Particle Detectors

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Abstract

Physics researchers identify subatomic particles through the traces they leave in detectors, just like hunters can recognize animals from tracks in snow or mud. Particle detectors are devices used to detect and measure particles such as electrons, protons, neutrons, and other subatomic particles. Detectors can be used to measure properties such as energy, momentum, and direction of these particles in order to understand the structure of matter and the laws of nature. Particle detectors are essential components of particle accelerators, which are used to study the properties of particles and to observe and investigate new phenomena. Depending on the design and type of the detector, these measurements can be obtained either directly or indirectly. Direct measurements involve measuring physical properties of the particle itself (e.g., energy). On the other hand, indirect measurements involve measuring the effects that the particle has on other particles or materials in the detector (e.g., energy deposition). In order to detect a particle, it has to interact and deposit energy. This paper will provide an overview of the various types of particle detectors and their applications in particle physics.

1 Introduction

Particle detectors are devices used to detect and measure particles such as electrons, protons, neutrons, and other subatomic particles. Detectors can be used to measure properties such as energy, momentum, and direction of these particles in order to understand the structure of matter and the laws of nature. Particle detectors are essential components of particle accelerators, which are used to study the properties of particles and to observe and investigate new phenomena. This paper will provide an overview of the various types of particle detectors and their applications in particle physics.

2 Fundamentals of Operation

At their core, particle detectors measure different characteristics of a particle, such as its energy, position, and direction of motion. Depending on the design and type of the detector, these measurements can be obtained either directly or indirectly. Direct measurements involve measuring physical properties of the particle itself (e.g., energy). On the other hand, indirect measurements involve measuring the effects that the particle has on other particles or materials in the detector (e.g., energy deposition).

In addition, some detectors can distinguish between different particles based on their charge, mass, velocity, or other properties. This ability can be augmented by combining various properties together, e.g., by measuring the speed and charge of a particle. Such types of detectors are generally known as *particle identification* detectors.
The two most important features of a particle detector are its sensitivity and background rejection. Sensitivity refers to how well the detector is able to detect a particle and its associated parameters. Background rejection is the ability of the detector to identify background particles or signals and ignore or reduce their effects on the result. The most sensitive and efficient detectors achieve both a high sensitivity and a good background rejection.

In order to detect a particle, it has to interact and deposit energy. Ultimately, the signals are obtained from the interactions of charged particles. Neutral particles, such as photons, neutrons) have to transfer their energy to charged particles to be measured, this is done using a calorimeter.

3 Types of Detectors

Since the inception of particle detectors, a great variety of detector designs have been developed and employed in particle and nuclear physics experiments. Broadly speaking, the detectors can be divided into two major categories – active detectors and passive detectors.
A preliminary definition of a particle detector is: an instrument to measure on e or more properties of a particle. The correspondence of the particle properties and the principle of detector is as follows

Particle property		Type of Detection Principle
Position and direction	$x, \vec{x}$	Position and Tracking
Momentum	$\|\vec{p}\|$	Tracking in a Magnetic Field
Energy	E	Calorimetry
Mass	m	Spectroscopy and PID
Velocity	β	Cherenkov Radiation or Time of Flight
Transition radiation	γ	Transition Radiation Detector (TRD)
Spin	s	Interaction with Magnetic Field

3.1 Active Detectors

Active detectors are usually segmented detectors, which are composed of several component cells, each comprising a specific material that can interact with a charged particle. When charged particles enter the detector, they interact with the component cells and deposit energy in them, producing secondary particles and producing signals in the component cells. The signals from the component cells are then further processed in order to reveal the particle’s position, energy, direction, and other properties.

Examples of active detectors include wire chambers, drift chambers, spark chambers, and modern-day Time Projection Chambers (TPCs). Wire chambers are composed of metallic wires or strips and produce signals when a particle passes through them due to the ionization of the gas between two adjacent wires. Drift chambers also use gas to detect particles and consist of multiple layers of wire grids or parallel strips that are perpendicularly aligned to each other. Spark chambers are similar to drift chambers but use sparks instead of wires. TPCs utilize both wire and detection planes, and track particles as they travel through the gas medium in the detector, allowing for much higher spatial resolution and better angular resolution.

3.2 Passive Detectors

Passive detectors are detectors that do not actively interact with particles. Instead, they rely on natural processes and principles in order to detect and measure particles. Examples of passive detectors include scintillators and Geiger counters. Scintillators are usually composed of a plastic-like material that emits light when a charged particle passes through it. The emitted light is then detected by photomultipliers, which convert the light into electrical signals. Geiger counters also use a gas-filled chamber with a wire and a metal plate. When a charged particle passes through the gas and enters the chamber, it ionizes the gas molecules, resulting in a cascade of electrons that is detected by the metal plate.

3.3 Important Particle Discoveries

By Spring 1911, Using the cloud chamber, Rees Wilson had track photographs from alpha rays, X-Rays and gamma rays.

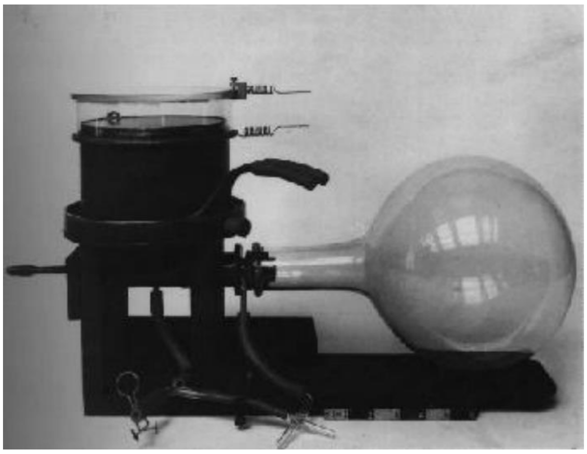


Figure 1 – Wilson Cloud Chamber 1911

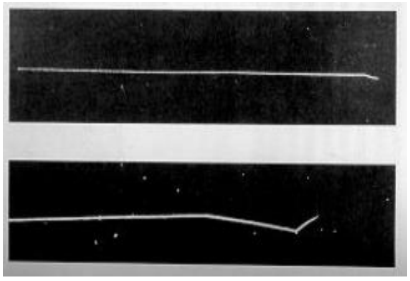


Figure 2 – Early Alpha-Ray Picture, Wilson 1912

In 1933, Carl Andersen, used a $15\,\mathrm{cm}$ diameter cloud chamber in a 15000 Gauss magnetic field, and discovered the positron. A $63\ \mathrm{Mev}$ positron passes through a $6\,\mathrm{mm}$ lead leaving the plate with energy $23\ \mathrm{Mev}$. The ionization of the particle and its behavior in passing through the foil is the same as that of an electron.

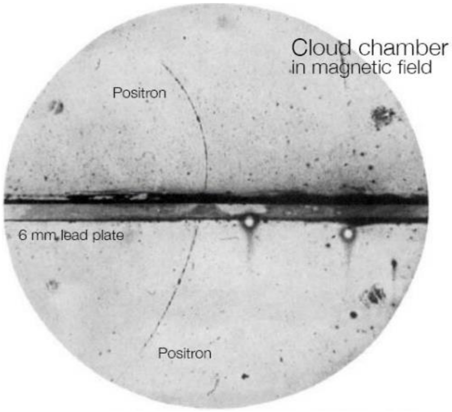


Figure 3 – Positron Discovery, Carl Andersen 1933[Nobel Price 1936]

Figure 4 – UA1 Detector that was used to discover W and Z bosons(Nobel Price 1984 – Carlo Rubbia and Simon Van der Meer)

4 Types of Particle Detectors

There are several different types of particle detectors, each of which has its own advantages and disadvantages. Some of the most commonly used particle detectors are:

- **Scintillation Detectors**: Scintillation detectors rely on the production of light when charged particles interact with certain materials, such as sodium iodide. These detectors are commonly used to detect ionizing radiation, such as gamma rays and X-rays.
- **Silicon Detectors**: Silicon detectors are semiconductor devices that can detect particle radiation. They are typically used to detect high energy particles, such as protons and neutrons.
- **Cherenkov Detectors**: Cherenkov detectors make use of the Cherenkov effect, which is the emission of light by particles travelling through a medium at speeds

faster than the speed of light in that medium. These detectors are typically used to detect high-energy charged particles, such as electrons, protons, and neutrons.

- **Time-of-Flight Detectors**: Time-of-flight detectors measure the time it takes for particles to travel from a source to a detector. These detectors are typically used to measure the energy of particles.

- **Magnetic Detectors**: Magnetic detectors measure the deflection of charged particles in a magnetic field. These detectors are typically used to measure the momentum of particles.

- **Calorimeters**: Calorimeters measure the energy of particles by measuring the heat produced when the particles interact with a medium. These detectors are typically used to measure the energy of particles.

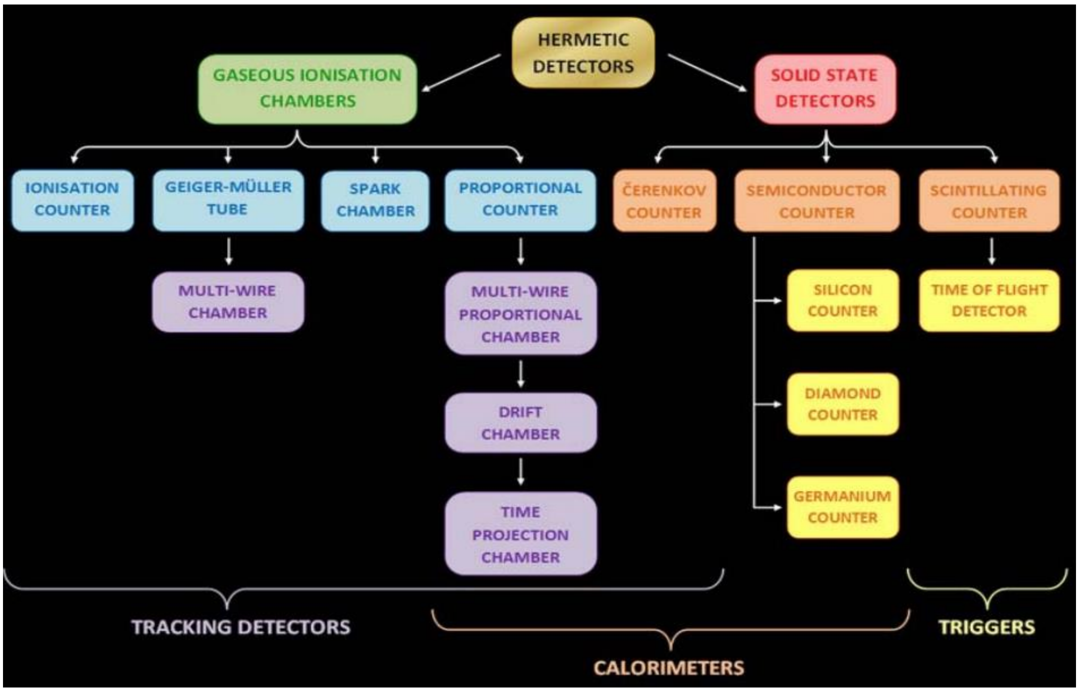


Figure 5 - Map of Particle Detectors

5 Applications of Particle Detectors

Particle detectors are used in a variety of applications, including:

- **Particle Physics Experiments**: Particle detectors are used in particle physics experiments to measure the properties of particles and to investigate new phenomena.

- **Medical Imaging**: Particle detectors are used in medical imaging, such as X-rays, to create images of the inside of the human body.

- **Nuclear Reactors**: Particle detectors are used in nuclear reactors to monitor the radiation produced by the reactor.

- **Industrial Inspection**: Particle detectors are used in industrial inspection to detect defects in materials.

- **Astronomy**: Particle detectors are used in astronomy to detect high energy particles from space.

6 Particle Detectors in Particle Physics Experiments

Particle detectors are used in particle physics experiments to measure the properties of particles and to investigate new phenomena. In these experiments, a particle accelerator is used to produce a beam of particles, which are then collided at high energies. The resulting particles are detected by particle detectors, which measure their properties. These experiments are used to investigate the fundamental structure of matter and the laws of nature.

6.1 Large Hadron Collider

The Large Hadron Collider (LHC) is a particle accelerator located at the European Organization for Nuclear Research (CERN) in Geneva, Switzerland. The LHC is the world's largest and most powerful particle accelerator, and it is used to investigate the fundamental structure of matter and the laws of nature. The LHC uses particle detectors to measure the properties of particles produced in collisions.

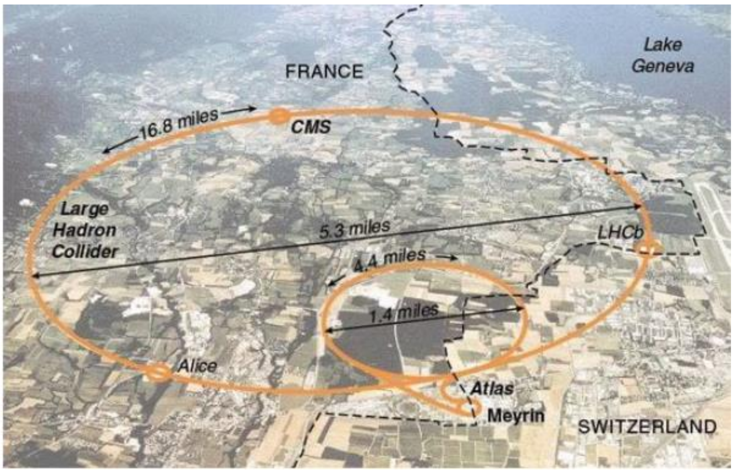


Figure 6 - Large Hadron Collider(LHD) Wide View

Magnetic fields force charged particle trajectories to bend, and the radius of curvature of these bent paths is used to determine the momentum of the particles: the higher the kinetic energy, the shallower the curvature. Therefore, a sufficiently long trajectory must be observed for particles with significant kinetic energy in order to precisely calculate the curvature radius. Calorimeters for determining the energy of particles are additional crucial components of a detector (both charged and uncharged). To absorb as much particle energy as possible, the calorimeters must also be as large as possible. The large size of the LHC detector is primarily due to these two factors.

Thousands of cables connect every component of a detector to an electronic readout system. The technology immediately captures the precise location and time of the impulse and sends it to a computer. Information is combined by a large number of computers. A highly quick system that determines if an event is interesting in a split second is at the top of the computer hierarchy. The vast data of 600 million occurrences is reduced to a few hundred events per second that are analyzed in detail using a variety of various selection criteria.

6.1.1 Calorimeter

A calorimeter is a device that measures the energy lost by particles as they pass through it. It is designed to absorb or stop most of the particles coming from a collision, forcing them to release all of their energy within the detector. This allows the calorimeter to measure the full energy of the particles. There are two main types of calorimeters: electromagnetic calorimeters, which measure the energy of electrons and photons as they interact with electrically charged particles in matter, and hadronic calorimeters, which measure the energy of hadrons as they interact with atomic nuclei. Calorimeters are able to stop most known particles, but not muons or neutrinos.

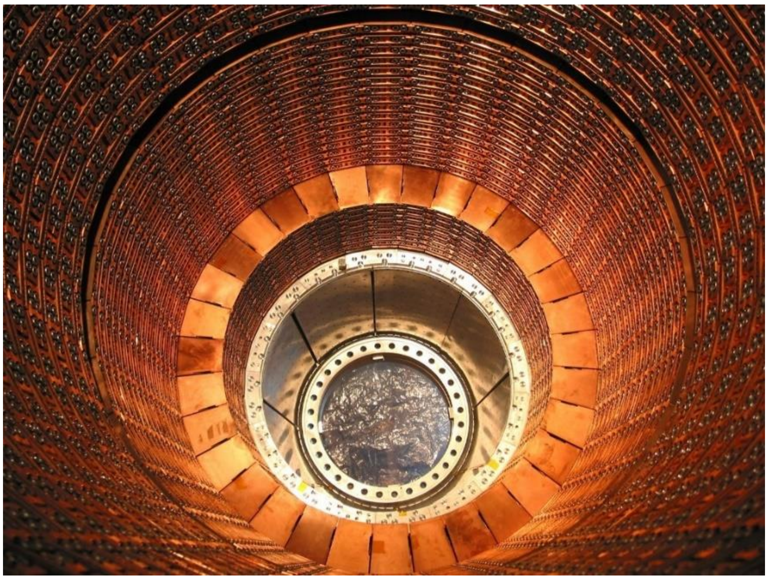
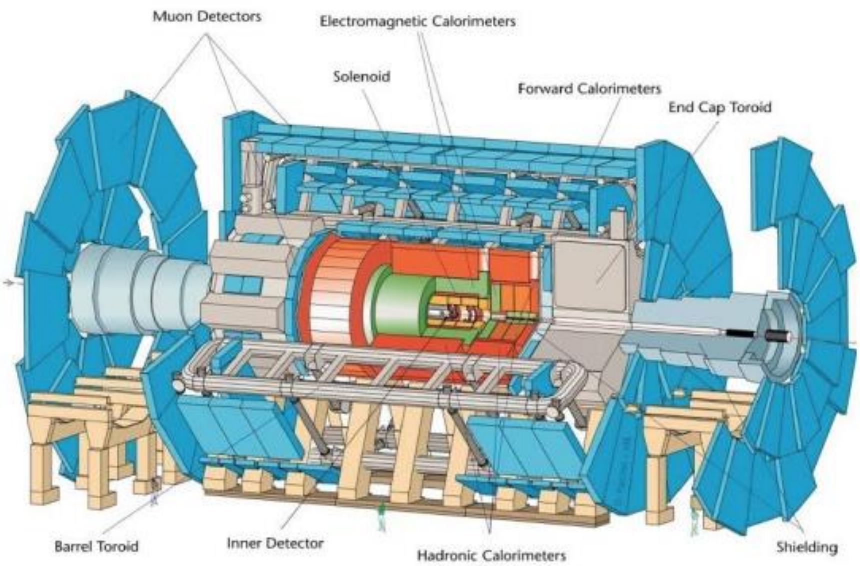


Figure 7 - The ATLAS experiment's liquid argon calorimeter is 6.4 meters long and operates at -183ºC

6.1.2 A Toroidal LHC Apparatus (ATLAS)

The ATLAS experiment is a particle physics experiment located at the Large Hadron Collider at CERN in Geneva, Switzerland. The ATLAS experiment uses the LHC to produce a beam of particles, which are then collided at high energies. The resulting particles are detected by the ATLAS detector, which measures their properties. The ATLAS experiment is used to investigate the fundamental structure of matter and the laws of nature.



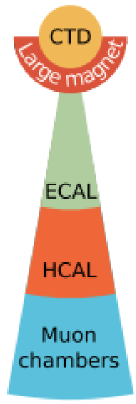


Figure 8 ATLAS detector at CERN, a transverse slice is shown above

i. Layout and Purpose of Layers

- Central tracking detector (CTD): this is designed to track all the charged particles and allow for complete event reconstruction.
- Large magnet: this produces a magnetic field strong enough to curve the tracks of charged particles in the tracking detector, allowing their momentum to calculated.
- Electromagnetic calorimeter (ECAL): this measures the shower energy of electrons and photons.
- Hadronic calorimeter (HCAL): this measures the hadronic shower energy.
- Muon tracking chamber: any particle registering on these tracking detectors (often drift chambers) has necessarily travelled through all the other layers and can only be a muon.

ii. Propagation of Particles Through the Layers

- Photons (γ): Neutral photons leave no tracks in the CTD but produce an electromagnetic shower in the ECAL.
- Electrons and positrons (e^-, e^+): Charged electrons and positrons leave tracks in the CTD and produce a shower in the ECAL.
- Muons (μ^-, μ^+): Muons leave tracks in all the detectors - they are the only particles to reach the muon chambers.
- Charged hadrons ($p, \pi^\pm, K^\pm$): Charged hadrons leave tracks in all the detectors up to the HCAL where they shower and deposit all their energy.
- Neutral hadrons (n, K_L^0): Neutral hadrons leave no tracks in any of the detectors and then they shower in the HCAL. K_S^0 mesons are not listed here because they decay before ever reaching the hadronic calorimeter.

6.1.3 Compact Muon Solenoid (CMS)

At the Large Hadron Collider, the Compact Muon Solenoid (CMS) is a general-purpose detector. Its extensive physics program includes research on the Standard Model, which includes the Higgs boson, as well as the search for additional dimensions and particles that might be involved in the formation of dark matter.

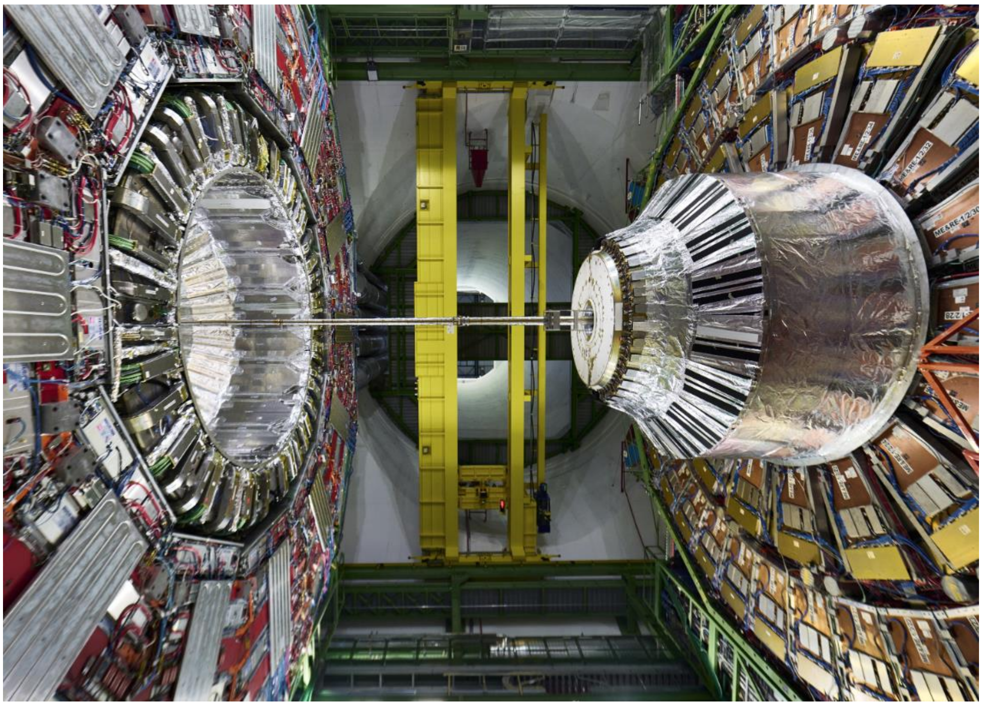


Figure 9 - CMS detector at LHC

Both ATLAS and CMS are all-purpose detectors created with the same scientific objectives: to look for dark matter, additional dimensions, and Higgs boson particles. Since only a small portion of particles in a particle beam interact with each detector, they can both be used concurrently and do this in distinct ways. This implies that an observation made in one can be verified in the other.

There are two techniques to detect muons, which accounts for the disparities between ATLAS and the CMS. First, utilize the same magnet as the tracker; second, set up a second magnet outside of the calorimeters. The first is handled by the CMS, and the second by ATLAS. The discovery that the Higgs boson had been produced in the LHC and discovered by ATLAS and CMS was made public in 2012.

6.1.4 A Large Ion Collider Experiment (ALICE)

The quark-gluon plasma from the early universe, which had been recreated in the SPS in the 1990s, was the subject of the ALICE experiment. ALICE was built to study the collisions of iron nuclei, as opposed to ATLAS and the CMS, which measure the consequences of collisions between protons. Unlike ATLAS and the CMS, it has a time projection chamber as its primary detector in addition to a tracking system and muon detectors. It is a particle detector that resembles a wire chamber.

6.1.5 Large Hadron Collider Beauty (LHCb)

Physicists can research CP (a violation of CP-symmetry, or charge conjugation parity symmetry: the combination of C-symmetry, charge symmetry, and P-symmetry, parity symmetry) violation by using the LHCb detector to find antimatter, especially the antibeauty quark (also known as the antibottom quark). It employs a succession of sub-detectors to detect particles propelled forward in the impact rather than encircling the entire collision point, unlike ATLAS and CMS.

7 Particle Detectors in Medical Imaging

Particle detectors are used in medical imaging, such as X-rays, to create images of the inside of the human body. These images are used to diagnose illnesses, such as cancer. They are also used to monitor the progress of cancer treatments. In medical imaging, a beam of X-rays or other particles is passed through the body, and the resulting particles are detected by a particle detector, which measures their properties. These measurements are used to create an image of the inside of the body.

8 Particle Detectors in Nuclear Reactors

Particle detectors are used in nuclear reactors to monitor the radiation produced by the reactors. These detectors are used to determine the levels of radiation in the reactor, which are used to ensure that the reactor is operating safely. The detectors are also used to detect leaks of radioactive materials from the reactor, which can be harmful to people and the environment.

9 Particle Detectors in Industrial Inspection

Particle detectors are used in industrial inspection to detect defects in materials. These detectors are used to detect flaws and defects in materials, such as cracks, holes, and other imperfections. These detectors are used to ensure that materials are of a high quality and will be suitable for use in products.

10 Particle Detectors in Astronomy

Particle detectors are used in astronomy to detect high-energy particles from space. These detectors are used to detect protons, neutrons, and other particles that are emitted from the Sun, other stars, and galaxies. These detectors are also used to detect cosmic rays, which are high-energy particles that come from outside the solar system.

11 Conclusion

This paper has provided an overview of the various types of particle detectors and their applications in particle physics. The paper has also provided an overview of the role of particle detectors in particle physics experiments, medical imaging, nuclear reactors, industrial inspection, and astronomy.

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