Electromagnetic Showers and Shower Detectors

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Abstract

The aim of this document is to explain the shower phenomenon and shower detection. The development of electromagnetic showers from an incident electron or photon is a well understood process. Identification of electrons and photons are the most important issues for the calorimeters. This document is a brief review to the main mechanisms of electromagnetic interactions of charged particles and photons with matter, pertinent in calorimetry.

Introduction

This note is divided into five sections. Section one discusses about particles, their properties and the standard model. This is important in the identification of particles in experiments. Section two deals with interactions especially ionization, bremsstrahlung and electromagnetic interactions of particles and photons. These phenomena associated with high-energy charged particles and photons are important in the study of showers. Section three explains the shower phenomenon and the simplified cascade model, which gives a brief mathematical outline of showers. A combination of the various detector methods helps to identify elementary particles and nuclei. At high energies absorption techniques in calorimeters provide additional particle identification and an accurate energy measurement. Section four is relevant in the explanation of detection of electromagnetic particles and neutral particles followed by conclusions in section five.

1 Particles

The concept of a particle is an abstraction of our everyday observation of matter. The idea that there must be some set of smallest constituent parts, which are the building blocks of all matter, has led us to investigate the structure and content of all matter. In the 1930s, it seemed that protons, neutrons, and electrons were the smallest objects into which matter could be divided and they were termed "elementary". Today, quarks and leptons, and their antiparticles, are candidates for being the fundamental building blocks from which all matter is made.

1.1 Standard Model

The high-energy physics community has arrived at a picture of the microscopic physical universe, called "The Standard Model", which enumerates the fundamental building blocks of the universe. The standard model is shown in Fig 1.1. The basic building blocks are the quarks and the leptons. There are six leptons,

- Electron (e), electron neutrino (ν_e)
- Muon (μ), muon neutrinoν_μ
- Tau (τ), Tau neutrino (ν_τ)

and six quarks:

- d (down), u (up)
- s (strange), c (charm)
- b (bottom), t (top)

Ordinary matter is made of protons (each a u-u-d quark triplet), neutrons (each a u-d-d quark triplet), and electrons. Quarks cannot exist singly, so the particles created in accelerator collisions include mesons (combinations of a quark and an anti-quark), baryons (combinations of three quarks), and leptons. All but the proton, electron and neutrinos are unstable and decay to the stable particles. Heavier types of quark and lepton have been discovered in studies of high-energy particle interactions, both at scientific laboratories with particle accelerators and in the natural reactions of high-energy cosmic-ray particles in the atmosphere.

In the Standard Model the forces are communicated between particles by the exchange of quanta, which behave like particles, the four intermediate vector bosons, namely

- Gluon (g) the strong force carrier
- Photon (γ) electromagnetic force carrier
- W and Z bosons (W,Z) the weak force carriers

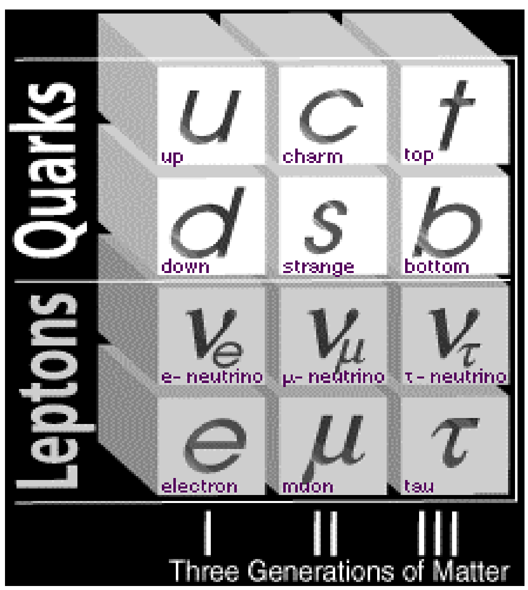

Fig 1.1 Standard Model

The Standard Model combines the two theories of particle physics into a single framework to describe all interactions of subatomic particles, except those due to gravity. The two components of the standard model are electro weak theory, which describes interactions via the electromagnetic and weak forces, and quantum chromo dynamics, the theory of the strong nuclear force. Both these theories describe the interactions between particles in terms of the exchange of intermediate vector bosons that have one unit of intrinsic angular momentum, or spin.

The standard model has a number of weaknesses, for example, it cannot explain why there are three generations of quarks and leptons. It makes no predictions of the masses of the quarks and the leptons or of the strengths of the various interactions. Physicists hope that, by probing the standard model in detail and making highly accurate measurements, they will discover some way in which the model begins to break down and thereby find a more complete theory. This may prove to be what is known as a grand unified theory, which uses a single theoretical structure to describe the strong, weak, and electromagnetic forces.

1.2 Particle properties

Each particle has a unique set of properties that distinguish the particle and describe how it is affected by the fundamental interactions. Some of the properties [1] that can distinguish particles are

- Charge
- Mass
- Spin
- Magnetic moment
- Lifetime
- Branching ratios

The analysis and interpretation of particle interactions depend on the applicability of a number of symmetries and conservation laws. So far every elementary particle or a short-lived intermediate state has been observed to have integral charge $\pm me$, where m is an integer and e is the charge of the electron. The energy and momentum of a system are unified in special relativity and are represented by a four-vector: (E, p_x, p_y, p_z). Each component of the four-vector is conserved. Conservation of total energy and angular momentum is observed in all reactions and decays. In addition, a full description of the particle must include the values for a set of internal quantum numbers, such as the baryon number and strangeness [9], which are from the conservation laws. The values of internal quantum numbers determine which particles may be produced together in various reactions and how unstable particles can decay.

2 Interactions

Interactions are processes in which particles respond to the force due to the presence of other particles or the particles decay into other particles. Neglecting gravity, which has no measurable effects on the scale of particle interactions, there are three basic types of interactions: Electromagnetic, Strong and the Weak Interactions.

Fundamental electromagnetic interactions occur between any two particles that have electric charge. These interactions involve the exchange or production of photons, which are the carrier particles of electromagnetic interactions. Electromagnetic decay processes can often be recognized by the fact that they produce one or more photons (also known as gamma particles). The electromagnetic interaction is the best understood of the three interaction types most important for elementary particle physics. Theoretical calculations agree with experimental results to a very high precision for processes in which the electromagnetic interaction is dominant.

Fundamental weak interactions occur for all fundamental particles except gluons and photons. Weak interactions involve the exchange or production of W or Z bosons. Weak forces are very short-ranged. Hadrons are viewed as being composed of quarks, either as quark-antiquark pairs (mesons) or as three quarks (baryons). There is much more to the picture than this, however, because a cloud of gluons surrounds the constituent quarks, the exchange particles for the color force. Particles that interact by the strong interaction are called hadrons. This general classification includes mesons and baryons but specifically excludes leptons, which do not interact by the strong force. The weak interaction acts on both hadrons and leptons. Gluons are the carrier particles for strong interactions. They are responsible for the binding force that confines all color-charged particles to form hadrons, such as protons, neutrons and pions. The resulting hadrons have no net color charge.

2.1 Electromagnetic Interactions

Typical electromagnetic interactions in high-energy physics are:

- Coulomb scattering (e.g. electron-nucleon scattering)
- Bhabha scattering (electron-positron scattering)
- Möller scattering (electron-electron scattering)
- Compton scattering (photon-electron scattering)
- Bremsstrahlung (photon emission in deceleration or acceleration)
- Annihilation (e.g., $e^+ e^- \rightarrow \gamma \gamma$)
- Pair creation ($\gamma \rightarrow e^+ e^-$)
- Decay of π^0

2.2 Interaction of electrons/positrons

Electrons and positrons lose energy by ionization and radiation. Radiation loss is significant due to their small mass. Other significant sources of energy loss for low energy electrons are elastic scattering and annihilation. For high-energy electrons, bremsstrahlung and pair production processes lead to production of electromagnetic showers. Electrons and positrons have similar electromagnetic interactions in matter.

2.3 Ionization

The nuclear particles traversing in a medium transfer energy to the constituent atoms of that medium. They do so via the process of ionization or excitation of the atoms. This is the basic phenomenon by which particles are detected. The major energy loss results in the formation of ion pairs (positive ion and electron) in the medium. In the first stage, the incident particle produces primary ionization [2] in atomic collisions. The higher energy electrons can produce fresh ion-electron pairs while traversing the medium and this process is known as secondary ionization. The number of such pairs produced is proportional to the energy lost by the incident particle in the medium.

2.4 Bremsstrahlung

When the charged particle scatters, it changes its direction and is accelerated. As a consequence it radiates. The radiation produced by charge particles passing through a medium is known as bremsstrahlung (the word is German for braking radiation). In particular, the term external bremsstrahlung is used for radiation caused by decelerations when passing through the field of atomic nuclei. The term internal bremsstrahlung is used to describe the radiation of non-virtual quanta, i.e. photons or gluons, by particles participating in an interaction. The Feynman diagram for bremsstrahlung is shown in Fig 2.4(a).

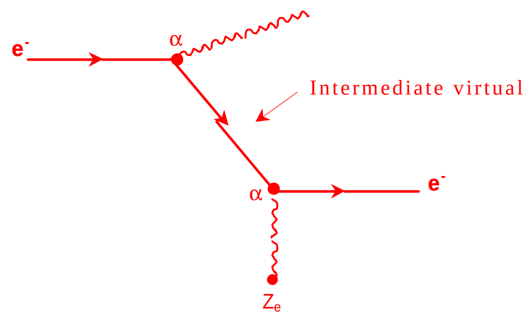

Fig 2.4 (a) Feynman diagram for bremsstrahlung

Radiation emitted by a charged particle moving in a magnetic field is called synchrotron radiation. Bremsstrahlung dominates the energy loss of electrons above the critical energy. Critical energy (E_c) of an electron is the energy at which the main energy loss mechanism changes from radiation losses to ionization losses.

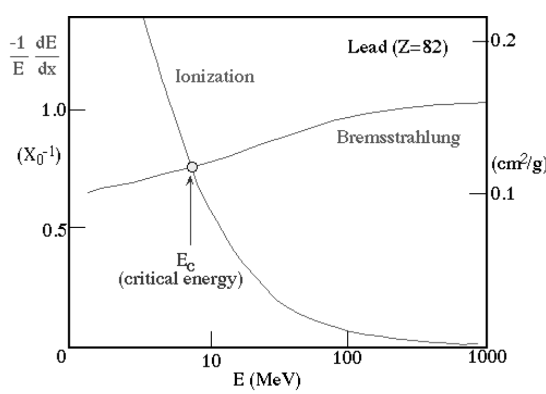

Fig 2.4 (b) Energy loss of electrons in lead (Pb)

The critical energy for electrons in lead [5] is about 7.6 MeV as shown in Fig 2.4(b). If the medium is transparent Cerenkov radiation can be emitted above a certain threshold. But also sub-threshold emission of electromagnetic radiation can occur, if discontinuities of the dielectric constant of the material are present (transition radiation) [8].

2.5 Interaction of photons

There are three major processes by which photons interact with matter, namely

- Photoelectric effect
- Compton effect
- Pair production

The photoelectric effect can be considered as an interaction between the photon and the atom as a whole. Incident photons whose binding energy exceeds the binding energy of an electron may be absorbed and consequently the atomic electron may be emitted. Compton effect involves the scattering of an incident photon with an atomic electron. The neutral pion decays to an electron, positron, and gamma ray by the electromagnetic interaction on a time scale of about 10^{-16} seconds. The pion, being the lightest meson, can be used to predict the maximum range of the strong interaction. Pair production is explained in Section 3.1.

3 Electromagnetic Showers

Electrons and positrons behave exactly the same way in a detector as far as shower is concerned. Consider an electron or positron with several GeV of energy traversing in some material. For energies above 100 MeV, the electrons lose energy almost entirely through bremsstrahlung. The emitted photons carry off a large fraction of the electron’s initial energy. For photons with energy greater than 100 MeV the major interaction is pair production, which gives another energetic electron or photon.

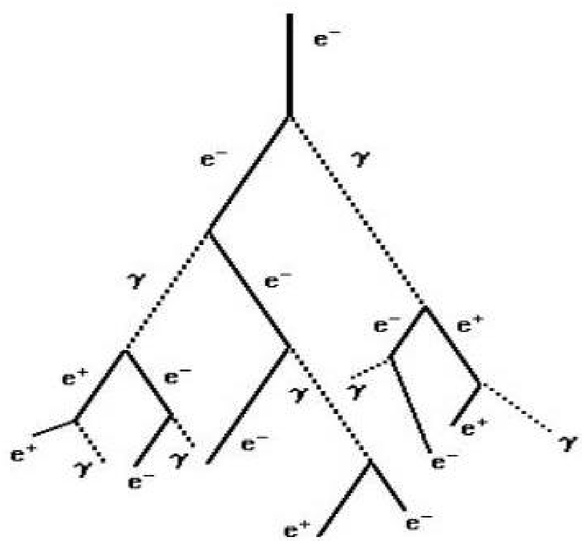

Fig 3 Schematic diagram of an electron initiated electromagnetic shower

Thus a single electron or photon is the starting point of an avalanche of electrons, positrons and further gamma rays. This avalanche is known as an electromagnetic shower. If these fast moving electrons and positrons go on to pass close to other nuclei then they will suffer accelerations due to the positive charge of the protons. An accelerated charged particle will emit electromagnetic radiation. The intense accelerations can produce photons capable of producing more electron-positron pairs. Secondary particle production continues until photons fall below the pair production threshold, and energy losses of electrons other than bremsstrahlung start to dominate: the number of shower particles decays exponentially. The process is shown schematically in Fig 3.

Electromagnetic shower is confined to smaller regions in solids that are dense. If the material is made up of atoms with a high atomic number then the greater nuclear charges can produce greater accelerations and so the cascade process can develop more readily than it would in a material with a lower atomic number.

3.1 Pair Production by Photons

Pair production is the formation or materialization of an electron and a positron, from a pulse of electromagnetic energy traveling through matter, usually in the vicinity of an atomic nucleus. The intense electric field near the nucleus can cause the photon to decay into an electron and a positron.

For pair production to occur, the photon must be at least equivalent to the mass of two electrons. The threshold energy for the process is therefore $2mc^2$ (1.02 MeV). Photon energy in excess of this amount, when pair production occurs, is converted into motion of the electron-positron pair. The pair production cross-section increases rapidly as the photon energy increases and approaches an asymptotic value.

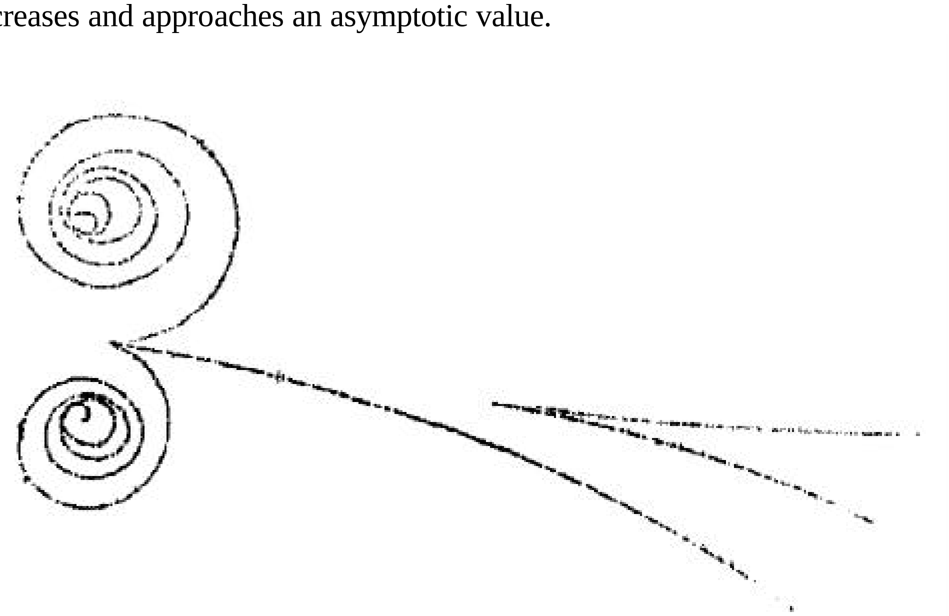

Fig 3.1(a) Pair production in the electric field of an electron ($\gamma + e^- \rightarrow e^+ + e^- + e^-$) and a nucleus ($\gamma$ + nucleus $\rightarrow e^+ + e^-$ +nucleus′)

Pair production may also take place near an atomic electron if the threshold energy is $4mc^2$ (2.04 MeV) and the recoil electron acquires significant kinetic energy. If pair production occurs in a track detector to which a magnetic field is properly applied, the electron and the positron curve away from the point of formation in opposite directions in arcs of equal curvature. The positron that is formed quickly disappears as it is converted again into photons in the process of annihilation with another electron in matter. Fig 3.1(a) shows the tracks of positron and electron (opposite curls) and the nucleus. These appear as a triplet of tracks in a track sensitive detector.

The Feynman diagrams for pair production are given in Fig 3.1(b). The pair production proceeds to the lowest order through the exchange of a single virtual photon. Hence this effect is very significant when the momentum transfer is small. The momentum of the nucleus is conserved, but it acquires little recoil energy.

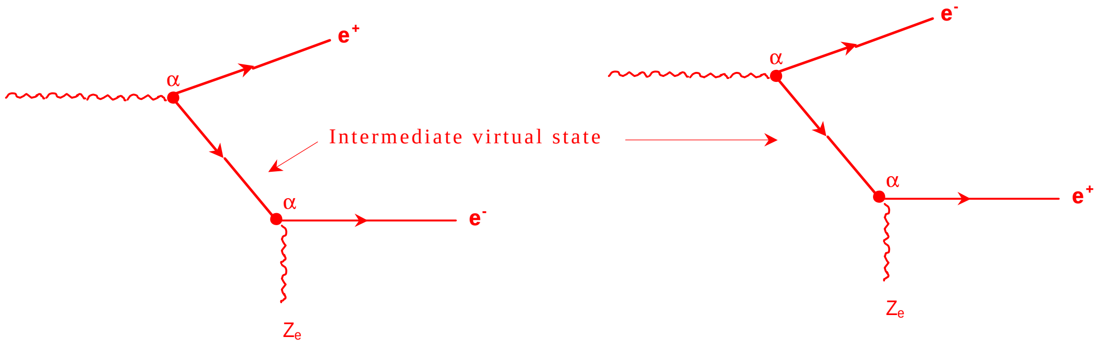

Fig 3.1(b) Lowest order Feynman diagrams for pair production.

3.2 The Simplified Cascade Model

The model is based upon the following restrictions:

- The incoming charged particles have a starting energy E_0 that is much greater than the critical energy, E_c, below which ionization losses predominate over pair production i.e. $E_o >> E_c$.
- Each electron with $E_o > E_c$ travels one radiation length and then gives up half of its energy to a bremsstrahlung photon
- Each photon produced with energy $E > E_c$ travels one radiation length creates an electron-positron pair with each particle carrying away half the energy of the original photon
- Electrons with $E < E_c$ cease to radiate and then lose the rest of their energy by collisions.
- At high energy the probabilities for bremsstrahlung and pair production are assumed to be independent of Z (atomic number) when distances are measured in radiation lengths.
- The theoretical cross sections are based on Born approximation and are most reliable for low Z materials. Deviations in large Z materials are proportional to Z^2.

- The difference in cross section for high-energy electrons and positrons are neglected.
- The asymptotic formulas for radiation and pair production are assumed valid.
- The Compton effect and the collision processes are neglected at high energy.

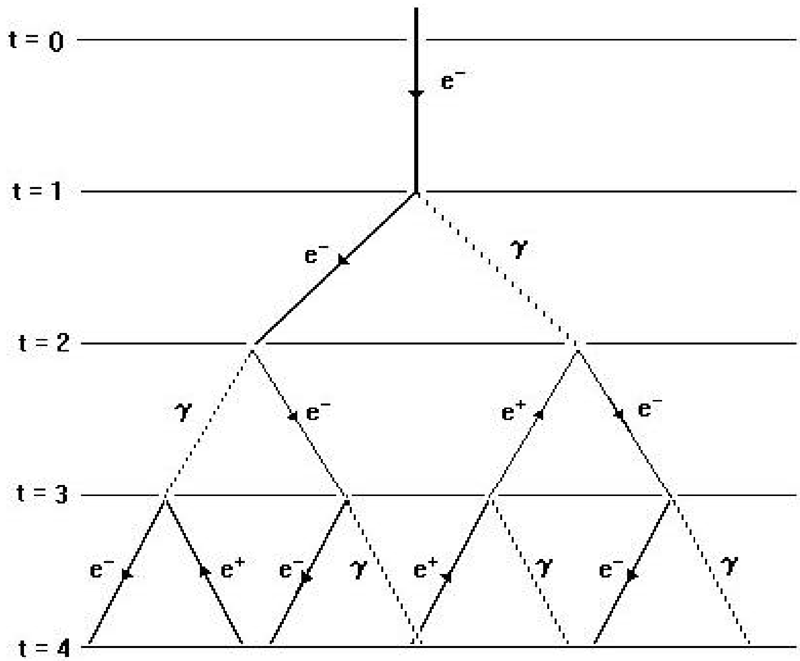

Fig 3.2(a) Schematic diagram of Cascade model.

The model is schematically shown in Fig 3.2(a). This simple branching model suggests that after t radiation lengths the shower will contain 2^t particles. There will be roughly equal numbers electrons, positrons and photons each with an average energy given by eq. (1)

$$E(t) = E_o / 2^t \qquad \text{Eq(1)}$$

The cascading process will stop abruptly when E(t) = E_c. The thickness of absorber at which the cascade ceases, t_{max}, can be written in terms of the initial and critical energies i.e.

$$E_c = E_o / 2^t \Rightarrow 2^t = E_o / E_c \Rightarrow t_{\max} = \ln(E_o / E_c) / \ln 2 \qquad \text{Eq(2)}$$

The model suggests that the maximum shower depth varies as the logarithm of the primary energy eq. (2) a feature that emerges from more sophisticated models of the process and is observed experimentally. It also predicts that the shower curve should rise rapidly to a peak value and then fall to zero. The broad peak of the experimental curve can be interpreted in terms of a spread of energies of the incoming particles. Experiment also shows that the curve does not eventually drop to zero but instead has a long tail. The long tail can be interpreted as being due to muon interactions producing knock-on electrons capable of making a contribution to the cascade process. This is shown in Fig 3.2(b)

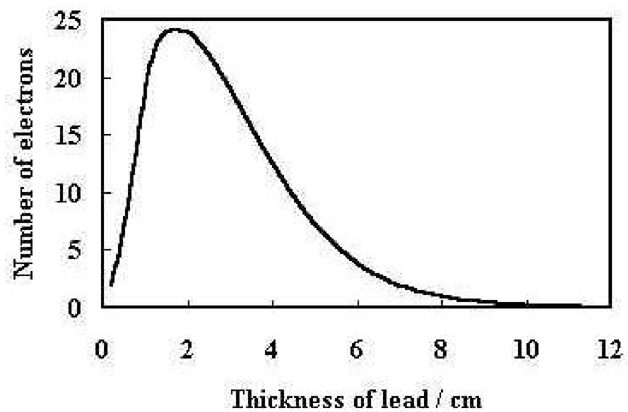

Fig 3.2(b) Number of Shower Particles Vs Thickness of the lead absorber

4 Shower Detection

The detection and identification of elementary particles and nuclei is of primary importance in high-energy physics. The aim of detection is to isolate events and study the data that is obtained from them. Identification involves determination of mass of the particle and its charge. The basic principle of particle detection is that every physics effect (effect of particles or radiation) can be used as a working principle or an idea to build a detector.

The electromagnetic calorimeter is used to measure the total energy of electrons, positrons and photons. A composite detector uses total absorption of particles to measure the energy and position of incident particles or jets. In the process of absorption, cascades of interactions generate showers; hence a calorimeter is also known as shower counter. Calorimetry is also the only practicable way to measure neutral particles among the secondaries produced in a high-energy collision. The interaction of charged and neutral particles is different. In most cases the observed signature of a particle is its ionization, where the liberated charge can be collected and amplified, or its production of electromagnetic radiation, which can be converted into a detectable signal. In this sense neutral particles are only detected indirectly, because they must first produce in some type of interaction a charged particle, which is then measured.

4.1 Detector Construction

In the course of showering, eventually, most of the incident particle energy will be converted into heat in a calorimeter. No temperature is measured in practical detectors, but characteristic interactions with matter (e.g. atomic excitation, ionization) are used to generate a detectable effect, via particle charges.

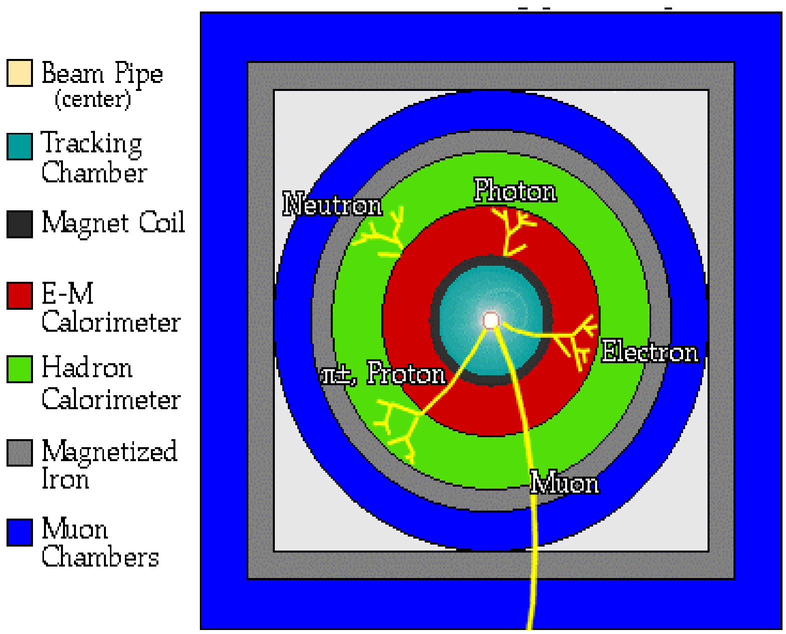

Fig 4.1 A detector cross section showing particle paths

Calorimeters are usually composed of different parts, custom-built for optimal performance on different incident particles. Each calorimeter is made of multiple individual cells, over whose volume the absorbed energy is integrated; cells are aligned to form towers typically along the direction of the incident particle. The analysis of cells and towers allows one to measure lateral and longitudinal shower profiles. Their arrangement is optimized for this purpose, and usually changes orientation in different angular regions. Typically, incident electromagnetic particles, viz. electrons and gammas, are fully absorbed in the electromagnetic calorimeter, which is made of the first (for the particles) layers of a composite calorimeter; its construction takes advantage of the comparatively short and concentrated electromagnetic shower shape to measure energy and position with optimal precision for these particles. A typical detector is shown in Fig 4.1

4.2 Electromagnetic Calorimeter

The shower phenomenon is used to detect high-energy electrons and photons. The electromagnetic calorimeter is a device used to measure the energy of the shower and hence the incident particle. Each device consists of alternate layers of metal radiator to enhance photon conversions and an active substance to sample energy loss. The calorimeter readout maybe digital or proportional. In a digital calorimeter the active region is finely divided into channels to provide a yes or no signal. In a proportional calorimeter the analog signals from the active regions are summed to produce a signal that is proportional to the total energy. The response of a given detector to two identical incident particles is different because of the statistical fluctuations of the shower development. A reasonable size for the shower detector implies that the radiation length of the material must be small. This in turn requires a high-Z material. There are two classes of such shower detectors:

- Homogeneous Calorimeters: In this case, the same medium is used both to cause the shower development and to detect the produced particles.
- Heterogeneous or Sampling Calorimeters: Here, the medium responsible for the showering is separate from that used in detection. Typical construction is that of a sandwich counter, with alternate high-Z passive layer of converter, such as lead and active detecting layers. Commonly used detectors are
    1. Sheets of plastic scintillator.
    2. Liquid ionization chambers
    3. Planes of proportional wire chambers, which provide spatial localization of the shower, as well as energy information.

The energy resolution for sampling calorimeters depends on the thickness of the absorber, as well as systematic effects such as uniformity and ageing of the active material.

4.3 Hadronic Calorimeter

The hadronic showering process is dominated by a succession of inelastic hadronic interactions. At high energy, these are characterized by multiparticle production and particle emission originating from nuclear decay of excited nuclei. The physical processes that cause the propagation of the hadronic shower are considerably different from the electromagnetic showers. Due to the relatively frequent generation of π^o's, there is also an electromagnetic component present in hadronic showers. A typical hadron is produced with a transverse momentum of ~ 350 MeV/c[1,2], so that hadronic showers tend to be more laterally spread out than electromagnetic ones. Also they take much longer to develop and are much deeper than than electromagnetic showers. To completely contain the shower, we need the detectors to be deeper.

Secondaries are mostly pions and nucleons. The hadronic multiplication process is measured at the scale of nuclear interaction length, which is essentially energy-independent.

Intrinsic limits on the energy resolution of hadronic calorimeters are:

- A fluctuating π^o component among the secondaries which interacts electromagnetically without any further nuclear interaction ($\pi^o \rightarrow \gamma\gamma$). The average fraction of π^o 's is given by 0.10 log(E) [E in GeV]. Showers may develop with a dominant electromagnetic component.

- A sizeable amount of the available energy is converted into excitation and breakup of nuclei. Only a small fraction of this energy will eventually appear as a detectable signal and with large event-to-event fluctuations.
- A considerable fraction of the energy of the incident particle is spent on reactions which do not result in an observable signal. Such processes may be energy leakage of various forms, like:

1. Backscattering,
2. Leakage due to μ,νor slow neutrons,
3. Nuclear excitation, nuclear breakup, nuclear evaporation.

The energy resolution of hadronic calorimeters are worse than that of electromagnetic calorimeters since they are subject to additional fluctuations due to nuclear interactions.

4.4 Detection of neutral particles

A neutral particle should undergo an interaction that gives out a charged particle within the sensitive region of the detector. The detector responds to the charged particles as explained above. Some of the neutral particles may initiate electromagnetic showers or hadronic showers which helps in the identification of those particles. Some of them include fast or slow neutrons and neutrinos.

5 Conclusions

Basic physical principles can be used to identify all kinds of elementary particles and nuclei. The precise measurement of the particle composition in showers is a very difficult problem. The cascade model provides an insight into the underlying physics process involved in development of showers. Calorimeters are vital in the detection of showers and hence particle identification. With the increasing center of mass energies, it is very important to understand showers and shower detection for high-energy collisions in future experiments.

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Web

[1] http://rkb.home.cern.ch/rkb/PH14pp/node19.html (Calorimeters)
[2] http://rkb.home.cern.ch/rkb/PH14pp/node57.html (Interactions)
[3] http://besch2.physik.unisiegen.de/~depac/DePAC/DePAC_tutorial_database/grupen_istanbul/node14.html
[4] http://www.prestoncoll.ac.uk/cosmic/cascade/cascades.htm (Showers)

Diagrams

Fig 1.1 http://www2.slac.stanford.edu/vvc/theory/fundamental.html (Fundamental Particles)
Fig 4.1 http://particleadventure.org/particleadventure/frameless/end_view.html (Detector)
Fig 2.4(b) http://www.upscale.utoronto.ca/GeneralInterest/DBailey/SubAtomic/Lectures/LectF04/Lect04.htm (Ionization)

Glossary

Interaction Length
The mean free path of a particle before undergoing an interaction that is neither elastic nor quasi-elastic (diffractive), in a given medium, usually designated by ?.

Baryons
Baryons are massive particles, which are made up of three quarks in the standard model. This class of particles includes the proton and neutron. Other baryons are the lambda (λ), sigma (Σ), xi (Ξ), and omega (Ω) particles. Baryons are distinct from mesons in that mesons are composed of only two quarks. Baryons and mesons are included in the overall class known as hadrons, the particles, which interact by the strong force.

Baryon Number
Of the specific rules for particle interactions and decays, one of the most important of conservation laws is the conservation of baryon number. Each of the baryons is assigned a baryon number B=1. This can be considered to be equivalent to assigning each quark a baryon number of 1/3. Mesons, with one quark and one antiquark, have a baryon number B=0. No known decay process or interaction in nature changes the net baryon number

Cerenkov radiation
When the velocity of a charged particle in a medium is faster than the velocity of light in that medium, then the particle radiates photons. This phenomenon is known as Cerenkov radiation.

Strangeness

During a study of cosmic ray interactions, a product of a proton collision with a nucleus was found to live for much longer time than expected: 10^{-10} s instead of the expected 10^{-23} s. This particle was named the lambda particle (Λ) and the property, which caused it to live so long, was dubbed "strangeness" and that name stuck to be the name of one of the quarks from which the lambda particle is constructed. The lambda is a baryon, which is made up of three quarks: an up, a down and a strange quark. The long observed lifetime of the lambda particle, helped develop a new conservation law for such decays called the "conservation of strangeness". The presence of a strange quark in a particle is denoted by a quantum number S=-1. Particle decay by the strong or electromagnetic interactions preserve the strangeness quantum number.

Color charge

Color is the strong interaction analog to charge in the electromagnetic force. The term "color" was introduced to label a property of the quarks, which allowed apparently identical quarks to reside in the same particle, for example, two "up" quarks in the proton. To allow three particles to coexist and satisfy the Pauli exclusion principle, a property with three values was needed. The idea of three primary colors like red, green, and blue making white light was attractive, and language about "colorless" particles sprang up.