, but with a positive electric charge, unlike the negative electron. Samples of electron trajectories in silicon are shown in Figure 1.

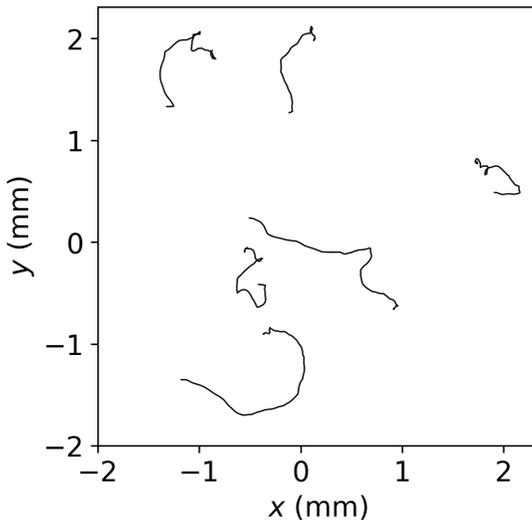


Figure 1: Simulated trajectories of electrons with an initial kinetic energy of 1 MeV in silicon. The trajectories of electrons and positrons are zigzagged because the particles have the same rest mass as the electrons in the electron shells with which they predominantly interact.

Consequently, they can change direction significantly in each interaction.

One of the possible ways they originate is through beta minus (electrons) and beta plus (positrons) radioactive beta decays. The energies of beta decays range from units of electronvolts (e.g., tritium ${}^3_1\text{H}$ with an energy of 18.6 eV) to megaelectronvolts (e.g., the fluorine isotope ${}^{20}_9\text{F}$ with an energy of 7.02 MeV). Both types of beta decay are three-body decays,

and therefore the energy spectra of beta particles are continuous. The stated energy values describe the total energy released during the decay, but this energy is distributed among the recoiling nucleus, the (anti)neutrino, and the beta particle. Tritium beta decays are monitored in the *KATRIN*¹ experiment, where they aim to determine the mass of the electron neutrino by precisely measuring the energy spectrum of beta electrons, a key result for contemporary physics.

Natural sources can also provide monoenergetic electrons. The energy levels of electrons in the electron shell and the energy levels of nucleons in the nucleus are discrete. When jumping from a higher energy level to a lower one, the excess energy is most often released in the form of a photon, which has a fixed energy determined by the difference between the two energy levels. However, it can also happen that this energy is transferred to an electron in the electron shell. In the case of energy release from the nucleus, we speak of conversion electrons (the whole phenomenon is called internal conversion), and in the case of an electron jump between two levels in the electron shell, we speak of Auger electrons.

Electrons and positrons are created in the form of an electron-positron pair during interactions of high-energy photons (> 1.022 MeV) with matter. This physical phenomenon causes showers of secondary particles in the Earth's atmosphere when it is struck by a high-energy photon. If the shower is sufficiently intense, it can be detected from the ground using Cherenkov telescopes, allowing astronomers to observe radiation from astronomical sources at the highest energies ($\gtrsim 30$ GeV). Ionizing electrons can also be created by the interaction of other ionizing radiation particles in matter, where an electron is kicked out of the electron shell and is given sufficient kinetic energy to ionize matter itself. X-ray or gamma photons can thus transfer all their energy to an electron via the photoelectric effect or part of their energy via the Compton effect. If an energetic electron was created by an ionizing charged particle, we speak of a delta electron.

Energetic protons and ions do not occur from natural sources on the Earth's surface. These massive charged particles have a large energy loss per unit length, and thus a large ionizing effect. Heavier ions with a higher charge create more delta electrons, thereby losing more energy (see Figure 2). At high kinetic energies, interactions with atomic nuclei via the strong nuclear interaction also gain importance alongside electromagnetic interactions.

High-energy protons and ions from cosmic sources bombard the outer layers of the atmosphere, but through interactions with air molecules, they create a shower of secondary particles that gradually lose energy by passing through the atmosphere and, with the exception of muons, do not reach the Earth's surface (see below). You can measure high-energy secondary protons at higher altitudes in the mountains or during airplane flights. On the Earth's surface, we encounter high-energy protons or ions only from artificial sources. These include, for example, scientific instruments (e.g., the LHC accelerator at CERN on the border of Switzerland and France), or proton accelerators used in medicine for cancer treatment (e.g., the Proton Center in Prague).

Muons and cosmic rays are part of the natural radioactive background. By the way, the muon is a heavier sibling of the electron – it has the same charge magnitude but has a $206.8\times$ higher rest mass. The upper layers of the Earth's atmosphere are bombarded by high-energy cosmic ray particles (about 89 % protons). These particles interact with air molecules, their nuclei, and

¹<https://www.katrin.kit.edu/68.php>

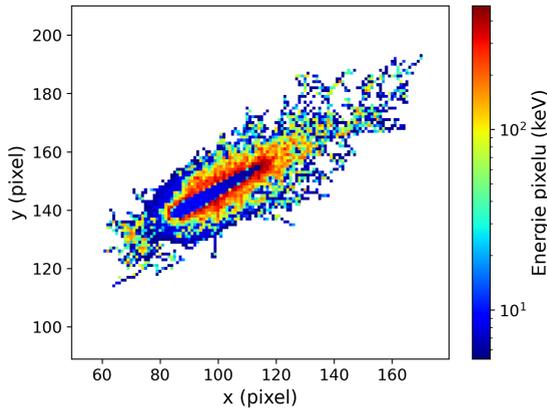


Figure 2: A high-energy lead ion in a silicon pixel detector. Many delta electrons are visible around it. The color of the pixels displays the absorbed energy. The low-energy region in the center of the ion track is an effect of the detector, whose electronics cannot handle high energies.

electron shells, creating a shower of secondary particles. Anything can be created – electrons, positrons, photons, protons, pions, muons, etc.

Much more energetic particles fly to us from space (kinetic energy up to 10^{20} eV) than we can create in terrestrial accelerators (the LHC can accelerate protons to $7 \cdot 10^{12}$ eV). However, only muons reach sea level from the secondary particles, because other particles either have too short a half-life and do not reach the ground, or they have much higher average energy losses per unit length and also do not reach it. An example of a muon track with delta electrons in silicon is in Figure 3. For observing energetic primary cosmic ray particles, for example, the Pierre Auger Observatory in Argentina is used.

Spontaneous fission appears only in the heaviest elements (actinides and heavier) and not even in all their isotopes. Unlike the alpha decay mentioned above, in spontaneous fission, a heavy nucleus splits into two comparably massive smaller nuclei, releasing energy in the order of 10^2 MeV and emitting several fast neutrons. However, spontaneous fission is usually not the main mode of decay for radioactive isotopes. For example, the isotope $^{235}_{92}\text{U}$ used in nuclear power plants and nuclear weapons decays dominantly by alpha decay, and spontaneous fission constitutes only $7 \cdot 10^{-9}$ % of all decays. However, the isotope $^{235}_{92}\text{U}$ has a high probability of a nuclear fission reaction if the nucleus is hit by a slow neutron (kinetic energy < 1 eV). This means that neutrons released from spontaneous nuclear fission have a chance, after slowing down, to induce fission of other nuclei and thus create a controlled (nuclear power plant) or uncontrolled (nuclear bomb) fission reaction.

The Bethe-Bloch equation describes ionization and excitation losses of charged particles heavier than electrons (for electrons, the equation must be modified due to the low weight of the

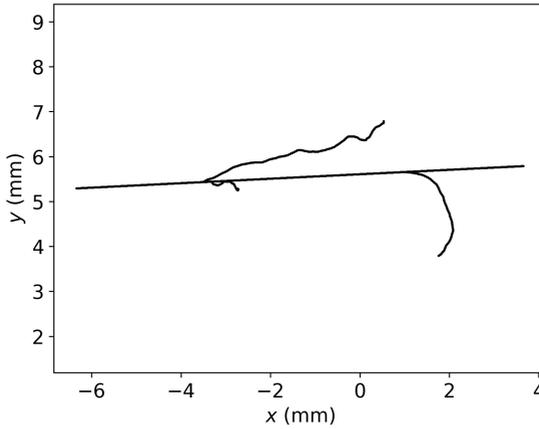


Figure 3: Simulated track of a muon (the straight line) with an initial kinetic energy of 4 GeV in silicon. A muon with such energy is a minimum ionizing particle and passed through, it did not stop in the silicon. The muon also created three delta electrons (three zigzag curves branching off from the muon track).

electron). The average energy loss per unit length and per unit density is

$$-\frac{1}{\rho} \left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left(\ln \left(\frac{2m_e c^2 \gamma^2 \beta^2}{I} \right) - \beta^2 - \frac{\delta(\beta)}{2} - \frac{C(\beta)}{Z} \right),$$

where ρ is the density of the material through which the particle passes, $K = 0.3071 \text{ MeV} \cdot \text{cm}^2 \cdot \text{g}^{-1}$ is a constant, z is the charge of the ionizing particle (in units of elementary charges e), Z and A are the proton and nucleon numbers of the material, c is the speed of light, $\beta = v/c$ is the beta factor of the particle,² which moves at speed v , $\gamma = 1/\sqrt{1 - \beta^2}$ is the gamma factor of the particle, m_e is the electron mass, I is the average excitation energy approximated by the relation $I \approx 16Z^{0.9} \text{ eV}$, $\delta(\beta)$ is a correction factor for high energies, and $C(\beta)$ is a correction factor for low energies. The Bethe-Bloch equation has a minimum approximately for $\beta\gamma \approx 4$. Such particles have the lowest energy loss per unit length and are called minimum ionizing particles (MIP). The energy loss is usually around $2 \text{ MeV} \cdot \text{cm}^2 \cdot \text{g}^{-1}$. For example, muons from cosmic rays are usually close to the MIP regime, which contributes to the fact that they can reach the Earth's surface and do not stop at higher altitudes. Let us repeat once more, however, that the Bethe-Bloch equation describes only ionization and excitation energy losses. It does not describe radiative energy losses, which occur at very high particle energies.

Electrically Neutral Particles

X-ray and gamma photons are the most used type of ionizing radiation with many applications. You will certainly think of X-ray imaging of bones at the doctor's, but the same principle is also used in X-ray scanners at airports or in industry. X-ray diffraction allows us to investigate

²The beta factor is actually a trick to have a dimensionless speed

the crystal structure of substances. Even in medicine, high-energy photons are used in multiple applications, such as the Leksell gamma knife for tumor treatment, computed tomography, positron emission tomography, etc.

High-energy photons can be created in many ways – electron jumps between levels in the electron shell emit X-ray photons, de-excitation of a nucleus from a higher energy state to a lower one emits gamma photons, charged particles under acceleration emit (bremsstrahlung, cyclotron radiation, synchrotron radiation). Photons, although electrically neutral, are carriers of the electromagnetic interaction, and thus interact with electrically charged particles (predominantly with electrons, interactions with atomic nuclei are not as frequent). The least energetic photons interact via the photoelectric effect, where they transfer all their energy to an electron and knock it out of the electron shell. At higher energies, the Compton effect dominates, where the photon transfers only part of its energy to the electron and flies off in a different direction with lower energy. Photons with the highest energy then create electron-positron pairs.³ Materials with a high number of electrons per unit volume are suitable for shielding X-ray and gamma photons, which is why heavy elements (e.g., lead) are the most effective. The intensity of a photon beam (i.e., photons that have not yet undergone interaction) decreases exponentially when passing through material

$$I(x) = I_0 e^{-\mu x},$$

where I_0 is the original beam intensity, x is the depth in the material, and μ is the linear absorption coefficient depending on the material.

Neutrons unlike electrons, do not interact electromagnetically, but only via the strong nuclear interaction with atomic nuclei. All neutrons (for example, in spontaneous fission) are created as fast neutrons with kinetic energy in the order of megaelectronvolts. Fast neutrons collide with atomic nuclei elastically and inelastically, thereby losing energy. An elastic collision with a light nucleus (e.g., hydrogen) can transfer sufficient energy for the accelerated nucleus to become an ionizing particle itself. An inelastic collision can “kick” the nucleus into an excited state, from which it subsequently releases energy by emitting a gamma photon. After slowing down neutrons to the energy of thermal motion, elastic collisions persist, but the neutron can also merge with a nucleus and induce radioactive decay (emission of a gamma photon, alpha decay, fission reaction, ...).

Neutrons are poorly shielded and poorly detected. Fast neutrons lose energy most efficiently during interactions with light nuclei, therefore materials with a high amount of hydrogen (e.g., plastics or water) are suitable for slowing them down and stopping them. To detect neutrons, it is necessary to use isotopes (e.g., ${}^3\text{He}$, ${}^6\text{Li}$, ${}^{10}\text{B}$) that have a large cross-section for reaction with neutrons and emit charged particles upon reaction, which are then easily detected. Fast neutrons can be detected using knocked-out hydrogen nuclei (protons).

Neutrinos are not technically ionizing radiation because they interact only via the weak nuclear interaction, which has low efficiency. Neutrinos are therefore not dangerous to living organisms at all and merely pass through. However, neutrinos are detected indirectly using electrons. Detecting neutrinos requires a large volume of transparent material (water, ice, liquid argon,

³The creation of an electron-positron pair can occur only in the presence of matter. You can write down the laws of conservation of momentum and energy and verify that a photon alone cannot decay into two particles such that both laws remain conserved. During the creation of an electron-positron pair, another charged particle (an electron or an atomic nucleus) must be present to carry away part of the momentum and energy.

...). A neutrino can transfer part of its energy to an electron. If the electron moves faster than the speed of light in the given material, it emits Cherenkov radiation. This can then be detected by sensitive photomultipliers and the electron's path reconstructed. In neutrino experiments, the biggest challenge is usually removing background from other sources (secondary cosmic ray particles, beta radioactive isotopes, ...), because neutrino interactions are rare.

Ionizing Radiation Detectors

Most detectors utilize the ionizing capability of ionizing radiation for its detection. When a charged ionizing particle enters a material, it creates, on average, a quantity of free charge carriers N , which is directly proportional to the absorbed energy E_{abs}

$$N = \frac{E_{\text{abs}}}{\varepsilon}, \quad (1)$$

where ε is the average amount of energy required to create a single charge carrier. However, by the term “charge carrier” here we actually mean 1 pair of negative and positive charges (e.g., an electron and an ion), which always originate together. Equation (1) gives only the average amount of charge carriers, which is a random variable. It might occur to you that the number of created charge carriers N would follow a Poisson distribution, and would therefore have an uncertainty (standard deviation)

$$\Delta N = \sqrt{N}, \quad \implies \quad \Delta E_{\text{abs}} = \varepsilon \sqrt{N}.$$

It turns out, however, that the creations of charge carriers are not mutually independent events, and thus the uncertainty is in fact lower

$$\Delta N = \sqrt{FN}, \quad \implies \quad \Delta E_{\text{abs}} = \varepsilon \sqrt{FN} \quad (2)$$

where F is the experimentally determined Fano factor for the given material. For semiconductors, the Fano factor tends to be low, around 0.1, but for example for scintillators it tends to be around 1. The relative energy resolution of the detector is given by the ratio of the standard deviation and the number of charge carriers

$$R = \frac{\Delta E_{\text{abs}}}{E_{\text{abs}}} = \frac{\Delta N}{N}.$$

In real detectors, however, other sources of noise contribute to the energy uncertainty besides the statistical uncertainty, such as noise in the readout electronics, imperfections in the detector, etc. A general model of energy uncertainty is

$$\Delta E = \sqrt{A + BE + CE^2}, \quad (3)$$

where A, B, C are constants for the given detector. The first term \sqrt{A} relates to noise independent of the particle's energy (e.g., thermal noise in the readout electronics), the second term \sqrt{BE} relates to the Fano noise (Equation (2)), and the third term $\sqrt{CE^2}$ relates to imperfections in the detector, which cause the same relative uncertainty independently of the particle's energy.

Gas Detectors

Gas detectors use (unsurprisingly) gas as the detection medium. There are many types of gas detectors with various detection principles, various shapes, and various gases. Every gas detector must be under a direct current electrical voltage. A passing ionizing particle creates free electrons and ions in the gas, which are immediately pulled apart by the electric field before recombination can occur. The electrons are attracted to the anode, which records the signal of the incoming electrons. There can be multiple readout anodes in the detector, making it possible to obtain more information about the particle's track. Gas detectors can have a large detection volume.

It is best to use non-reactive gases as fillings, whose ions will not cause corrosion of the detector's interior, so using oxygen as a detection gas would be a bad idea. Noble gases are frequently used. The average ionization energies of some noble gases are given in Table 1.

Table 1: Average ionization energies required to create an electron and an ion for some gases used in gas particle detectors.

Gas	Avg. ionization energy ε (eV)	Fano factor
He	45	0.21
Ne	30	0.13
Ar	26	0.16
Xe	22	0.17

A low electric field intensity is used by so-called ionization chambers. The field must be strong enough so that electrons do not have time to recombine, but not so strong that accelerated electrons could cause further ionization. In this regime, the applied voltage does not matter. The amount of electrons that drift to the anode does not change with voltage and is directly proportional to the absorbed energy according to Equation (1). An ionization chamber can either continuously record the current of generated electrons, thus measuring the overall level of ionizing radiation, or it can operate in a pulse mode and record the voltage drop between the electrodes with each particle. When we strengthen the electric field, the electrons gain sufficient velocity between collisions with gas atoms to be able to ionize them. The newly created electrons also further ionize and an electron avalanche is formed. The quantity of electrons in the avalanche grows exponentially

$$n(x) = n_0 e^{\alpha x},$$

where α is the Townsend coefficient and x is the distance from the beginning of the avalanche. However, for the detector to be useful, the amplification must occur only at the last moment before the anode. In the majority of the detector's volume, the electric field is weak and multiplication does not occur, but in the vicinity of the anode, the field is enhanced (e.g., field enhancement caused by the geometry of the field lines around a thin wire, see Figure 4) and only there does an avalanche arise. Thus, a quantity of electrons N' enhanced by a multiplication factor A travels to the anode

$$N' = NA = \frac{E_{\text{abs}}}{\varepsilon} A.$$

With this arrangement, it does not matter where in the detector's volume the particle passed through, because multiplication always occurs at the same distance from the anode. These

gas detectors are called proportional counters and are, like ionization chambers, capable of measuring the absorbed energy. If the readout electronics at the anodes can also accurately measure the arrival time of the signal, the shape of the particle's trajectory can be calculated from the relative delay at the individual anodes. Such a detector is called a time projection chamber (TPC).

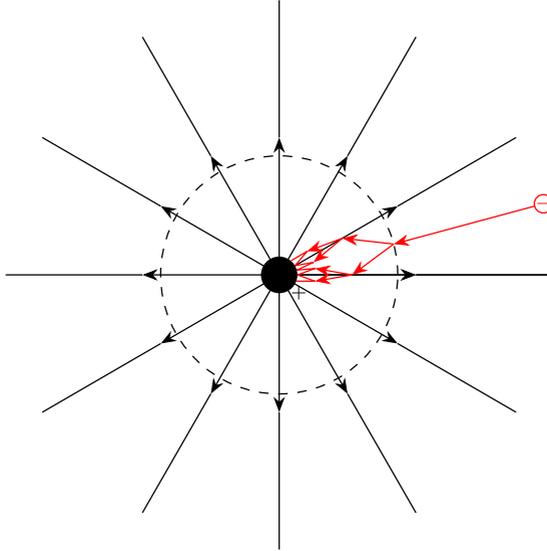


Figure 4: Multiplication of electrons in a stronger electric field in the vicinity of an anode in the shape of a thin wire. The multiplication always starts at the same distance.

In proportional counters, however, the avalanche discharge also involves the excitation and subsequent de-excitation of atoms, and thus the emission of fluorescent photons. These photons can cause ionization elsewhere in the detector leading to a false avalanche. Therefore, a gas mixture is used in the detectors, where 90–95 % is the main ionization gas with a low ionization energy, and 5–10 % of the gas is a quenching gas, which absorbs the fluorescent photons. At a very high voltage, the relationship between the absorbed energy and the signal strength disappears. Fluorescent photons will cause electron avalanches throughout the entire volume of the detector and a discharge will occur independently of the particle's original energy. This is how Geiger-Müller tubes work. Gas detectors have a low cost per unit of detection volume, so they are suitable for applications where large areas and large volumes need to be covered. However, gases have a low density, therefore they are not at all suited for the detection of high-energy gamma photons, and with the exception of special applications, they are not suited for measuring other neutral particles either (but, e.g., ^3He gas detectors are used to detect neutrons, as the ^3He isotope has a high cross-section for interactions with neutrons and is a gas under normal conditions).

Semiconductor Detectors

The core of semiconductor detectors is the PN junction. At the interface of p -type semiconductors (the majority charge carriers are positive holes) and n -type (the majority charge carriers are negative electrons), diffusion of holes from p to n and diffusion of electrons from n to p occurs. The charge carriers recombine with each other, and thus a region without free charge carriers (depletion region) is formed at the PN junction. By applying an electrical voltage in the reverse bias, we expand the depletion region even further.

If an ionizing particle passes through the depletion region, it creates electrons and holes. The charge carriers are separated from each other by the electrical voltage, so recombination does not occur. Semiconductor detectors have an ionization energy that is an order of magnitude ($10\times$) lower than gas detectors, and therefore they measure the energy of particles more precisely. Ionization energies and Fano factors for some semiconductors are given in Table 2. It is also possible to achieve a high spatial resolution, because individual PN junctions can be made small and densely packed next to each other, creating pixels (pixel size from $\sim 10\mu\text{m}$ upwards). However, semiconductor detectors are expensive, so they are suitable for applications where the precision of trajectory or energy measurement is crucial and the cost is secondary. The surface shape of the PN junction can be chosen arbitrarily, so semiconductor detectors do not have to be only pixel-based, but there are also strip detectors or even diodes with only a single PN junction, which generally achieve the highest precision in energy measurement. Besides the uncertainty caused by Fano noise (Equation (2)), the readout electronics noise also contributes to the energy uncertainty (not only) in semiconductor detectors. Therefore, the best energy resolution is achieved if all the generated charge is concentrated on a single PN junction, and thus on only a single readout circuit. This, of course, requires larger pixels, or a diode with a single PN junction, so a better energy resolution is usually traded off for a worse spatial resolution.

Table 2: Average ionization energies required to create an electron-hole pair in some semiconductors.

Semiconductor	Avg. ionization energy ε (eV)	Fano factor
Si	3.64	0.115
Ge	2.97	0.112
CdTe	4.43	0.24
$\text{Cd}_{0.8}\text{Zn}_{0.2}\text{Te}$ (CZT)	4.6	0.14
diamond	13.1	0.382

Scintillators

Scintillators use ionization only indirectly through scintillation photons. When a charged ionizing particle appears in a scintillator, it begins to ionize and excite atoms and molecules. Recombination and de-excitation then create photons of ultraviolet or visible light, which are detected by detectors sensitive even to single photons – photomultipliers or silicon photomultipliers. From the previous description, it is clear what the basic requirements for a scintillator are. The material must be transparent to the emitted photons and the entire assembly must be in the dark, so that external photons do not overwhelm the photomultiplier(s). The response

of a scintillator is characterized by the yield, that is, how many photons are generated per unit of absorbed energy, and also by the scintillation lifetime τ , since the light intensity $I(t)$ decays exponentially after excitation

$$I(t) = I_0 e^{-t/\tau}.$$

Some scintillators have two parallel recombination pathways with different lifetimes. Here we must divide scintillators into two main families – crystalline inorganic and organic. In crystalline inorganic detectors, a negative free electron is created in the conduction band and a positive hole in the valence band (see Figure 5)⁴

The electron travels freely through the crystal lattice. For the scintillator to function well, it must usually contain an impurity or other defects in the crystal lattice – luminescence centers. A luminescence center has an energy level in the forbidden energy band, between the conduction and valence bands. The electron loses part of its energy in the form of heat and falls into the luminescence center. It then recombines with a hole and emits a photon of light in the process. Since the emitted photon has a lower energy than the width of the forbidden band, it cannot be absorbed to create another electron-hole pair and propagates through the scintillator over a long distance. For example, in sodium iodide NaI, a thallium impurity is used in the NaI(Tl) scintillator. The Bi₄Ge₃O₁₂ scintillator (called BGO) does not need an impurity, because recombination and luminescence take place on bismuth atoms. The light yield of inorganic scintillators is typically on the order of 10⁴ photons/MeV, and the mean lifetime ranges from tens of nanoseconds to tens of microseconds. The parameters of selected inorganic scintillators are given in Table 3.

Table 3: Light yields in selected inorganic scintillators.

Scintillator	Yield (photons/MeV)	τ (ns)
NaI(Tl)	37700	230
CsI(Na)	38500	630
LYSO(Ce)	32000	40
BGO	8200	300
LaBr ₃ (Ce)	63000	16

Organic scintillators are most commonly molecules that contain a benzene ring in their structure. Scintillation here occurs via the excitation and de-excitation of electrons in the molecule, so the scintillation lifetime is shorter and the scintillator has a faster response, even on the order of units of nanoseconds. However, the scintillation photons are typically from the ultraviolet spectrum, and these do not travel far in the material. Therefore, pure organic scintillators cannot be large and are used only rarely. A class of organic scintillators called plastic scintillators has widespread use. Their base is a plastic (most often polyvinyltoluene,

⁴The valence and conduction bands are concepts from solid-state physics. The valence band includes the energy states of electrons when the electron is still bound to its atom or molecule. The conduction band contains higher energy states where the electron is not bound to a specific atom or molecule and can move freely through the crystal lattice and also react to an external electric field. In insulators and semiconductors, the valence and conduction energy level bands are separated by a forbidden energy band, where no available energy level for electrons occurs. When an electron jumps from the valence band to the conduction band, it leaves behind a hole in the valence band. Another electron from the valence band can jump into the hole, thereby moving the hole. Holes in the valence band de facto behave as positive charge carriers.

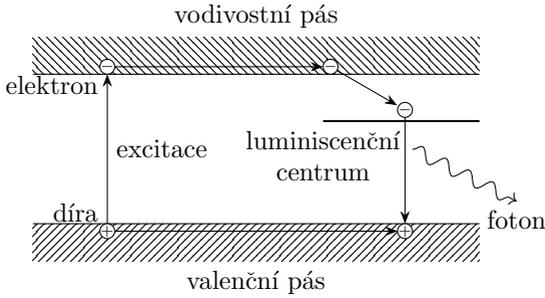


Figure 5: Diagram of the band structure in a scintillator. **(Left)** A particle of ionizing radiation creates a positive hole in the valence band and a free electron in the conduction band. Both can move through the crystal lattice. **(Right)** The electron has fallen into a luminescence center with lower energy. From the luminescence center, the electron jumps back to the conduction band, recombines with a hole, and emits a scintillation photon in the process.

polystyrene, or polymethyl methacrylate), which itself does not scintillate or scintillates only minimally. An organic scintillator is dissolved within it. A fluorescent additive (other organic molecules) is also added to the material, which absorbs the ultraviolet photons and re-emits them with a longer wavelength. Optical photons can propagate through the plastic over a significantly greater distance than ultraviolet ones.

Compared to inorganic scintillators, plastic scintillators tend to have a lower light yield, on the order of 10^3 photons/MeV. Plastic scintillators can be manufactured in any shape, and their production is cheap. They are suitable for applications where large areas or large volumes need to be covered and the precision of energy measurement is not important. They are irreplaceable where a fast response to the arrival of a particle is crucial, for example, as a trigger initiating other detectors. Also, as plastics with an abundance of hydrogen, they are suitable for detecting fast neutrons. Inorganic scintillators have a high density and higher precision in energy measurement. They are used, for example, for measuring gamma photon spectra or in PET imaging in medicine. Another type of scintillator used only in specific applications are scintillators made of liquefied noble gases. Liquid argon (LAr) or xenon (LXe) emit scintillation photons, but the detector can also function as a time projection chamber if the liquid is under a voltage. Electrons that did not recombine and did not create scintillation photons drift in the electric field towards the anodes, where we can measure the arrival time of the electrons at the individual anodes. Maintaining a liquefied noble gas is technically demanding, and therefore these scintillators are used only in scientific applications; for instance, a LAr scintillator is part of the calorimeter in the ATLAS detector⁵ and a LXe scintillator is used to search for hypothetical dark matter WIMP particles⁶.

⁵<https://atlas.cern/Discover/Detector/Calorimeter>

⁶<https://xenonexperiment.org/time-projection-chamber/>

Calorimeters and Magnetic Spectrometers

Calorimeters and magnetic spectrometers are systems of detectors. A calorimeter measures the energy of a particle by letting it deposit all of its energy in the detector. Therefore, high-density detectors must be used in a calorimeter so that the particle loses all its energy over a reasonably short distance. For example, the LND detector⁷ aboard the Chang'e 4 lunar lander consists of silicon detectors in 10 layers and functions as a calorimeter for protons and heavy nuclei up to an energy of < 30 MeV/nucleon. More energetic ions will fly through.

The electron-positron LAT telescope⁸ measuring γ photons with energies of 0.02–300 GeV aboard the Fermi satellite has a CsI(Tl) scintillator calorimeter as its final component, where the energy of the electron and positron from the electron-positron pair is measured. A sandwich calorimeter alternates passive plates of heavy metal (tungsten, lead, etc.) with layers of detectors, thanks to which the calorimeter can be shorter.

However, this is at the cost of a worse energy resolution. For example, the hadronic calorimeter in ATLAS is made of layers of steel and plastic scintillators. The precision of energy measurement in a calorimeter depends on the number of generated charge carriers N , which is governed by the Fano noise (Equation (2)). If we neglect the terms with A and C in Equation (3), then the energy uncertainty from the calorimeter is directly proportional to

$$\Delta E \propto \sqrt{N} \propto \sqrt{E},$$

so the relative resolution of the calorimeter $\Delta E/E$ increases with energy.

Magnetic spectrometers measure the momentum of charged particles using the curvature of their trajectory in a magnetic field. Recall that a particle with an electrical charge q and momentum p in a homogeneous magnetic field with induction B moves along an arc of a circle with a radius

$$r = \frac{p}{qB}.$$

More precisely, the magnetic spectrometer measures the ratio of momentum and charge p/q , so the magnitude of the charge must be determined by another method in order to calculate the momentum. The sign of the charge can be determined from the curvature of the track, since negative charges curve in the opposite direction to positive charges.

A fundamental requirement for detectors in a magnetic spectrometer is a high spatial resolution, in order to measure the particle's trajectory in the magnetic field as best as possible. The higher the momentum of the particle, the higher the radius of curvature. At too high a momentum, the particle's track will not differ from a straight line. The resolution of the spectrometer therefore decreases with the increasing momentum of the particle. The relative uncertainty of the momentum is directly proportional to the momentum

$$\frac{\Delta p}{p} \propto p.$$

Cherenkov Detectors

So far, we have discussed detectors that directly or indirectly utilized the ionization of a material. Cherenkov detectors, on the other hand, detect Cherenkov radiation. This is an analogue of a sonic boom in the air, which is created when moving at a supersonic speed. Cherenkov

⁷<https://link.springer.com/article/10.1007/s11214-020-00725-3>

⁸<https://fermi.gsfc.nasa.gov/science/instruments/lat.html>

radiation is produced when an electrically charged particle moves through a medium faster than the speed of light in the given medium

$$v_{\text{particle}} > v_{\text{light}} = \frac{c}{n},$$

where c is the speed of light in a vacuum and n is the refractive index of the medium. The light propagates at an angle θ (see Figure 6) from the particle's direction of flight

$$\cos \theta = \frac{c}{nv_{\text{particle}}}.$$

The goal of Cherenkov detectors is typically not only to capture Cherenkov photons but ideally also to reconstruct the angle θ , and thus determine the particle's velocity. This is done, for example, by RICH (ring-imaging Cherenkov detector) type detectors.

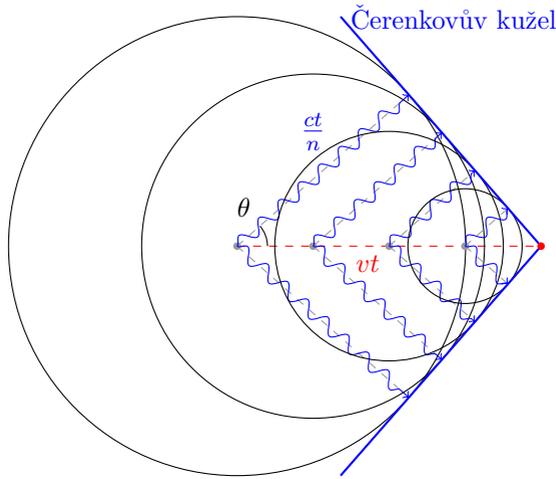


Figure 6: A charged particle (red) at faster-than-light speed (i.e., a speed higher than the speed of light in the given medium) emits photons at an angle θ . Together, these photons form a cone of Cherenkov radiation.

The energy of Cherenkov photons emitted by a particle per unit path length dx and per unit photon wavelength $d\lambda$ is

$$\frac{d^2 E}{dx d\lambda} \propto \frac{q^2}{\lambda^3} \sin^2 \theta,$$

where q is the charge of the particle. We can see that more energy is released at shorter wavelengths, which explains why Cherenkov radiation is blue. At the same time, however, there is no risk of the power being infinite as $\lambda \rightarrow 0$, because at short wavelengths the refractive index $n(\lambda)$ approaches 1, so short-wavelength Cherenkov radiation is not produced.

Energy losses via Cherenkov radiation are usually negligible compared to ionization energy losses. We can also notice that the intensity of Cherenkov radiation depends on the particle's velocity (through the angle θ) and that the maximum value is limited ($\sin^2 \theta_{\text{max}} = 1 - 1/n^2$).

In order for us to observe Cherenkov radiation, the particle must pass through a transparent medium (water, air, etc.). Due to its low intensity, Cherenkov radiation must be detected by photomultipliers, which are detectors sensitive even to single photons.

Transition Radiation Detectors

Transition radiation is produced when a charged particle transitions between two media with different electrical permittivities. Unlike Cherenkov radiation, transition radiation is produced independently of the particle's velocity. The maximum energy of transition radiation photons is directly proportional to the gamma factor of the passing particle

$$E_{\max} \propto \gamma = \frac{1}{\sqrt{1 - \beta_{\text{particle}}^2}}$$

and the total energy of all photons combined is directly proportional to the product of the square of the charge and the gamma factor

$$E_{\text{total}} \propto q^2 \gamma.$$

Transition radiation detectors are important for characterizing extremely energetic particles ($\gamma \gg 1$), because from the properties of the transition radiation we can calculate the particle's γ factor. In these extreme cases, transition radiation photons tend to have high energy (extreme ultraviolet to X-ray, e.g., a particle with $\gamma = 1000$ will generate photons with an energy of 2–20 keV).

Similar to Cherenkov radiation, the energy loss via transition radiation is usually minuscule compared to the particle's kinetic energy. Therefore, transition radiation detectors are constructed with a large number of thin foils made of light material, so that the particle passes through many interfaces, but at the same time so that the thin foils do not stop too many transition radiation photons. A transition radiation detector can be found, for example, as part of the AMS-02 experiment⁹ aboard the International Space Station, which aims to measure the spectrum of charged particles arriving from space and to search for antiparticles. In cooperation with other components of AMS-02 (RICH detector, magnetic spectrometer, and others), we are able to determine a lot of information about the passing particle.

Passive Detectors

Passive detectors are those that do not provide a signal in real time but accumulate damage from ionizing particles, potentially over a long period. The accumulated signal is then evaluated as a whole without time information about when each particle arrived. This is how, for example, photographic emulsions work in passive personal dosimeters. In Czechia, these are evaluated monthly or quarterly, and the dose received by the human body over the given period is calculated from the tracks in the emulsion.

Another type of passive detector is solid-state nuclear track detectors. An energetic heavy ion damages the crystal lattice along its trajectory. In contrast, electrons and muons have much lower ionization losses along their trajectory, and thus damage the crystal lattice minimally. When the detector's surface is etched with acid after exposure, the regions with a damaged crystal structure from the passage of heavy ions dissolve faster, thus making the particle tracks

⁹<https://ams02.space/>

visible. Nuclear track detectors are used, for example, in the MoEDAL experiment¹⁰ at CERN, where the goal is to search for exotic tracks and discover the magnetic monopole. Passive detectors have the advantage of low cost and low operational demands, but their disadvantage is more complicated data processing and the limited amount of information they provide.

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¹⁰Video: <https://home.cern/science/experiments/moedal-mapp>