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A review of particle detection using scintillation detector

Ruifu Chen[1]

[1] International Department of Chengdu Shude High School Chengdu, China 610000

jefferyv@163.com

Abstract. Acquiring properties of microscopic particles helps establish modern physics models and theories, and detectors are the main method. This literature review researches on modern particle physics papers, summarizing the detection principle adopted for four types of particles, concluding the detection principle of the most commonly used detectors, scintillators, and summing up the use of scintillators in the four main kinds of particle detection. Based on the investigation, various kinds of detection materials absorb particles or their secondary particles based on different interaction mechanism in detection, and different kinds of particles have their suitable detectors. Scintillators are classified into three categories based on difference in physical properties, and detect particles by releasing energy during de-excitation in electric pulse signal forms. They can be made into large size, have relatively large detection efficiency and is suitable for γ ray detection. These ability gain scintillators a wide range of application in detection of the principal types of detectors.

Keywords: particle detection, γ rays, scintillator, particle physics, literature review.

1. Introduction

Various microscopic particles have a wide range of application in particle physics, and investigation of their properties is required. A beam of these particles is called ray, and by detecting microscopic particles and rays using instruments, their properties can be revealed. Knowledge of these properties builds up the cornerstone of modern physics theories and promote new technology. By reviewing on modern particle physics literature, this research draw conclusion about the detection principle of four main types of particles, charged particles, γ rays, neutrons and high energy particles, and the detection process and categories of a kind of commonly used detectors called scintillators.

This review effectively examines various kinds of detection principles suitable for different kinds of particles, allowing researchers quickly determine the way of detection and the adoption of detection material. Moreover, readers can acquire a clear overview of scintillators, from their detection principle and process to the categories based on physical properties. The advantages and shortcomings of using scintillators in detection of the four main types of particles are analyzed, and typical or new materials for detection is discussed. These information helps readers have an overall understanding of particle detection and scintillators, which is also the aim of this article.

2. Detection Principle of Particles

In the fields of particle detection, some significant physical quantities represent basic concepts that should be known. One important physical quantity is cross section, which refers to the interacting probability when a particle vertically passing through a target material with unit area $1cm^2$ and unit length $1cm$[1]. If N_r is the number of interactions, N is the atomic number in unit volume, $N_\perp$ refers to the number of particles that is incident perpendicularly to the target material, and d is the thickness of target material, the formula of atomic interaction cross section is written as following:

$$\sigma = N_r / N \cdot N_\perp \cdot d \quad (1)$$

Using cross section area, the reaction of certain radiation can be quantitatively measured.

2.1. Detection Principle of Charged Particles

Charged particles are principally detected through excitation and ionization or Cherenkov effect. When they enter atoms of target material, they interact with orbiting electrons under Coulomb force. According to theories regarding atomic structure, the energy state is discrete with multiple energy levels, and electrons absorb certain energy to jump to higher energy levels. This process is called excitation of electrons. As electrons gain enough energy to overcome the attractive pull from nucleus, it jumps out to become free electrons, and this is called ionization. Different kinds of detectors adopt three ways to detect charged particles using excitation and ionization: gas, semiconductor and liquid detectors collect ions during ionization; scintillators collect photons multiplied by photomultiplier tube and emitted when excited electrons de-excite and fall to lower energy levels; track detectors like cloud chamber use ion groups as track center to trace charged particles.

Cherenkov effect refers to the situation when a charged particle is moving faster than the relative speed of light inside a medium and emits a faint radiation in the range of visible light [2]. As a result, Cherenkov detectors are invented to detect high speed charged particles using photomultiplier tube to magnify the faint radiation.

2.2. Detection Principle of X or γ rays

X or γ rays are photon beams. These high energy electromagnetic waves cannot be directly detected through excitation or ionization process inside detectors. Rather, they interact with electrons or atomic nucleus through three electromagnetic effects, producing secondary electrons. Detecting these secondary electrons using excitation or ionization inside detectors provides an indirect way to detect X or γ rays.

The first interaction is photoelectric effect. The photoelectric effect is the emission of electrons or other free carriers when light shines on a material. γ rays consist discrete quantum called photons, and the energy of each photon is

$$E = hf \quad h = 6.63 \times 10^{-34} \quad (2)$$

where h is known as Planck's constant, and f is the frequency of that single photon as well as the light. When light beam shines on detection material, a single photon of frequency f is absorbed by a single electron in the material, so the electron's energy increases by hf, allowing it to jump to higher energy levels.[3] If the acquiring energy is enough for electrons to overcome the attractive nuclear force with frequency greater than a certain value, secondary electrons will be ejected and excited or ionized in the detector for detection.

The second type of interaction is Compton effect. As γ rays enter the detectors and interact with extranuclear electron, photons may be scattered and deviate from their original moving direction rather than being absorbed. The energy of interacting electrons can affect the scattering state. When the energy of photons is approximately the same as the binding energy of the nuclear electrons, electrons cannot be considered as free electrons and the scattering angle is relatively small; when photon energy far exceeds the binding energy of nuclear electrons, electrons can be considered as free or stationary electrons, and this process, called Compton scattering, is the most common and the focus in discussion. Under this situation, photons lose certain amount of energy and change direction, and only in low energy condition the loss of energy can be ignored, which is called the Thomson scattering.

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The last kind of interaction is electron pair effect. When the energy of incident photon is greater than $1.02\mathrm{MeV}$, it may react with the nucleus, forming an electron and a positron with itself disappearing.[4] The $1.02\mathrm{MeV}$ part of photon energy produces the electron pair based on Einstein's mass-energy equation, and the rest constitutes the original kinetic energy of the electron pair, as shown in the equation below:

$$\mathrm{KE_{e^-}} + \mathrm{KE_{e^+}} + 2\mathrm{m_e c^2} = \mathrm{E_\gamma} \quad 2\mathrm{m_e c^2} = 1.02\mathrm{MeV} \tag{3}$$

Both energy and momentum are conserved during this process, and γ rays are detected by detecting resultant electron pairs.

Detecting these secondary electrons produced during photoelectric effect, Compton effect or electron pair effect by ionization and excitation in detectors, the information of original γ rays is collected. Roughly speaking, photoelectric principally happens when the photon energy is low and the number of protons of the interaction atom is high; Compton effect mainly occurs when the proton number is low with intermediate photon energy; electron pair effect mainly occurs when the energy of photon as well as the proton number of reacting atom are high. Since emitting electrons of photoelectric and electron pair effect are of single energy, they are easily detected. Therefore, detection material for γ rays should have possibly great proton number, whether of scintillators (NaI), semi-conductors (Ge) or gas detectors(Xe).

2.3. Detection Principle of neutrons

Neutrons carries no charge. With electric neutrality, there's no Coulomb interaction and negligible electromagnetic interaction due to magnetic moment between neutrons and electrons. Otherwise, neutrons do not experiment Coulomb repulsion from the nucleus, making it easy for strong interaction to occur when neutrons enter the nucleus. The reaction cross section is exceptionally large especially for slow neutron as the long residence time increases the probability for strong interaction to happen. There are multiple interaction types and resultant secondary particles for the strong interaction between the nucleus and neutrons. Therefore, there exist multiple neutron detection ways based on different interaction type and secondary particles.

The first way is nuclear reaction method, which use excitation or ionization of secondary charged particles like protons or alpha particles produced in strong interaction for detection. Since neutrons with low speed and low energy have much greater reaction cross section, this method is mainly used to detect slow neutrons with energy lower than $1\mathrm{MeV}$. B is the most widely used element as detection material in this case with low cost and relatively good detection efficiency.

The second method is through nuclear recoil. When the energy of incident neutron is large, neutron is elastically scattered away by the nucleus, changing its direction of moving and thus losing a certain amount of energy. This part of energy is transported to the nucleus, so detecting the nucleus allows the detection of neutrons as well as their energy. When the atomic number of the nucleus is low, the recoil energy is the greatest and observations are easily made, so hydrogen atom is the mostly used. This method is principally applied to detect fast neutrons with energy higher than $0.3\mathrm{MeV}$.

The third means is by nuclear fission. As neutrons and the nucleus underdo nuclear fission, a significant amount of energy will be released. Since the emission energy is much greater than the energy of incident neutrons, this method is mainly adopted to measure the flux rather than the energy of neutrons. Through different nuclear fission material, the detection of both slow and fast neutrons is possible.

The last way is called activation method.[5] When neutrons enter the nucleus, there's possibility for the nucleus to absorb neutrons and becomes a different nuclide of the same element. Since the original nucleus is usually stable, the new nuclide will be radioactive to emit β or γ rays. As a result, β or γ detectors are applied to indirectly detect neutrons, and this method can also be used to produce β or γ emission nuclide. If the effective capture cross section for a single atom is denote by σ, A represents the number of captured neutrons in unit time and unit area $1\mathrm{cm}^2$, f is the flux of neutron, the number

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of neutrons that pass through $1\mathrm{cm}^2$ of target in unit time, N represents the number of atoms in $1\mathrm{cm}^2$ of target, and d is the width of the target, then the relation is summarized below.

$$\mathrm{A} = \mathrm{fN\sigma d} \tag{4}$$

These four methods are adopted for neutron detection by detecting secondary particles produced in the interaction between the neutron and the nucleus, and different methods are more suitable for neutrons of different properties.

2.4. Detection Principle of high energy particles

Particles mentioned above are all in the low energy range, with relatively simple interaction mechanism. For high energy particles, the interaction is much more complicated. Generally speaking, secondary charged particles' average multiplicity increases with energy, and the number of charged particles is Poisson distributed around the average multiplicity. For high energy electrons and γ rays, they produce huge number of secondary particles through cascade shower. During this process, photons and electron pairs are repeatedly converting to each other until the eventual particle energy is too low to support further conversion.[6] The result is lots of low energy electrons and γ rays. When the incident particles have even higher energy, high energy nucleons and mesons will undergo secondary nuclear reaction or decay, and this reaction may happen for many times. The resultant secondary particles can be classified into three categories: nuclear component, meson component, and electromagnetic component, all with very low energy. By detecting the secondary particles produced in various kinds of showers, high energy particles can be measured. Usually, detection of high energy particles happens in high energy physics or detection of cosmic rays.

3. Detection Process and Categories of Scintillators

Among the various types of detectors, scintillators have the widest range of application. As mentioned, scintillators detect particles using photomultiplier tube to magnify faint fluorescence or photoelectrons multiple times and recording the resultant electric pulse signal. This detection principle allows scintillators to detect various kinds of particles including neutral particles. On the other hand, scintillators can be made in large size and have large density, so the detection efficiency is relatively large, even making it possible to detect high energy particles. Meanwhile, scintillators allow detection under high counting speed, making it suitable for strong particle source. These properties of scintillation detectors gain them a wide range of application.

3.1. Detection Process of Scintillators

The detecting process of scintillators involves several steps. Firstly, particles will go into scintillation crystal, and atoms or molecules excite or ionize as electrons are excited to conduction band and forbidden zone from valence band. Then, the excited atoms or molecules de-excite and emitting photons in the range of visible light.[7] During this process, certain amount of energy loses in forms of thermal energy. Next, the remaining photons make their way to the photocathode, which absorbs photons and emits photoelectrons. Certain number of photons will be absorbed or scattered in this process, failing to approach the photocathode. Eventually, the photoelectrons are multiplied in a photomultiplier tube to form a voltage pulse at the anode. Then, the pulse is output by emitter follower or preamplifier, and are amplified, analyzed, and recorded by electronic analyzers. Thus, the properties of detected particles are yielded by measuring the energy of the photons and their secondary charged particles in scintillation crystal under excited circumstance.

3.2. Categories of Scintillators

Scintillators can be sorted into three main categories. The first and the most widely used type of scintillators is inorganic scintillators. Inorganic scintillation crystal is insulator with relatively wide forbidden band. As a result, excited electrons cannot acquire enough energy to ionize to conduction band, and they gather in a band below conduction band, which is called the exciton band. When the

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electrons de-excited to valance band, the extra energy is emitted in forms of photons. Parts of photons are absorbed or scattered by atoms or molecules in the scintillator, increasing the energy loss. To increase energy conversion efficiency, a trace amount of impurity atoms is added to the crystal and form an impurity energy level in the forbidden gap. These impurity atoms will capture some free electrons or activated electrons in the impurity energy level, and these electrons de-excite to the valence band without been absorbed by crystal since the emitting light has energy less than the width of forbidden gap.

The most commonly used inorganic scintillators is sodium iodide activated with a trace amount of thallium, or NaI(Tl). Its properties like high density, large atomic number, large light yield and high energy resolution make it exceptionally suitable in the detection of γ rays.[8] For protons and electrons, the relationship between light output and energy is nearly proportional, representing good detection efficiency.

The second main kind is organic scintillators. Although the luminous efficiency is relatively lower and the luminescence decay time is short, organic scintillator is cheap with low density and small proton number. Also, organic scintillators contain massive amount of hydrogen atoms, becoming exceptionally outstanding in the detection of fast neutrons. Based on physical properties, organic scintillators can be classified as organic crystals, organic liquids and plastic scintillators. Organic crystals emit photons based on inherent property, which is caused by the change in molecule energy. For the other two types, certain solvent will be added as activator, and the second solute may be used if necessary and acts as a wavelength shifter.

The last type is gas scintillators, which often adopt noble gases as the detection material. Gas scintillators must undergo strict purification repeatedly to ensure detection efficiency, and require wavelength shifter to cooperate with photomultiplier tube. The luminous efficiency of gas scintillators falls slowly with the rise in pressure, but decreases significantly with increase in the thickness of detection chamber. Besides certain mixed gas, Xe has the greatest luminous efficiency and is commonly used.

3.3. Applications of Scintillators

Since scintillators have a wide range of applications, they are able to detect the four kinds of particles discussed. For charged particles, scintillators perform poor in energy detection due to low energy resolution, but can be applied to information detection including counting, flux and position. For example, CsI(Tl) inorganic scintillator is adopted to distinguish the resultant particles in the reaction of B and Be.[9]

For the detection of γ rays, however, scintillators undertake the main work. The detection efficiency is extremely high due to high density and large size, making up for deficiencies in energy resolution. NaI(Tl) is used to be the most commonly used, but cerium doped lutetium-based scintillation crystal, or LYSO scintillator, has even better performance and applies to medical and cosmic physics fields like PET-CT or energy sources identification of cosmic rays.[10]

In neutron detection, eliminating the interference from γ rays is very important. ZnS(Ag) is commonly used to detect slow neutrons, while fast neutrons are principally detected by the hydrogen atoms in organic scintillators.[11] For high energy particles, scintillators are made in very large size to absorb all the secondary particles, becoming full absorption detectors. As the energy of incident particle goes higher, the scintillation layer is enclosed in a layer of heavy matter, only absorbing certain amount of energy and producing signals proportional to the energy of the incident particle. This method is used to reduce the cost.

4. Conclusion

In summary, detectors are used to detect microscopic particles including charged particles, photon beams, neutrons and high energy particles. With certain difference, the detection process is that detection materials absorb these particles or their secondary particles and transport the resultant electric pulse signal to devices for analysis. Among various type of detectors, scintillators have the widest application

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and detect particles through the energy emission in de-excitation. Scintillators can be classified into three main categories, and are used in the detection of the four types of particles.

This research on microscopic particle detection principle is focus on scintillators, thus lacking illustration of other detectors. Also, certain professional terms and formulae are omitted in convenient for popularization of science. Through the investigation, new materials in should be the focus of future research. These mixtures, like the LYSO scintillation crystal, allows greater detection efficiency and performs better in different fields. As a result, further research on their properties or massive production is fairly beneficial for research and development.

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