17
Glossary

Knowledge is a process of piling up facts; wisdom lies in their simplification.

Harold Fabing and Ray Marr

The glossary summarises the most important properties of detectors along with their main fields of application. An abridged description of the characteristic interactions of particles is also presented.

17.1 Interactions of charged particles and radiation with matter

Charged particles interact mainly with the electrons of matter. The atomic electrons are either excited to higher energy levels ('excitation') or liberated from the atomic shell ('ionisation') by the charged particles. High-energy ionisation electrons which are able themselves to ionise are called δ rays or 'knock-on electrons'. In addition to the ionisation and excitation of atomic electrons, bremsstrahlung plays a particular rôle, especially for primary electrons as charged particles.

Energy loss by ionisation and excitation is described by the Bethe–Bloch formula. The basic features describing the mean energy loss per unit length ($\mathrm{d}E/\mathrm{d}x$) for heavy particles are given by

$$-\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_{\mathrm{ion}} \propto z^2 \cdot \frac{Z}{A} \cdot \frac{1}{\beta^2}\left[\ln(a \cdot \gamma^2\beta^2) - \beta^2 - \frac{\delta}{2}\right] , \tag{17.1}$$

where

z – charge of the incident particle,

Z, A – atomic number and atomic weight of the target,

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β, γ – velocity and Lorentz factor of the incident particle,

δ – parameter describing the density effect,

a – parameter depending on the electron mass and the ionisation energy of the absorber.

Typical average values of the energy loss by ionisation and excitation are around $2\,\mathrm{MeV/(g/cm^2)}$. The energy loss in a given material layer fluctuates, which is not described by a Gaussian, but is characterised, in particular for thin absorber layers, by a high asymmetry (Landau distribution).

Detectors only measure the energy deposited in the sensitive volume. This is not necessarily the same as the energy loss of the particle in the detector, since a fraction of the energy can escape from the detector volume as, e.g., δ rays.

The energy loss of a charged particle in a detector leads to a certain number of free charge carriers n_T given by

$$n_\mathrm{T} = \frac{\Delta E}{W} \ , \tag{17.2}$$

where ΔE is the energy deposited in the detector and W is a characteristic energy which is required for the production of a charge-carrier pair ($W \approx 30\,\mathrm{eV}$ in gases, $3.6\,\mathrm{eV}$ in silicon, $2.8\,\mathrm{eV}$ in germanium).

Another interaction process of charged particles particularly important for electrons is **bremsstrahlung**. The bremsstrahlung energy loss can essentially be parametrised by

$$-\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_\mathrm{brems} \propto z^2 \cdot \frac{Z^2}{A} \cdot \frac{1}{m_0^2} \cdot E \ , \tag{17.3}$$

where m_0 and E are the projectile mass and energy, respectively. For electrons ($z = 1$) one defines

$$-\left.\frac{\mathrm{d}E}{\mathrm{d}x}\right|_\mathrm{brems} = \frac{E}{X_0} \ , \tag{17.4}$$

where X_0 is the **radiation length** characteristic for the absorber material.

The **critical energy** E_c characteristic for the absorber material is defined as the energy at which the energy loss of electrons by ionisation and excitation on the one hand and bremsstrahlung on the other hand are equal:

$$-\left.\frac{\mathrm{d}E}{\mathrm{d}x}(E_\mathrm{c})\right|_\mathrm{ion} = -\left.\frac{\mathrm{d}E}{\mathrm{d}x}(E_\mathrm{c})\right|_\mathrm{brems} = \frac{E_\mathrm{c}}{X_0} \ . \tag{17.5}$$

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Multiple Coulomb scattering of charged particles in matter leads to a deviation from a straight trajectory. It can be described by an rms planar scattering angle

$$\sigma_\theta = \sqrt{\langle\theta^2\rangle} \approx \frac{13.6\,\mathrm{MeV}/c}{p\beta}\sqrt{\frac{x}{X_0}} \;, \tag{17.6}$$

where

p, β – momentum and velocity of the particle,

x – material traversed in units of radiation lengths X_0.

In addition to the interaction processes mentioned so far, direct electron-pair production and photonuclear interactions come into play at high energies. Energy losses by Cherenkov radiation, transition radiation and synchrotron radiation are of considerable interest for the construction of detectors or applications, but they play only a minor rôle as far the energy loss of charged particles is concerned.

Neutral particles like neutrons or neutrinos first have to produce charged particles in interactions before they can be detected via the interaction processes described above.

Photons of low energy ($< 100\,\mathrm{keV}$) are detected via the photoelectric effect. The cross section for the **photoelectric effect** can be approximated by

$$\sigma^{\mathrm{photo}} \propto \frac{Z^5}{E_\gamma^{7/2}} \;, \tag{17.7}$$

where at high γ energies the dependence flattens to $\propto E_\gamma^{-1}$. In the photoelectric effect one electron (usually from the K shell) is removed from the atom. As a consequence of the rearrangement in the atomic shell, either characteristic X rays or Auger electrons are emitted.

In the region of medium photon energies (100 keV–1 MeV) the scattering on quasifree electrons dominates (**Compton scattering**). The cross section for the Compton effect can be approximated by

$$\sigma^{\mathrm{Compton}} \propto Z \cdot \frac{\ln E_\gamma}{E_\gamma} \;. \tag{17.8}$$

At high energies ($\gg 1\,\mathrm{MeV}$) electron-pair production is the dominating interaction process of photons,

$$\sigma^{\mathrm{pair}} \propto Z^2 \cdot \ln E_\gamma \;. \tag{17.9}$$

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The above photoprocesses lead to an absorption of X rays or γ radiation which can be described by an absorption law for the photon intensity according to

$$I = I_0 \, \mathrm{e}^{-\mu x} \ . \tag{17.10}$$

μ is a characteristic absorption coefficient which is related to the cross sections for the photoelectric effect, Compton effect and pair production. Compton scattering plays a special rôle since the photon is not completely absorbed after the interaction like in the photoelectric effect or for pair production, but only shifted to a lower energy. This requires the introduction and distinction of attenuation and absorption coefficients.

Charged and also neutral particles can produce further particles in inelastic interaction processes. The strong interactions of hadrons can be described by characteristic nuclear interaction and collision lengths.

The electrons produced by ionisation – e.g. in gaseous detectors – are thermalised by collisions with the gas molecules. Subsequently, they are normally guided by an electric field to the electrodes. The directed motion of electrons in the electric field is called drift. Drift velocities of electrons in typical gases for usual field strengths are on the order of $5\,\mathrm{cm}/\mu\mathrm{s}$. During the drift the charged particles (i.e. electrons and ions) are subject to transverse and longitudinal diffusion caused by collisions with gas molecules.

The presence of inclined magnetic fields causes the electrons to deviate from a drift parallel to the electric field.

Low admixtures of electronegative gases can have a considerable influence on the properties of gas detectors.

17.2 Characteristic properties of detectors

The quality of a detector can be expressed by its measurement resolution for time, track accuracy, energy and other characteristics. Spatial resolutions of 10–$20\,\mu\mathrm{m}$ can be obtained in silicon strip counters and small drift chambers. Time resolutions in the subnanosecond range are achievable with resistive-plate chambers. Energy resolutions in the eV range can be reached with cryogenic calorimeters.

In addition to resolutions, the efficiency, uniformity and time stability of detectors are of great importance. For high-rate applications also random coincidences and dead-time corrections must be considered.

17.3 Units of radiation measurement

The radioactive decay of atomic nuclei (or particles) is described by the decay law

$$N = N_0 \, \mathrm{e}^{-t/\tau} \tag{17.11}$$

with the lifetime $\tau = 1/\lambda$ (where λ is the decay constant). The half-life $T_{1/2}$ is smaller than the lifetime ($T_{1/2} = \tau \cdot \ln 2$).

The activity $A(t)$ of a radioactive isotope is

$$A(t) = -\frac{\mathrm{d}N}{\mathrm{d}t} = \lambda \cdot N \tag{17.12}$$

with the unit **Becquerel** (= 1 decay per second).

The absorbed dose D is defined by the absorbed radiation energy $\mathrm{d}W$ per unit mass,

$$D = \frac{\mathrm{d}W}{\varrho \, \mathrm{d}V} = \frac{\mathrm{d}W}{\mathrm{d}m} \ . \tag{17.13}$$

D is measured in **Grays** ($1\,\mathrm{Gy} = 1\,\mathrm{J/kg}$). The old unit of the absorbed dose was rad ($100\,\mathrm{rad} = 1\,\mathrm{Gy}$).

The biological effect of an energy absorption can be different for different particle types. If the physical energy absorption is weighted by the relative biological effectiveness (RBE), one obtains the equivalent dose H, which is measured in **Sieverts** (Sv),

$$H\,\{\mathrm{Sv}\} = RBE \cdot D\,\{\mathrm{Gy}\} \ . \tag{17.14}$$

The old unit of the equivalent dose was rem ($1\,\mathrm{Sv} = 100\,\mathrm{rem}$). The **equivalent radiation dose due to natural radioactivity** amounts to about 3 mSv per year. Persons working in **regions of controlled access** are typically limited to a maximum of 20 mSv per year. The lethal dose for humans (50% probability of death within 30 days) is around 4000 mSv.

17.4 Accelerators

Accelerators are in use in many different fields, such as particle accelerators in nuclear and elementary particle physics, in nuclear medicine for tumour treatment, in material science, e.g. in the study of elemental composition of alloys, and in food preservation. Present-day particle physics experiments require very high energies. The particles which are accelerated must be charged, such as electrons, protons or heavier ions. In some cases – in particular for colliders – also antiparticles are required.

Such particles like positrons or antiprotons can be produced in interactions of electrons or protons. After identification and momentum selection, they are then transferred into a storage-ring system where they are accelerated to higher energies. Beams of almost any sufficiently long-lived particles can be produced by colliding a proton beam with an external target, and selecting the desired particle species by sophisticated particle identification.

Most accelerators are circular (synchrotrons). For very high-energy electron machines ($\geq 100\,\mathrm{GeV}$), linear accelerators must be used because of the large energy loss due to synchrotron radiation in circular electron accelerators. For future particle physics investigations also neutrino factories are considered.

17.5 Main physical phenomena used for particle detection and basic counter types

The main interaction process for ionisation counters is described by the Bethe–Bloch formula. Depending on a possible gas amplification of the produced electron–ion pairs, one distinguishes ionisation chambers (without gas amplification), proportional counters (gain $\propto \mathrm{d}E/\mathrm{d}x$), Geiger counters, and streamer tubes (saturated gain, no proportionality to the energy loss). Ionisation processes can also be used for liquids and solids (without charge-carrier multiplication).

Solid-state detectors have gained particular importance for high-resolution tracking as strip, pixel and voxel devices and also because of their intrinsically high energy resolution.

The excitation of atoms, also described by the Bethe–Bloch formula, is the basis of scintillation counters which are read out by standard photomultipliers, multianode photomultipliers or silicon photodiodes. For particle-identification purposes Cherenkov and transition-radiation counters play a special rôle.

17.6 Historical track detectors

17.6.1 Cloud chambers

Application: Measurement of rare events in cosmic rays; demonstration experiment; historical importance.

Construction: Gas–vapour mixture close to the saturation vapour pressure. Additional detectors (e.g. scintillation counters) can trigger the expansion to reach the supersaturated state of the vapour.

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Measurement principle, readout: The droplets formed along the ionisation track in the supersaturated vapour are photographed stereoscopically.

Advantage: The cloud chamber can be triggered.

Disadvantages: Very long dead and cycle times; tiresome evaluation of cloud-chamber photographs.

Variation: In non-triggerable diffusion cloud chambers a permanent zone of supersaturation can be maintained.

17.6.2 Bubble chambers

Application: Precise optical tracking of charged particles; studies of rare and complex events.

Construction: Liquid gas close to the boiling point; superheating of liquid by synchronisation of the bubble-chamber expansion with the moment of particle incidence into the chamber.

Measurement principle, readout: The bubbles formed along the particle track in the superheated liquid are photographed stereoscopically.

Advantages: High spatial resolution; measurement of rare and complex events; lifetime determination of short-lived particles possible.

Disadvantages: Extremely tedious analysis of photographically recorded events; cannot be triggered but only synchronised; insufficient mass for the absorption of high-energy particles.

Variation: Holographic readout allows three-dimensional event reconstruction with excellent spatial resolution (several μm).

17.6.3 Streamer chambers

Application: Investigation of complex events with bubble-chamber quality in a detector which can be triggered.

Construction: Large-volume detector in a homogeneous strong electric field. A high-voltage signal of very short duration induces streamer discharges along the ionisation track of charged particles.

Measurement principle, readout: The luminous streamers are photographed stereoscopically head-on.

Advantages: High-quality photographs of complex events. Diffusion suppression by addition of oxygen; targets can be mounted inside the sensitive volume of the detector.

Disadvantages: Demanding event analysis; the very short high-voltage signals (100 kV amplitude, 2 ns duration) may interfere with the performance of other detectors.

17.6.4 Neon-flash-tube chambers

Applications: Investigation of rare events in cosmic rays; studies of neutrino interactions; search for nucleon decay.

Construction: Neon- or neon/helium-filled, sealed cylindrical glass tubes or spheres ('Conversi spheres'), or polypropylene tubes with normal gas-flow operation.

Measurement principle, readout: A high-voltage pulse applied to the chamber causes those tubes which have been hit by charged particles to light up in full length. The discharge can be photographed or read out electronically.

Advantages: Extremely simple construction; large volumes can be instrumented at low cost.

Disadvantages: Long dead times; low spatial resolution; no three-dimensional space points but only projections.

17.6.5 Spark chambers

Applications: Somewhat older track detector for the investigation of cosmic-ray events; spectacular demonstration experiment.

Construction: Planar, parallel electrodes mounted in a gas-filled volume. The spark chamber is usually triggered by a coincidence of external detectors (e.g. scintillation counters).

Measurement principle, readout: The high gas amplification causes a plasma channel to develop along the particle track; spark formation occurs. The readout of chambers with continuous electrodes is done photographically. For wire spark chambers a magnetostrictive readout or readout via ferrite cores is possible.

Advantages: Simple construction.

Disadvantages: Low multitrack efficiency, can be improved by current limitation ('glass spark chamber'); tedious analysis of optically recorded events.

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17.6.6 Nuclear emulsions

Application: Permanently sensitive detector; mostly used in cosmic rays or as vertex detector with high spatial resolution in accelerator experiments.

Construction: Silver-bromide or silver-chloride microcrystals embedded in gelatine.

Measurement principle, readout: Detection of charged particles similar to light recording in photographic films; development and fixation of tracks. Analysis is done under the microscope or with a CCD camera with subsequent semi-automatic pattern recognition.

Advantages: 100% efficient; permanently sensitive; simple in construction; high spatial resolution.

Disadvantages: Non-triggerable; tedious event analysis.

17.6.7 Plastic detectors

Application: Heavy ion physics and cosmic rays; search for magnetic monopoles; radon-concentration measurement.

Construction: Foils of cellulose nitrate usually in stacks.

Measurement principle, readout: The local damage of the plastic material caused by the ionising particle is etched in sodium hydroxide. This makes the particle track visible. The readout is done as in nuclear emulsions.

Advantages: Extremely simple, robust detector; perfectly suited for satellite and balloon-borne experiments; permanently sensitive; adjustable threshold to suppress the detection of weakly ionising particles.

Disadvantages: Non-triggerable; complicated event analysis.

17.7 Track detectors

17.7.1 Multiwire proportional chamber

Application: Track detector with the possibility of measuring the energy loss. Suitable for high-rate experiments if small sense-wire spacing is used (see also microstrip detectors).

Construction: Planar layers of proportional counters without partition walls.

Measurement principle, readout: Analogous to the proportional counter; with high-speed readout (FADC = Flash ADC) the spatial structure of the ionisation can be resolved.

Advantages: Simple, robust construction; use of standard electronics.

Disadvantages: Electrostatic repulsion of anode wires; limited mechanical wire stability; sag for long anode wires for horizontal construction. Ageing problems in harsh radiation environments.

Variations: (1) Straw chambers (aluminised mylar straws with central anode wire); wire breaking in a stack of many straws affects only the straw with a broken wire.

(2) Segmentation of cathodes possible to obtain spatial coordinates.

17.7.2 Planar drift chamber

Application: Track detector with energy-loss measurement.

Construction: For the improvement of the field quality compared to the multiwire proportional chamber, potential wires are introduced between the anode wires. In general, far fewer wires are used than in a multiwire proportional chamber.

Measurement principle, readout: In addition to the readout as in the multiwire proportional chambers, the drift time of the produced charge carriers is measured. This allows – even at larger wire spacings – a higher spatial resolution.

Advantages: Drastic reduction of the number of anode wires; high track resolution.

Disadvantages: Spatial dependence of the track resolution due to charge-carrier diffusion and primary ionisation statistics; left–right ambiguity of drift-time measurement (curable by double layers or staggered anode wires).

Variations: (1) 'Electrodeless' chambers: field shaping by intentional ion deposition on insulating chamber walls.

(2) Time-expansion chambers: introduction of a grid to separate the drift space from the amplification region allowing adjustable drift velocities.

(3) Induction drift chamber: use of anode and potential wires with very small spacing. Readout of induced signals on the potential wires to solve the left–right ambiguity; high-rate capability.

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17.7.3 Cylindrical wire chambers

Cylindrical proportional and drift chambers

Application: Central detectors in storage-ring experiments with high track resolution; large solid-angle coverage around the primary vertex.

Construction: Concentric layers of proportional chambers (or drift chambers). The drift cells are approximately trapezoidal or hexagonal. Electric and magnetic fields (for momentum measurement) are usually perpendicular to each other.

Measurement principle, readout: The same as in planar proportional or drift chambers. The coordinate along the wire can be determined by charge division, by measuring the signal propagation time on the wire, or by stereo wires. Compact multiwire drift modules with high-rate capability can be constructed.

Advantages and disadvantages: High spatial resolution; danger of wire breaking; $\vec{E} \times \vec{B}$ effect complicates track reconstruction.

Jet drift chambers

Application: Central detector in storage-ring experiments with excellent particle-identification properties via multiple measurements of the energy loss.

Construction: Azimuthal segmentation of a cylindrical volume into pie-shaped drift spaces; electric drift field and magnetic field for momentum measurement are orthogonal. Field shaping by potential strips; staggered anode wires to resolve the left–right ambiguity.

Measurement principle, readout: As in common-type drift chambers; particle identification by multiple $\mathrm{d}E/\mathrm{d}x$ measurement.

Advantage: High spatial resolution.

Disadvantages: $\vec{E} \times \vec{B}$ effect complicates track reconstruction. Complicated structure; danger of wire breaking.

Time-projection chamber (TPC)

Application: Practically 'massless' central detector mostly used in storage-ring experiments; accurate three-dimensional track reconstruction; electric drift field and magnetic field (for track bending) are parallel.

Construction, measurement principle, readout: There are neither anode nor potential wires in the sensitive volume of the detector. The produced charge carriers drift to the endcap detectors (in general, multiwire proportional chambers) which supply two track coordinates; the third coordinate is derived from the drift time.

Advantages: Apart from the counting gas there is no material in the sensitive volume (low multiple scattering, high momentum resolution; extremely low photon conversion probability). Availability of three-dimensional coordinates, energy-loss sampling and high spatial resolution.

Disadvantages: Positive ions drifting back into the sensitive volume will distort the electric field (can be avoided by an additional grid ('gating')); because of the long drift times the TPC cannot be operated in a high-rate environment.

Variation: The TPC can also be operated with liquid noble gases as a detector medium and supplies digital three-dimensional 'pictures' of bubble-chamber quality (requires extremely low-noise readout since in liquids usually no gas amplification occurs).

17.7.4 Micropattern gaseous detectors

Application: Vertex detectors of high spatial resolution; imaging detectors of high granularity.

Construction: Miniaturised multiwire proportional chamber with 'anode wires' on plastics or ceramic substrates; electrode structures normally produced using industrial microlithographic methods. Possible problems with ion deposition on dielectrics which may distort the field.

Measurement principle, readout: Electron avalanches measured on miniaturised electrode structures.

Advantages: Very high spatial resolution; separation of gas amplification region and readout structure possible.

Disadvantages: Sensitivity to harsh radiation environment, ageing problems, discharges may destroy the electrode structure.

Variation: Many different kinds of miniature structures, micromegas, gas electron multiplier (GEM), and so on.

17.7.5 Semiconductor track detectors

Application: Strip, pixel or voxel counters of very high spatial resolution, frequently used as vertex detectors in colliding-beam experiments or light-weight trackers in satellite experiments.

Construction: p–n or p–i–n semiconductor structures mostly of silicon with pitch of $\approx$ 20–50 µm for strip counters and $\approx$ 50 µm $\times$ 100 µm for pixel counters.

Measurement principle, readout: Charge carriers (electron–hole pairs) are liberated by ionisation energy loss and collected in an electrical drift field.

Advantages: Extremely high spatial resolution ($\approx$ 10 µm). The intrinsically high energy resolution is related to the low energy required for the production of an electron–hole pair (3.65 eV in Si). It can be taken advantage of for $\mathrm{d}E/\mathrm{d}x$ measurements.

Disadvantages: Ageing in harsh radiation environments; only specially treated silicon counters are radiation tolerant. A beam loss into a silicon pixel counter produces pin holes and can even disable the whole counter.

Variation: p–n or p–i–n structures can be custom tailored to the intended measurement purpose. The problem of a large number of channels in strip counters can be circumvented with the silicon drift chamber.

17.7.6 Scintillating fibre trackers

Application: Small-diameter scintillating fibres can be individually viewed by multianode photomultipliers allowing high spatial resolutions.

Construction: Bundles of fibres (diameter 50 µm–1 mm) arranged in a regular lattice. The individual fibres are optically separated by a very thin cladding.

Measurement principle, readout: The scintillation light created by the energy loss of charged particles is guided by internal reflection to the photosensitive readout element at the ends of the fibres.

Advantages: Compact arrangements with high spatial resolution. Better radiation tolerance compared to other tracking detectors.

Disadvantages: The readout by photomultipliers is difficult in high magnetic fields and it is space consuming.

17.8 Calorimetry

17.8.1 Electromagnetic calorimeters

Application: Measurement of electron and photon energies in the range above several hundred MeV.

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Construction: Total-absorption detectors in which the energy of electrons and photons is deposited via alternating processes of bremsstrahlung and pair production. In sampling calorimeters the energy deposition is usually only sampled in constant longitudinal depths.

Measurement principle, readout: Depending on the type of sampling detector used, the deposited energy is recorded as charge signal (e.g. liquid-argon chambers) or as light signal (scintillators) and correspondingly processed. For the complete absorption of 10 GeV electrons or photons about 20 radiation lengths are required.

Advantages: Compact construction; the relative energy resolution *improves* with increasing energy ($\sigma/E \propto 1/\sqrt{E}$).

Disadvantages: Sampling fluctuations, Landau fluctuations as well as longitudinal and lateral leakage deteriorate or limit the energy resolution.

Variation: By using a segmented readout, calorimeters can also provide excellent spatial resolution. Homogeneous 'liquid' calorimeters with strip readout provide 1 mm coordinate resolution for photons, almost energy-independent. Also 'spaghetti calorimeters' should be mentioned in this respect. Wavelength-shifting techniques allow compact construction of many modules (e.g. tile calorimeters).

17.8.2 Hadron calorimeters

Application: Measurement of hadron energies above 1 GeV; muon identification.

Construction: Total-absorption detector or sampling calorimeter; all materials with short nuclear interaction lengths can be considered as sampling absorbers (e.g. uranium, tungsten; also iron and copper).

Measurement principle, readout: Hadrons with energies > 1 GeV deposit their energy via inelastic nuclear processes in hadronic cascades. This energy is, just as in electron calorimeters, measured via the produced charge or light signals in the active detector volume.

Advantage: Improvement of the relative energy resolution with increasing energy.

Disadvantages: Substantial sampling fluctuations; large fractions of the energy remain 'invisible' due to the break-up of nuclear bonds and due to neutral long-lived particles or muons escaping from the detector volume. Therefore, the energy resolution of hadron calorimeters does not reach that of electron–photon calorimeters.

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Variation: By compensation methods, the signal amplitudes of electron- or photon- and hadron-induced cascades for fixed energy can be equalised. This is obtained, e.g. by partially regaining the invisible energy. This compensation is of importance for the correct energy measurement in jets with unknown particle composition.

17.8.3 Calibration and monitoring of calorimeters

Calorimeters have to be calibrated. This is normally done with particles of known identity and momentum. In the low-energy range β and γ rays from radioisotopes can also be used for calibration purposes. To guarantee time stability, the calibration parameters have to be permanently monitored during data taking. This requires special on-line calibration procedures ('slow control').

17.8.4 Cryogenic calorimeters

Application: Detection of low-energy particles or measurement of extremely low energy losses.

Construction: Detectors that experience a detectable change of state even for extremely low energy absorptions.

Measurement principle: Break-up of Cooper pairs by energy depositions; transitions from the superconducting to the normal-conducting state in superheated superconducting granules; detection of phonons in solids.

Readout: With extremely low-noise electronic circuits, e.g. SQUIDs (Superconducting Quantum Interference Devices).

Advantages: Exploitation in cosmology for the detection of 'dark matter' candidates. Also usable for non-ionising particles.

Disadvantages: Extreme cooling required (milli-Kelvin range).

17.9 Particle identification

The aim of particle-identification detectors is to determine the mass m_0 and charge z of particles. Usually, this is achieved by combining information from different detectors. The main inputs to this kind of measurement are

(i) the momentum p determined in magnetic fields: $p = \gamma m_0 \beta c$

(β – velocity, γ – Lorentz factor of the particle);

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(ii) particle's time of flight τ: $\tau = s/(\beta \cdot c)$
(s – flight path);

(iii) mean energy loss per unit length: $-\frac{\mathrm{d}E}{\mathrm{d}x} \propto \frac{z^2}{\beta^2} \ln \gamma$;

(iv) kinetic energy in calorimeters: $E_{\mathrm{kin}} = (\gamma - 1) m_0 c^2$;

(v) Cherenkov light yield: $\propto z^2 \sin^2 \theta_{\mathrm{c}}$;
($\theta_{\mathrm{c}} = \arccos(1/n\beta)$, n – index of refraction);

(vi) yield of transition-radiation photons ($\propto \gamma$).

The measurement and identification of neutral particles (neutrons, photons, neutrinos, etc.) is done via conversion into charged particles on suitable targets or inside the detector volume.

17.9.1 Charged-particle identification

Time-of-flight counters

Application: Identification of particles of different mass with known momenta.

Construction, measurement principle, readout: Scintillation counters, resistive-plate chambers or planar spark counters for start–stop measurements; readout with time-to-amplitude converters.

Advantage: Simple construction.

Disadvantages: Only usable for 'low' velocities ($\beta < 0.99$, $\gamma < 10$).

Identification by ionisation losses

Application: Particle identification.

Construction: Multilayer detector for individual $\mathrm{d}E/\mathrm{d}x$ measurements.

Measurement principle, readout: The Landau distributions of the energy loss are interpreted as probability distributions. For a fixed momentum different particles are characterised by different energy-loss distributions. The reconstruction of these distributions with as large a number of measurements as possible allows for particle identification. In a simplified method the truncated mean of the energy-loss distribution can be used for particle identification.

Advantages: The $\mathrm{d}E/\mathrm{d}x$ measurements can be obtained as a by-product in multiwire proportional, jet or time-projection chambers. The measurement principle is simple.

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Disadvantages: In certain kinematical ranges the mean energy losses for different charged particles overlap appreciably. The density effect of the energy loss leads to the same $\mathrm{d}E/\mathrm{d}x$ distribution for all singly charged particles at high energies ($\beta\gamma \approx$ several hundred) even in gases.

Identification using Cherenkov radiation

Application: Mass determination (threshold Cherenkov counters) in momentum-selected beams; velocity determination (differential Cherenkov counter).

Construction: Solid, liquid or gaseous transparent radiators; phase mixtures (aerogels) to cover indices of refraction not available in natural materials.

Measurement principle, readout: Cherenkov-light emission for particles with $v > c/n$ (n – index of refraction) due to asymmetric polarisation of the radiator material. Readout with photomultipliers or multiwire proportional chambers with photosensitive gas. Application in γ-ray astronomy (Imaging Air Cherenkov Telescopes).

Advantages: Simple method of mass determination; variable and adjustable threshold for gas Cherenkov counters via gas pressure; Cherenkov-light emission can also be used for calorimetric detectors; also imaging systems possible (ring-imaging Cherenkov counter (RICH)).

Disadvantages: Low photon yield (compared to scintillation); Cherenkov counters only measure the velocity β (apart from z); this limits the application to not too high energies.

Transition-radiation detectors

Application: Measurement of the Lorentz factor γ for particle identification.

Construction: Arrangement of foils or porous dielectrics with the number of transition layers as large as possible (discontinuity in the dielectric constant).

Measurement principle, readout: Emission of electromagnetic radiation at boundaries of materials with different dielectric constants. Readout by multiwire proportional chambers filled with xenon or krypton for effective photon absorption.

Advantages: The number or, more precisely, the total energy radiated as transition-radiation photons is proportional to the *energy* of the charged particle. The emitted photons are in the X-ray range and therefore are easy to detect.

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Disadvantages: Separation of the energy loss from transition radiation and from ionisation is difficult. Effective threshold effect of $\gamma \approx 1000$.

17.9.2 Particle identification with calorimeters

Particle identification with calorimeters is based on the different longitudinal and lateral development of electromagnetic and hadronic cascades.

Muons can be distinguished from electrons, pions, kaons and protons by their high penetration power.

17.9.3 Neutron detection

Applications: Detection of neutrons in various energy ranges for radiation protection, at nuclear reactors, or in elementary particle physics.

Construction: Borontrifluoride counters; coated cellulose-nitrate foils or LiI(Eu)-doped scintillators.

Measurement principle: Neutrons – as electrically neutral particles – are induced to produce charged particles in interactions, which are then registered with standard detection techniques.

Disadvantages: Neutron detectors typically have a low detection efficiency.

17.10 Neutrino detectors

Application: Measurement of neutrinos in astroparticle physics and accelerator experiments.

Construction: Large-volume detectors using water or ice for cosmic-ray, solar, galactic or extragalactic neutrinos. Massive detectors at accelerators at large neutrino fluxes. Massive bubble chambers.

Measurement principle, readout: Conversion of the different neutrino flavours in weak interactions into detectable charged particles, which are measured by standard tracking techniques or via Cherenkov radiation.

Advantages: Substantial gain in physics understanding. Search for point sources in the sky (neutrino astronomy).

Disadvantages: Large-scale experiments require new techniques for deployment in water and ice. Rare event rates. Background from mundane sources requires excellent particle identification.

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17.11 Momentum measurement

Applications: Momentum spectrometer for fixed-target experiments at accelerators, for investigations in cosmic rays, and at storage rings.

Construction: A magnet volume is either instrumented with track detectors or the trajectories of incoming and outgoing charged particles are measured with position-sensitive detectors.

Measurement principle, readout: Detectors determine the track of charged particles in a magnetic field; the track bending together with the strength of the magnetic field allows one to calculate the momentum.

Advantages: For momenta in the GeV/c range high momentum resolutions are obtained. The momentum determination is essential for particle identification.

Disadvantages: The momentum resolution is limited by multiple scattering in the magnet and in the detectors, as well as by the limited spatial resolution of the detectors. The momentum resolution *deteriorates* with momentum ($\sigma/p \propto p$). For high momenta the required detector length becomes increasingly large.

17.12 Ageing

- Ageing in wire chambers is caused by the production of molecule fragments in microplasma discharges during avalanche formation. Depositions of carbon, silicates or oxides on anode, potential and cathode wires can be formed.
- Ageing effects can be suppressed by a suitable choice of gases and gas admixtures (e.g. noble gases with additions containing oxygen). In addition, one must be careful to avoid substances which tend to form polymers (e.g. carbon-containing polymers, silicon compounds, halides and sulphur-containing compounds).
- Ageing effects can also be reduced by taking care in chamber set-up and by a careful selection of all components used for chamber construction and the gas-supply system.
- Ageing in scintillators leads to loss of transparency.
- Ageing in semiconductor counters (silicon) leads to the creation of defects and interstitials and type inversion.

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17.13 Example of a general-purpose detector

With the idea of general-purpose detectors one usually associates big experiments such as at previous e^+e^- colliders (ALEPH, DELPHI, L3, OPAL), at B factories (Belle, BABAR), at the Large Hadron Collider at CERN (ATLAS, CMS, LHCb, ALICE), or in astroparticle physics experiments (IceCube, Auger experiment, ANTARES, PAMELA). Also large cosmic-ray experiments or spaceborne experiments require sophisticated instrumentation.

One important aspect of such general-purpose detectors is tracking with high spatial resolution with the possibility to identify short-lived particles (e.g. B mesons). Particle identification can be done with Cherenkov detectors, transition radiation, time-of-flight measurements or multiple $\mathrm{d}E/\mathrm{d}x$ sampling. Momentum measurements and calorimetric techniques for electrons, photons and hadrons are essential to reconstruct event topologies and to identify missing particles like neutrinos or supersymmetric particles, which normally go undetected. These properties are described for the example of the Belle detector operating at the e^+e^- storage ring at KEK. The main objectives of this experiment are to study B physics, CP violation and rare B decays with the aim to determine the angles in the unitarity triangle, which are relevant for the understanding of the elements in the Cabibbo–Kobayashi–Maskawa matrix and electroweak interactions as a whole. In cosmic-ray experiments on the other hand, a large coverage at affordable cost is required, e.g. for neutrino astronomy and/or particle astronomy at $\geq$ EeV energies, while space experiments necessitate compact instruments with excellent spatial resolution and particle identification at limited payloads.

17.14 Electronics

The readout of particle detectors can be considered as an integral part of the detection system. There is a clear tendency to integrate even sophisticated electronics into the front-end part of a detector. The front-end electronics usually consists of preamplifiers, but discriminators can also be integrated. The information contained in analogue signals is normally extracted by analogue-to-digital converters (ADCs). With fast flash ADCs even the time structure of signals can be resolved with high accuracy. Particular care has to be devoted to problems of noise, cross-talk, pickup and grounding. Logic decisions are normally made in places which are also accessible during data taking. These logic devices usually have to handle large numbers of input signals and are consequently configured in different levels. These trigger levels – which can be just coincidences in the most simple case – allow a stepwise decision on whether to accept an event or not. Modern trigger systems also make massive use of microprocessors for the handling of complex event signatures. Events which pass the trigger decision are handed over to the data-acquisition system.

For good data quality, on-line monitoring and slow control are mandatory.

For simpler detection techniques the amount of electronics can be substantially reduced. The operation of visual detectors uses only very few electronic circuits and some detectors, like nuclear emulsions or plastic detectors, require no electronics at all.

17.15 Data analysis

The raw data provided by the detectors consist of a collection of analogue and digital signals and preprocessed results from the on-line data acquisition. The task of the data analysis is to translate this raw information off-line into physics quantities.

The detector data are first used to determine, e.g., the energy, momentum, arrival direction and identity of particles which have been recorded. This then allows one to reconstruct complete events. These can be compared with some expectation which is obtained by combining physics events generators based on a theory with detector simulation. A comparison between recorded and simulated data can be used to fix parameters which are not given by the theory. A possible disagreement requires the modification of the model under test, or it may hint at the discovery of new physics. As an example for the problems encountered in data analysis, the search for the Higgs particle at LEP is discussed.

17.16 Applications

There is a wide range of applications for particle detectors. Mostly, these detectors have been developed for experiments in elementary particle physics, nuclear physics and cosmic rays. However, there are plenty of applications also in the fields of astronomy, cosmology, biophysics, medicine, material science, geophysics and chemistry. Even in domains like arts, civil engineering, environmental science, food preservation, pest control and airport screening, where one would not expect to see particle detectors, one finds interesting applications.