Chapter 2
Shower Detection Methods and Basic Event Reconstruction

Overview This chapter contains an outline of the different air shower detection methods, many of which are discussed in detail in dedicated chapters later on. Detection techniques that had been explored only briefly in the past or are presently in an exploratory phase, such as radar ranging and acoustic detection, respectively, are not treated in separate chapters but are discussed extensively here. Directly and indirectly accessible shower parameters are introduced and briefly described, followed by the elementary concepts of shower reconstruction and a brief overview of the response of common particle detectors to shower particles, including transition effects. Indirectly accessible parameters are discussed in Chap. 10.

2.1 Introduction

An air shower is characterized by a thin but radially very extended particle disk that propagates essentially with the speed of light along the shower axis. The latter is defined theoretically by the direction of the momentum vector of the incident primary. The shower particle disk which exhibits a slightly curved front surface has a high density at the center that decreases approximately exponentially with increasing radial distance. The location of the density maximum defines experimentally the position of the shower axis at impact on the ground. The charged particles produce highly polarized optical Cherenkov as well as radio emission as they propagate through the atmosphere, and air fluorescence along their tracks, leaving a long column of slowly recombining ionized air.

Additional but little explored electromagnetic processes such as the interaction of the charged particles with the geomagnetic or even the geoelectric field in the atmosphere and other processes may also contribute to radio emission. In dense homogeneous media, such as water, extremely energetic and compact showers may produce acoustic effects.

Each of the above mentioned phenomena represents a specific signature of an air shower and can in principle be used for detection and classification of an event. In some experiments more than one of these intimately related characteristic effects are being used. However, some of the phenomena caused by the particle disk in travers-
ing the atmosphere that are listed above have not yet been explored sufficiently that they can be used as standard tools for air shower investigations.

Today, air showers are mainly detected by means of particle or optical Cherenkov detector arrays, or with one or several Fly’s Eye type hemispherical atmospheric fluorescence detectors.\(^1\) Small aperture narrow-angle atmospheric Cherenkov telescopes as they are being used in high energy gamma ray astronomy are not suitable for general all-sky air shower observations. The detection of radio emission from air showers is a long standing topic, still in its infancy, which so far could not be exploited successfully, and likewise RADAR tracking of the ionization column of giant showers in the atmosphere.

In an even more preliminary phase is the technique of acoustic detection of high energy events impacting on a homogeneous medium, such as a large body of water or ice. This method had been pursued during the last three decades mostly with the aim to detect extremely high energy neutrinos in the ocean, as was intended with the pioneering DUMAND (Bosetti et al., 1989; Grieder, 1992) and later follow-up projects (e.g., Anassontzis et al., 1995; Spiering, 2003; Hill, 2005). In the following we briefly describe the different detection methods.

### 2.2 Particle Detector Arrays

The most common method of shower detection is based on the arrival of the particle disk at ground level with the help of a more or less loosely packed particle detector array.\(^2\) This implies that the particle disk, which contains the full particle mix present in a shower, is only being sampled on arrival at ground level. In other words, one obtains only an incomplete two-dimensional picture of the shower at a particular moment and stage of its development with some timing information from the arrival sequence of the current particle generation at the different detectors of the array. The latter yields very limited information on the longitudinal cascade development.

The time structure of the particle disk is outlined in Sect. 1.1. Details are discussed in Chap. 9, where theoretical and experimental data are presented. Temporal properties and data of particular particle groups are discussed in the appropriate chapters of Part II. It is evident that the higher the detector density of an array is the richer the extracted data set is and the more accurate a shower can be reconstructed and analyzed.

The shower particle pattern is circular for vertically incident showers. Besides density fluctuations within the particle disk caused by fluctuations in the shower generating processes that may disturb the symmetry, the particle distribution is more

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\(^1\) In some applications only sectors of a hemispherical detector geometry are being used that cover a restricted solid angle of the sky, such as is the case at the Auger Observatory (Blümer, 2003).

\(^2\) The layout of a selection of air shower particle detector arrays of the past and present are displayed in Sect. A.1.
or less affected by the geomagnetic field. Depending on the direction of the shower axis with respect to the direction of the geomagnetic field, the particle trajectories exhibit a slight momentum dependent curvature, positively charged particles in one direction and negatively charged particles in the other, causing some degree of lateral charge separation, and asymmetry of the particle distribution in the plane of observation may occur (see Fig. 8.17).

With increasing zenith angle the contour of the particle pattern on the ground changes more and more from a circular to an asymmetrical elliptical form, mainly for geometrical reasons. In addition, an increasing azimuthal asymmetry of the particle density distribution begins to appear with increasing inclination and radial distance from the shower axis. This is due to differences in the trajectory length and therefore in the degree of development within a shower and affects mainly the electromagnetic component.

The relevant observables that must be acquired by a particle detector array to reconstruct a shower are the arrival time, $t_i$, of the particles at detector $i$ with respect to some reference time, $t_0$, the particle density, $\rho_i$, and the detector location with respect to the reference system, $x_i$ and $y_i$, or $r_i$ and $\varphi_i$. Frequently the instant of arrival and registration of the first particle at the array is taken as the reference time, $t_0$.

In early experiments the particle detectors consisted of Geiger counters. Today, mainly scintillation and/or water Cherenkov detectors are being used as common shower detectors for fast timing and particle density or energy deposit measurements. However, a number of other detector types are also used for this purpose.

An array may be laid out symmetrically, asymmetrically or in an arbitrary pattern about a predefined array center. An asymmetrical layout permits larger radial coverage of the showers in a particular direction and the detection of larger showers than a symmetrical array for a given site area, number of detectors and for specific trigger conditions. However, because of fluctuations in the lateral distribution of the particles within a shower and the lack of full symmetry, the event interpretation is more subtle with such arrays.

A flat topography is desirable but not a necessity. Frequently the shower detectors are placed closer to each other near the designated array center and spread out more and more with increasing radial distance. This results in a higher lateral resolution in the core region of the showers, where the particle and photon densities and energies are high, for those events whose axis strike near the array center.\(^3\) On the other hand, an increasing separation of the outer detectors with increasing distance from the array center requires larger detectors because of the decreasing particle density.

Shower detection is based on coincidence requirements of the arrival of one or more particles in each of a number of detector units within a predefined time window. The width of the coincidence time window to accept an event for recording

\(^3\) Note that trigger conditions may be set such that event selection can be influenced in many ways to meet special requirements.
depends on the array size, the detector separation and the zenith angular window of shower acceptance desired. Frequently a small number of specially dedicated so-called fast-timing array trigger detectors, usually fast plastic or liquid scintillation detectors, preferentially placed symmetrically at moderate distances from the array center and operated at low threshold levels, are being used for this purpose.

The leading edge of the pulses of the fast-timing array trigger detectors are used to compute the arrival direction of the shower, i.e., the zenith and azimuthal angles. Additional trigger requirements may be imposed on these or the other detectors, such as minimum particle densities, to impose a more restrictive second-level trigger, in order to accept a shower for recording. In this case, a broader time window of acceptance, centered about the initial trigger window, is in general required. In this way one can select the minimum shower size to be accepted. Additional, still more restrictive trigger requirements may be imposed for specific purposes.

The described method selects preferentially showers whose core (axis) lies close to the array center. There, special equipment such as calorimeters or spectrometers to study ultrahigh energy particles and interactions in the shower core (hadronic interactions, muons or delayed particles, etc.) are usually placed. In the past, at rare occasions, cloud chambers were also implemented near the array center.

Well equipped arrays possess a number of large-area muon detectors distributed across the array. Large-area detectors are required for this purpose because of the generally lower density of the muons, particularly at larger distances from the axis. Muon detection is achieved by shielding common charged particle detectors from the bulk of the low energy electromagnetic component with a layer of several centimeters of lead, or by placing them underground. Occasional punch-throughs of energetic particles cannot be excluded but are less likely at larger distances from the shower core. The energy thresholds for such muon detectors are usually chosen anywhere between 0.25 GeV to a few GeV. In some cases sophisticated magnet or absorption type muon spectrometers are implemented, in general near the array center, to analyze the energetic muon component in or near the shower core.

A very particular kind of air shower particle detector is the large-area Haverah Park type deep water Cherenkov detector (Tennent, 1967). The typically several square meters large, 1.2 m deep water tanks were spread in clusters of three or four units, widely apart from each other, in particular patterns across the array ground (see Fig. A.20). They record the optical Cherenkov radiation produced by the particle mix that enters the tanks and propagates in the water. With the exception of an occasional direct hit of a detector by a shower core, the detectors are mostly exposed to low energy particles, on average several 100 m from the shower axis.4

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4 Mainly low energy muons and electrons, but also photons via conversion processes in the water that produce positron–negatron pairs, Compton scattered and knock-on electrons are being recorded.
Many of the shower muons traverse the water column but some are being stopped as is most of the electromagnetic component of the particle mix. The Cherenkov light flash thus produced is expressed in units of \textit{vertical equivalent muons} and is used as a measure of particle density and energy deposit (Hollows et al., 1969). Because of the fast response of these detectors they yield excellent timing information.

Simple air shower simulations have shown that the all-particle energy density deposit at several hundred meters from the shower axis in deep-water Cherenkov detectors is a rough measure of the primary energy of the shower initiating particle and is fairly independent of its mass (see Chaps. 8, 10 and 11, and Sect. 12.5) (Hillas, 1970; Hillas et al., 1970, 1971). The relatively large thickness (height) of this type of detector extends its applicability to very large zenith angles, since it still exposes a sufficient area to inclined and even horizontal showers.

In some rare cases particle tracking detectors, such as wide-gap spark or discharge chambers, had been used in a more exploratory attempt for shower (axis) direction determination (Heintze et al., 1989a, b; Doll et al., 2002; Poirier et al., 2007), but this method is not very practical for this purpose. Today tracking detectors are sometimes being used in muon telescopes or spectrometers (magnetic or absorption spectrometers) to measure the muon angle with respect to the shower axis in order to estimate the height of origin of high energy muons in showers, or to locate particle trajectories in hadron calorimeters (see Chaps. 13 and 14 for more details).

For completeness we should also mention the large but relatively shallow water pool detector Milagro (Barwick et al., 1993; Yodh, 1996; McCullough, 1999; Atkins et al., 2000). It is used mainly for gamma ray astronomy. The pool measures $80 \times 60 \text{ m}^2$ and has a depth of 8 m. It is located at an altitude of 2,630 m outside of Los Alamos, NM (USA). Two horizontal layers of optical detectors (photomultiplier tubes) arranged in the form of matrices are submerged at depths of 1.5 and 6 m, respectively. The upper layer is used to reconstruct air showers whereas the lower acts as muon detector for hadron shower rejection. A similar detector project was proposed by Russian scientists to be installed at Issyk-Kul lake in Kyrgyzstan but has not yet materialized (Ermatov et al., 1981; Albers et al., 1983; Erofeeva et al., 1987).

A unique instrument which should also be mentioned in this context is the huge \textit{resistive plate detector} ARGO at Yangbajing in Tibet (China), located at an altitude of 4,300 m (606 g cm$^{-2}$), that covers an area of almost $6,000 \text{ m}^2$ (Bacci et al., 2000, 2002; Cao, 2005; Martello, 2007). ARGO is used for air shower studies and gamma ray astronomy.

Details of the sites of many of the arrays of past and present, such as the altitude and average barometric pressure are tabulated in Sect. A.1, where the layouts of some arrays are illustrated. A discussion of the extraction and interpretation of data from particle measurements that are relevant for the shower development, the determination (estimation) of the primary energy spectrum and the mass composition are

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5 Relativistic muons lose about 2 MeV g$^{-1}$ cm$^2$. 
discussed in Chap. 10. The results thus obtained yielding primary spectra and mass compositions are presented in Chap. 11.

2.3 Air Cherenkov Detector Arrays

Large aperture, wide-angle acceptance optical detector arrays that record atmospheric Cherenkov emission of air showers are operated essentially in the same manner as particle detector arrays. However, the photon pattern, i.e., the lateral distribution function, is different from that of the charged particles, and the photons are highly polarized. Such arrays may be operated autonomously or in conjunction with a particle detector array.

Unlike Cherenkov telescopes that are used for gamma ray astronomy that use a large light collection mirror with a very narrow field of view that can point in any direction of the night sky and have a very high angular resolution, wide-angle Cherenkov detector arrays cover simultaneously a large fraction of the sky and detect any event that is in their field of view. A modern example of such an array is the installation at the Tunka Valley, near Lake Baikal (Budnev et al., 2005). Suitable climatic, meteorological and environmental site conditions, such as low optical background, a mostly cloudless sky, little precipitation and a dust-free atmosphere with low aerosol contamination are required to operate air Cherenkov detectors and Cherenkov telescopes successfully and with a reasonable duty factor.

Moreover, this kind of detector can only be used during clear moonless nights and the atmospheric conditions (absorption, etc.) must be frequently checked for accurate measurements. The relevant data that must be acquired by a Cherenkov detector array are the number density $Q_i$ and arrival time, $t_i$, of the optical photons, and the corresponding coordinates of the $i$ detectors, $x_i$ and $y_i$, or $r_i$ and $\phi_i$, with respect to the reference frame of the array.

The basic event reconstruction procedure is analogous to the one used for particle detector arrays but air Cherenkov data contain more longitudinal shower information. Because of the generally good transparency of the atmosphere for the optical portion of the Cherenkov emission (little absorption and scattering), the light collected by a ground array contains photons from all stages of the shower, along the entire trajectory. Therefore the Cherenkov component carries the history of a shower to the observer at ground level, thus revealing a three-dimensional picture of an event. Hence, Cherenkov measurements represent in fact a sort of atmospheric Cherenkov calorimetry of the shower where in principle all stages of development are accessible through the photons. As mentioned in the previous section, this feature is more obscured in the particle time profile, since the recorded particles originate from the last generation of interactions, many generations after the first interaction with many scattering events in between.

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6 Using special ultraviolet sensitive photomultiplier tubes and/or appropriate filters in front of the photomultipliers permit to operate an optical atmospheric Cherenkov array at certain times during the presence of the moon.
An important advantage of the atmospheric Cherenkov shower detection method over particle detection is that because of the much larger number of photons of a Cherenkov light burst of a shower arriving at a detector as compared to the number of particles striking a conventional particle detector, the photon burst is not subject to Poissonian fluctuations as is the particle count. Fluctuations of Cherenkov signatures are therefore of a different nature. They are caused by fluctuations of the actual physical processes that take place in a shower and the strongly fluctuating superimposed background photon flux. The net shower photon count is then estimated by subtracting the background count from the measured signal.

The longitudinal information is packed partly in a time code and partly in a geometrical code, i.e., the Cherenkov photons from a particular longitudinal section of a shower have a definite time stamp within the light pulse and are deposited within definite annular zones about the shower axis. This information is of course smeared out to some extend by the angular spread (scattering) of the parent particles at any depth, by the changing atmospheric density that affects the index of refraction and therefore the Cherenkov angle, and by fluctuations of the different processes that affect the parent particles.

Theoretical and experimental aspects of air shower induced Cherenkov radiation are discussed in detail in Chap. 16 where a wealth of data from measurements and their interpretation are presented and analyzed. Data related to the primary energy spectrum and the mass composition resulting from atmospheric Cherenkov studies are discussed in Chap. 11.

2.4 Air Fluorescence Detectors

Unlike atmospheric Cherenkov radiation, atmospheric fluorescence produced by air showers is emitted isotropically, mainly in the 300–400 nm band, by the excited nitrogen molecules (second positive band) and nitrogen ions (first negative band). The isotropic emission has far reaching consequences for the detection. It implies that in fluorescence light showers can in principle be observed from all directions, in particular also from the side with an appropriate optical detector. There is no need for the shower to point toward the detector as in the case of Cherenkov detection, or even to strike it directly as is required for particle detector arrays. All that is needed is a hemispherically sensitive imaging kind of detector that can observe showers all around it and track them. Because of the resemblance of such a detector to a fly’s eye this kind of detector is called a Fly’s Eye type air fluorescence detector (Bergeson et al., 1975a, b).

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7 Note that showers whose axis is directed towards a fluorescence detector or its immediate vicinity are usually excluded from analysis because the intense Cherenkov beam obscures the fluorescence signal.
The relevant observables that must be recorded are the photon density, $Q$, the instantaneous arrival direction of the photons, i.e., the zenith and azimuthal angles, $\theta$ and $\varphi$, and the arrival time, $t$; thus, one records $Q(\theta, \varphi, t)$.

A Fly’s Eye type detector consists in principle of a large number of optical detector modules (large individual photomultiplier tubes or clusters of small tubes) that are arranged on a hemispherical shell. Each module points in a particular direction and views a certain aperture limited element of solid angle of the sky. The entire ensemble is arranged in such a way that it covers in general nearly the full $2\pi$ steradian of the sky.

With the exception of the first few designs (Bunner et al., 1967), where the modules were laid out on a hemispherical shell, later designs are quite different in appearance (Hara et al., 1970b). In current practice large mirrors or mirror systems (Schmidt, etc.,) are being used in place of the small diameter modules to collect more light per unit. This new design made it necessary to abandon the compact layout on a hemisphere and to place the individual modules, that have now dimensions on the order of meters, apart from each other, however, still pointing into individual directions each, as before (Baltrusaitis et al., 1985; Cassiday, 1985).

A Fly’s Eye detector can monitor a huge volume of atmosphere over a large area and is expected to be an excellent instrument to record rare ultrahigh energy showers that strike far away and would be missed even by a very large array. Another advantage of recording the showers from the side is that one can obtain first hand information of the longitudinal shower development and the location of the shower maximum. This information can only be extracted from array data, mainly from air Cherenkov arrays, in connection with elaborate simulation studies (see Chaps. 7 and 16). A Fly’s Eye type detector is therefore expected to be a good tool for $X_{\text{max}}$, primary mass and energy estimations (see Chaps. 11 and 17).

The same very restrictive site requirements apply to fluorescence detectors as are listed above for air Cherenkov detection. Because of the weaker intensity of fluorescence light and the generally larger distances between shower and detector as compared to the situation for Cherenkov arrays, aerosols and dust that cause scattering and absorption require an even more severe surveillance of the atmosphere with frequent monitoring of its parameters. An additional problem arises when showers strike near or directly at a fluorescence detector. In this case portions of the intense forward directed Cherenkov light beam can get scattered into the field of view of the fluorescence detector, or worse even, the detector may get hit by part of the direct Cherenkov beam, which complicates the data analysis significantly.

Another advantage of a fluorescence detector over the more conventional particle detector array is that it can be operated as a quasi single $2\pi$ steradian autonomous device from a relatively small site. With two or more units located apart one can get a stereo view of the showers that reduces errors and uncertainties significantly. Moreover, in conjunction with a particle detector array a unique set of complementary and redundant data can be acquired. As a matter of fact, a coincident signal of even

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8 The Fly’s Eye detector had in fact been operated jointly at times with the CASA-MIA, BLANCA and DICE arrays at Dugway (Utah) (Bird et al., 1995; Cassidy et al., 1997; Swordy and Kieda, 2000).
a single particle detector allows an improved reconstruction of the shower geometry obtained from a fluorescence detector, in a similar way as by the stereo view. This method is employed by the Auger detector and is called hybrid reconstruction.

In exceptional cases air fluorescence detectors may be designed to have a restricted zenith and/or azimuthal angular aperture for being placed outside or at the fringes of a particle detector array, to overlook only the air space above the array. This idea had been proposed by Grieder in conjunction with the DUMAND (Deep Underwater Muon And Neutrino Detector) system. The intention was to view from shore that portion of the atmosphere that lies above the submerged detector matrix located at a depth of 5 km some 30 km off shore in the Pacific near Hawaii, in order to investigate the showers that produce ultrahigh energy downward-going atmospheric muons that could have reached the deeply submerged matrix (Grieder, 1980; Elbert et al., 1981). Such a design is now being used by the Auger and Telescope Array experiments (Mantsch, 2005; Kasahara, 2007).

Chapter 17 is dedicated to the air fluorescence phenomenon and to the fluorescence detection method of showers. There the fluorescence mechanism, the detection technique and related problems such as event reconstruction, background problems and data interpretation are discussed. The achieved scientific results that are related to the primary energy spectrum and the mass composition using the fluorescence method are presented in Chap. 11, cross section and particle physics data in Chap. 3.

### 2.5 Radio Emission Detection

The detection of radio frequency (RF) pulses produced by air showers is a very old idea. However, the identification of radio frequency shower signatures is difficult because of the so-called electromagnetic smog, i.e., radio noise (static) produced by electric and electronic equipment, particularly in urban areas where large portions of the electromagnetic frequency spectrum are intensely utilized for radio (AM and FM), television and communication services. But there is also a significant natural atmospheric and extraterrestrial electromagnetic noise, particularly of galactic origin (cf. Fig. 18.4). Numerous authors have tackled the problem over the past 50 years but abolished the idea regularly. For a summary of the early work the reader is referred to the comprehensive review of Allan (1971).

The high hopes that accompanied initially the many efforts aimed to determine the energy spectrum and even the mass of the rare ultrahigh energy primary particles that initiate the giant air showers by having a large spatial coverage when using the radio emission from showers as a novel probe did not materialize, so far. Up to date it is not really clear which one of the different mechanisms that are believed to contribute to radio emission from showers is the most relevant\(^9\) and it has not yet been possible to extract any useful information on air showers from radio signatures only (Green et al., 2003), though the situation is improving (Lafebre et al., 2005; 2006; 2007).

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\(^9\) At present geo-synchrotron radiation is believed to be the chief contributor.
Ravel, 2007). Moreover, it has not even been possible so far to definitely associate a radio pulse with the occurrence of a shower without using the information from conventional particle detectors.

Nevertheless, the topic re-surfaces regularly again and again. Major efforts are currently under way to explore the method anew and to exploit it if the attempts prove finally successful, and presently success appears to be tangible (e.g., Falcke and Gorham, 2003; Huege and Falcke, 2003, 2005; Van den Berg, 2007; Saftoiu et al., 2007). In Chap. 18 we review the field in some detail and summarize the different mechanisms that are expected to be responsible for the emission of radio waves in the form of electromagnetic pulses by air showers and present an overview of the available experimental results.

Within the frame of the AMANDA and IceCube neutrino astronomy projects, the possibility to detect radio emission caused by cascades initiated by high energy neutrinos in ice at the surface or even from space is currently being investigated (Hill, 2005; Auffenberg et al., 2007). This method could offer a complementary possibility to optical or acoustic detection of such events in large bodies of ice, such as at Antarctica, if it proves successful.

### 2.6 RADAR Ranging and Detection

Giant air showers are rare events that require very large and costly surface arrays to be detected at a reasonable rate, to construct reliable shower size and primary energy spectra, and to extract even more subtle information, such as the nature of the primary. At a very early stage of air shower research Blackett and Lovell (1941) suggested that the long and relatively narrow ionization trails produced by distant giant air showers that traverse the entire atmosphere might possibly be detectable by means of **RADAR** *(RAdio Detecting And Ranging)* echo ranging and they explored the subject theoretically. In the following we briefly summarize their estimation and argumentation for the detectability of showers by RADAR.

Consider a shower at a distance $R$ from a powerful radio transmitter with a wavelength, $\lambda$, large compared with the diameter of the column of ionization. Diffraction theory shows that the amplitude of a reflected wave at the location of the transmitter will be approximately equal to that which would be produced by a point cluster of $n$ ions, where $n$ is the number of ions contained in a shower column, whose length $L$ is that of the first Fresnel zone, that is, where

$$L = \sqrt{\frac{\lambda}{R}}.$$  \hspace{1cm} (2.1)

From the electromagnetic cascade theory (Sect. 4.6), one can calculated the maximum number of ions produced per centimeter of air, $n$, at a pressure $P$, expressed as a fraction of an atmosphere, produced by an incident electron of energy $E_0$. A rough calculation yields

$$n = 5 \cdot 10^{-8} P E_0.$$ \hspace{1cm} (2.2)
Thus, the number of electrons in the equivalent point cluster is

$$N_e = nL = 5 \cdot 10^{-8} P E_0 \sqrt{\lambda R}. \quad (2.3)$$

If the reflection coefficient, $\kappa$, is defined as the ratio of the reflected amplitude to that incident on the cluster, then a point cluster of $N_e$ electrons at a distance $R$ from the transmitter will have a reflection coefficient

$$\kappa = \frac{N_e r_e}{R}, \quad (2.4)$$

where $r_e$ is the classical electron radius ($2.8 \cdot 10^{-13}$ cm).

Considering Eqs. (2.3) and (2.4), we obtain for the reflection coefficient of a shower of primary energy $E_0$ at a distance $R$,

$$\kappa = 5 \cdot 10^{-8} P E_0 r_e \sqrt{\frac{\lambda}{R}}. \quad (2.5)$$

If we take $\kappa = 2 \cdot 10^{-5}$, $P = 1$, $\lambda = 50$ m, $R = 10$ km, we get $E_0 = 2 \cdot 10^{16}$ eV. The conclusion which Blackett and Lovell drew from this analysis was that large extensive air showers can produce measurable radio reflections.

The duration of a radio echo is expected to last for the lifetime of the free ions, and this is governed mainly by the rate of attachment to molecules. Consequently, the duration of the echoes will be roughly inversely proportional to the pressure, and will have a value of $\sim 10^{-5} - 10^{-6}$ s at ground level and of the order of a second at 100 km (Blackett and Lovell, 1941). Thus, though the amplitude of an echo will decrease with the pressure, its duration will increase in the same proportion, leaving the product of amplitude and duration unchanged.

However, the proposal of Blackett and Lovell did not receive much attention, except for a few exploratory experimental attempts in the 1960s and early 1970s. The reason for the lack of interest at that time was mainly that it did not appear to be a very practical method because of background problems, trigger requirements and encouraging new results obtained with the classical particle detector arrays. In addition, it was known that thunderstorms and meteorite trajectories in the atmosphere leave RADAR detectable ionization trails that may confuse the interpretation of RADAR echoes.\(^\text{10}\)

In spite of the discouraging outlook, the Tokyo group began to explore the method in the early 1960s, using the echo of pulsed radio waves from a LORAN (LOng RAnge Navigation) system to record signals reflected by giant showers of primary energy $> 10^{20}$ eV (Suga, 1962; Matano et al., 1968; Hara et al., 1970a).

\(^{10}\) Micro meteorites having masses as small as $\sim 1 \mu g$ and diameters $\simeq 0.1$ mm may cause ionization line densities in the atmosphere on the order of $\sim 10^{13}$ electrons m$^{-1}$ which are detectable by RADAR (Gorham, 2001).
In the following we briefly outline as a concrete example the pioneering Tokyo experiment, the assumptions on which it was based and the results obtained.

Consider a shower of size $10^{10}$ particles. The ionization density produced by such an event is $> 10^4$ [ion pairs cm$^{-3}$] and comparable to that of the ionosphere. In the column ionized by a shower, however, the collision mean time of electrons is very short, approximately $10^{-9}$ s. The mean life of electrons due to electron attachment is of the order of $10^{-7}$ s and the mean life for recombination of the positive and negative ions is several minutes. The power of the echo signal is given by Matano et al. (1968) as

$$2.5 \cdot 10^{-32} \frac{a^2 P G^2 \lambda^3}{R^3} \left( \frac{m_e}{M} \right)^2 \left( \frac{1}{(4\pi r_M/\lambda^2) + 1} \right) \left( \frac{1}{(\nu_c/\pi \nu)^2 + 1} \right) [W], \quad (2.6)$$

where

- $a$ is the number of ions or electrons per meter of shower column,
- $P$ the power of the emitter [W],
- $G$ the antenna gain of the emitter and receiver,
- $r_M$ the characteristic distance (Molière radius) of the lateral distribution of the shower particles, i.e.,

$$f(r) \propto \left( \frac{1}{r} \right) \exp\left(-r/r_M\right), \quad (2.7)$$

- $\lambda$, $\nu$ are the wavelength and frequency of the radio wave,
- $m_e$, $M$ the mass of the electron and air molecule, respectively,
- $\nu_c$ the collision frequency between the electrons and air molecules ($\sim 10^9$ Hz), and
- $R$ is the distance between receiver and air shower.

In a first attempt a pulsed radio wave of 1,850 kHz was transmitted isotropically with a power of more than 100 kW from a LORAN station. The pulse width and the repetition rate were 40 $\mu$s and 20–30 Hz, respectively. The experimental configuration is illustrated in Fig. 2.1. The signal-to-noise ratio of the received echo was very low because the sky noise masked the signal. Reflections from the ionosphere disturb the detection beyond a certain distance. In particular, if $h$ is the height of the ionosphere and $d$ the distance of the receiver from the LORAN transmitter, then the shower whose echo pulse has a time delay of $\Delta t$ with respect to the direct pulse is located on the ellipse with major axis $a = c\Delta t + d$ and minor axis $b = \sqrt{[(c\Delta t + d)^2 - d^2]}$.

Since the first reflected pulse from the ionosphere comes with a time delay of $c\Delta t = \sqrt{[d^2 + (2h)^2]} - d$ after the direct pulse, the detection area with low noise is limited by the ellipse corresponding to this time delay (see Fig. 2.1). When $d \ll h$, the large ellipse tends to a circle with radius $h$, and the corresponding time delay is $2h/c$ which is almost 400 $\mu$s for the D-layer ($h = 70$ km). Therefore only the
Fig. 2.1 Detection area of air showers for the radio echo (RADAR) method using a LORAN transmitter. $d$ is the distance between the transmitter, A, and the receiver, B, $R$ the distance between the shower axis and the receiver, and $h$ is the height of the ionosphere. The solid ellipse contains the area where the radio echo from the shower precedes the reflection from the ionosphere and shower detection is possible (Matano et al., 1968).

An echo pulse which falls within 400 μs after the direct pulse may be detected under low-noise conditions.

A survey of the background noise in the Tokyo area gave a noise level of about $3 \cdot 10^{-6}$ V at the output of the antenna (antenna gain 1.5 and bandwidth of amplifier 1,850 ± 12 kHz) in the region where no reflected pulse from the ionosphere existed. It was about $3 \cdot 10^{-5}$ V in the reflected pulse region (when $d \ll h$, for the D-layer and in the morning). If one inserts the LORAN pulse amplitude into Eq. (2.6), putting $N = 10^{10}$, $R = 10$ km, $P = 100$ kW, $G = 1.5$ (for a dipole antenna), and $\lambda = 160$ m (1,850 kHz), then the received echo power is about $3 \cdot 10^{-20}$ W, which corresponds to $3 \cdot 10^{-9}$ V across an input resistor of 300 Ω.

Matano et al. (1968) concluded that due to the fact that the ions in an air shower remain for several minutes, about $10^4$ echo pulses can be obtained during that time. By integrating these pulses the signal-to-noise ratio improves by about a factor of $10^4$. The echo signal reaches then a level of $\sim 3 \cdot 10^{-5}$ V, which is 10 times the background noise. The observed shower rate was approximately 150 showers per year. If one neglects the scattering losses of the signal, the radius of the effective area increases with energy to $\sim 50$ km for $N = 10^{11}$ and to $\sim 200$ km for $N = 10^{12}$, thus yielding about 70 showers per year and 30 showers per year, respectively, assuming an integral size spectrum of $I(N) = 10^{-13}(N/10^9)^{-1.6}$ m$^{-2}$ s$^{-1}$ sr$^{-1}$.

In the latter case ($N = 10^{12}$) only few showers are expected to have a good signal-to-noise ratio ($\sim 10$) because of ionospheric limitations. The authors conclude from their work that it may therefore be better to use another frequency band or
directional antennae to reduce the background when tackling the ultrahigh energy region (Hara et al., 1970a).

In recent years with the availability of new technologies the RADAR echo detection of extremely large air showers has been revisited by various authors and different projects have been proposed (Wahl et al., 2007). Gorham (2001) has carried out a very detailed feasibility study and came to the conclusion that radar detection of the ionization track of air showers of primary energy \( \geq 1 \text{ EeV} \) (\( 10^{18} \text{ eV} \)) can be achieved with common radar trackers operating in the VHF (30–100 MHz) range.

### 2.7 Acoustic Detection

Large showers impacting on homogeneous media such as large bodies of water (lakes, oceans) or ice are expected to produce a *thermo-acoustic shock wave* that should in principle be detectable. Numerous studies had been conducted in the past and some accelerator experiments were carried out that confirmed the existence of such signatures.

The occurrence of acoustic signals in liquids upon impact of high energy (relativistic) ionizing particle beams was first suggested by Askar’yan (1957) and subsequently confirmed experimentally by Volovik and Popova (1975) and Sulak et al. (1977, 1979). The subject was further explored by Volovik and Kristiansen (1975), Askar’yan and Dolgoshein (1976), Bowen (1976, 11 1977, 1979a, b, 1980), Hunter et al. (1979, 1980), Jones (1977a, b), and Bowen and Learned (1979), to mention just the pioneers of the field.

Detailed studies revealed that the formation of a thermal shock-like expansion of the liquid caused by the sudden energy deposit of relativistic particles, called a thermo-acoustic shock, governs the process. Subsequently, appropriate theoretical models were developed that describe the process adequately (Askar’yan et al., 1979; Learned, 1979; Tam, 1986).

The basic wave equation for a pressure pulse in a liquid can be written as

\[
\nabla^2 \left( P + \frac{1}{\omega_0} \dot{P} \right) - \frac{1}{c_s^2} \ddot{P} = -\frac{\beta}{C_p} \frac{\partial E}{\partial t},
\]

where \( P \) is the pressure, \( \omega_0 \) the characteristic attenuation frequency (\( \approx 2.5 \cdot 10^{10} \text{ s}^{-1} \)) which is in fact a function of frequency itself (Fisher and Simmons, 1977), \( c_s \) the speed of sound in the medium (\( \approx 1,500 \text{ m s}^{-1} \)), \( C_p \) the specific heat at constant pressure (\( \approx 3.8 \cdot 10^3 \text{ J kg}^{-1} \text{ K}^{-1} \)), \( \beta \) the bulk coefficient of thermal expansion of the medium, and \( t \) is the time. The values specified in parenthesis apply to sea water. For the attenuation coefficient, \( \alpha \), Fisher and Simmons give the following expression,

---

11 According to Askar’yan et al. (1979) the acoustic signal estimated by Bowen in this chapter is grossly overestimated by a factor of \( 10^7-10^8 \).
2.7 Acoustic Detection

**Fig. 2.2** Attenuation coefficient of sound waves in salt and distilled water at a temperature of 25° as a function of frequency (Fisher and Simmons, 1977)

\[
\alpha = \frac{10^4}{(2\pi f)^2 \ln(10\omega_0 c_s)}, \tag{2.9}
\]

where \( f \) is the frequency concerned. This function is plotted in Fig. 2.2.

For simple calculations the heat deposit mechanism is considered to be instantaneous, thus, \( E(\vec{r}', t) = E(\vec{r}')\delta(t) \). The pressure wave can be calculated at the location \( \vec{r} \) as a function of time as

\[
P(\vec{r}, t) = \int_V E(\vec{r}')G(\vec{r} - \vec{r}', t)d^3\vec{r}', \tag{2.10}
\]

where

\[
G(\vec{r}, t) = -\frac{\beta}{4\pi C_p} \cdot \frac{t - r/c_s}{r^3 \sqrt{2\pi}} \exp\left(-\frac{(t - r/c_s)^2}{2\tau^2}\right), \tag{2.11}
\]

with

\[
\tau = \sqrt{\frac{r}{\omega_0 c_s}}. \tag{2.12}
\]

The energy deposition region is elongated in the direction of the incident momentum vector of the initiating particle and the acoustic emission is coherent in the plane perpendicular to it.

The initial efforts to detect acoustic shocks in large volumes of water were exclusively aimed at the detection of extremely high energy neutrinos \( (E_\nu \geq 10^{20} \text{eV}) \) in conjunction with the pioneering DUMAND (Deep Underwater Muon And Neutrino Detector) high energy neutrino telescope in Hawaii (Bosetti et al., 1982, 1989; Babson et al., 1990). In this context the intention was to add an acoustic detector matrix in the form of outriggers to the huge optical Cherenkov detector matrix in the deep ocean as a low cost extension, to increase the effective neutrino detection
volume by a large factor and thus to extend the tangible energy range of the telescope far beyond the capabilities of the optical Cherenkov detector matrix. However, this pioneering project, which set the design template and guidelines for all future large neutrino telescopes, had to be discontinued for lack of funding and did not explore acoustic detection.

A project to detect giant air showers impacting on large bodies of water at high altitude was pursued by Kakimoto et al. (1981) and Kaneko et al. (1983) in a series of experiments at Lake Titicaca and Lake Khara Kkota in Bolivia (altitude \(\sim 4,080 \text{ m} \)).

Today the technique is still in its infancy but numerous feasibility studies are currently under way to develop very large volume neutrino detectors in the oceans and a variety of concrete projects have surfaced in recent years (Dedenko et al., 2001; Lehtinen et al., 2001, 2002; Niess, 2005). The specific aim is the detection of cascades induced by extremely high energy neutrinos in the deep ocean, in major lakes or in large volumes of ice such as at Antarctica, where the acoustic noise level is low and therefore the signal to noise ratio for short sharp pulses is optimal (Aynutdinov et al., 2005; Niess and Bertin, 2006; Antipin et al., 2007; Böser et al., 2007a, b). The energy calibration of an acoustic array, too, is a non-trivial problem and requires simultaneous cross checking with other well established methods.

So far no dedicated air shower detector system based on acoustic event detection in the ocean or a lake is operational. The main reason for the lack of interest to employ this method is that an acoustic air shower detector matrix would have to be installed close to the water surface where the shower core dissipates its energy but also a high level of acoustic background is present (wind, waves, etc.), not to mention the difficulty to install and operate a near surface array. In addition, the very limited amount of information that such a system yields as compared to other methods and projects currently under construction to explore the highest energy regions of the cosmic ray spectrum are rather discouraging.

### 2.8 Hybrid Detector Systems and Coupled Experiments

#### 2.8.1 Surface Experiments

At some array sites a combination of different detectors had been used simultaneously, e.g., particle and atmospheric Cherenkov detectors (large aperture and/or narrow angle pointing devices) such as at Yakutsk (Diminstein et al., 1973), at EAS- TOP (Aglietta et al., 1986) and at HEGRA (Aharonian et al., 1991), but also particle detector arrays and fluorescence detectors, or a combination of all three, such as during particular periods at the Akeno (Hara et al., 1970b) and Fly’s Eye sites (Bird et al., 1995). In the latter case, several autonomous but synchronized particle and/or atmospheric Cherenkov detector arrays had been operated at times in the vicinity of the fluorescence detector (CASA/MIA, Borione et al., 1994; Bird et al., 1995; DICE, Boothby et al., 1995; CASA-BLANCA, Cassidy et al., 1997), in order to collect as much information as possible from the same simultaneously observed showers.
In later hybrid experiments, e.g., at the Fly’s Eye site the HiRes and MIA detectors were operated jointly (Abu-Zayyad et al., 2001). In some cases radio antenna arrays had been incorporated with particle detectors to explore radio pulses generated by air showers, e.g., at Chacaltaya (BASJE experiment, Barker et al., 1967), Haverah Park (Allan, 1971), CASA/MIA (Green et al., 2003) and recently at the KASCADE-Grande experiment in Karlsruhe (Horneffer et al., 2003; Haungs et al., 2007) and at the Auger Observatory (Van den Berg, 2007).

The two very large new experiments that have just come into full operation to explore the highest energy region of the cosmic ray spectrum are the Auger Observatory at Malargüe in Argentina (Camin, 2004; Dawson, 2007), and the Telescope Array in Utah, USA (Kasahara et al., 2007). Both installations are hybrid experiments and use surface particle detectors that are distributed over an area of \( \sim 3,000 \text{ km}^2 \) and \( \sim 680 \text{ km}^2 \), respectively, and have several atmospheric fluorescence detectors, each. An Auger counterpart in the northern hemisphere at Lamar (CO, USA) is presently in the planing and design phase. This detector combination, i.e., surface array and fluorescence detectors, yields excellent three-dimensional information of the shower development in the atmosphere and very detailed ground level data.

### 2.8.2 Special Detector Systems

In order to study specific particles or groups of particles in showers, such as hadrons (nucleons, antinucleons, pions), muons, or electrons and photons, or to search for new hypothetical particles, dedicated detector systems are integrated into the shower arrays. Most frequently used are muon sub-arrays to monitor the low energy muon component, in particular the lateral and temporal distributions of the muons. Sometimes absorption spectrometers and rarely magnet spectrometers had been incorporated at the surface or at shallow depth at specific locations within an array to study the muon spectrum (Vernov et al., 1979) (see Chap. 14 for details).

Only few experiments had been equipped with a hadron calorimeter to analyze the high energy hadron component (e.g., Tien Shan in Kazakhstan, EAS-TOP in Italy, and KASCADE in Germany), and only few air shower arrays had been equipped occasionally with a cloud chamber (e.g., the installations at Tokyo and Mount Norikura in Japan, at Ootacamund in India, and at Sydney in Australia). In an exceptional experiment Hook et al. (1970) have used a magnet spectrometer to record negative pions in showers at Haverah Park (see Chap. 13).

Since the high energy particles are inside the shower core and in its immediate vicinity, the special detector systems to analyze these components are usually placed at or near the array center as defined by the array layout and the trigger requirements that select events where the core strikes the device or its neighborhood. These instruments come in a variety of designs, particularly the hadron calorimeters.

Important properties of hadron calorimeters are high spatial, temporal and energy resolution. Moreover, calorimeters should be sufficiently large, both in area and depth, to record an adequate number of events, to avoid energy leakage in both
directions, in and out, and to absorb the hadron cascades completely in order to analyze them fully.

Muon telescopes and absorption spectrometers are usually placed underground or under a hadron calorimeter, if available, to get a high threshold energy for the muons to study hadron-muon correlations and for obtaining target diagrams. The designs and the operation of the different devices are discussed in the appropriate chapters where the respective particle data are presented (Chaps. 13, 14, 15, 16, 17 and 18 of Part II).

### 2.8.3 Coupled Surface and Underground Experiments

As mentioned earlier, ultrahigh energy muons play an important role in air shower research. They are extremely difficult to observe because their number is relatively small, they are within the core region and its immediate vicinity, and are therefore accompanied by a large number of other very energetic particles. These must be filtered out to have access to the muons. The only practical way to do this is to have a suitable muon detector buried deep underground, under ice or under water, located underneath an air shower array.

Five pairs of experiments, most of which are no longer in operation, offered this unique combination. They included the combined surface and underground installations at the Kolar Gold Fields (KGF) in India (Narasimham, 2004; Acharya et al., 1981), at the Homestake site in Lead, South Dakota, USA (Cherry et al., 1985), the MACRO and LVD underground installations in combination with the EAS-TOP array at Gran Sasso in Italy (Ahlen et al., 1992, 1993; Ambrosio et al., 2002; Bari et al., 1989; Aglietta et al., 1992, 1998, 2004a, b), and the Baksan surface array and underground detector combination in Russia (Alexeyev et al., 1979, 1993). In addition, there was the magnetic muon spectrometer at the Moscow State University (MSU) that was located at the shallow depth of 40 m water equivalent, near the center of the air shower array (Vernov et al., 1979).

The Kolar Gold Fields underground experiments which had been used for this purpose had muon threshold energies of 220 GeV and 1.8 TeV and were located almost perpendicularly below the surface array (see Fig. A.40). The situation at Homestake was similar but the muon threshold was 2.7 TeV. At Gran Sasso the underground experiments were laterally displaced with respect to the EAS-TOP array. The line connecting the centers of the surface and underground experiments subtended an angle of about 35° with respect to the vertical and the muon threshold for coincident events was \( \sim 1.3 \) TeV. At Baksan where the installations are still in operation, the underground detector has a threshold of 230 GeV. The rather shallow depth of the MSU muon spectrometer did not affect its usefulness. Background rejection was sufficient, so that actual muon spectra in showers could be measured. The instrument had a maximum detectable momentum for muons of 900 GeV c\(^{-1}\).

The problem with all these experiments was the low event rate because of the small aperture, i.e., the small solid-angle-area product of the surface and underground detectors combined. However, the situation for carrying out high energy
muon measurements in air showers will improve dramatically in the near future when the large experimental installations at the South Pole begin to accumulate data. There the IceCube detector, now completed, is a unique giant muon detector embedded deep in the ice, located between 1,450 and 2,450 m under the surface, with an almost congruent well equipped air shower particle detector array at the surface, called IceTop (Klepser, 2007), that is complemented by an array of antennas for the detection of the radio bursts generated by the air showers (Karle, 2007).

A selection of special detector systems that are incorporated in some experiments are described in the appropriate chapters of Part II where we present data on specific shower components. The layouts of a number of arrays of past and present are displayed in Sect. A.1.

2.9 Directly and Indirectly Accessible Shower Parameters

An air shower harbors an enormous amount of information, from the energy and nature of the primary particle to the properties of high energy hadronic, electromagnetic and leptonic interactions, such as cross sections, the type, multiplicity and momentum distributions of secondary particles, their energy and collision partner dependence as well as the specific properties of the different particle groups involved. Different detector systems and detector combinations supply different categories of information. Some yield only very rudimentary, others a wide scope of highly sophisticated shower and particle data.

Some of the basic information that characterizes a shower, such as the arrival time of the charged particles, the associated non-optical photons, and the lateral particle and photon density distributions in the plane of observation at a specific atmospheric depth, is immediately accessible with simple shower particle detector arrays. From the particle arrival time information the arrival direction of the shower can be determined directly with simple methods of analysis and event reconstruction.\(^{12}\)

The particle density distribution in conjunction with a simple fitting procedure using the Nishimura-Kamata-Greisen (NKG) lateral distribution function (LDF) yield the location of the shower axis and the shower size. Since the shower size at shower maximum is directly related to the primary energy, a rough estimate of the latter can be obtained quickly. However, in general detailed simulations and fitting procedure are required to get a reliable primary energy assignment (for details see Chaps. 8 and 10).

The situation is similar, in principle, for the parameters that can be extracted from measurements of the optical photon component of atmospheric Cherenkov emission that is associated with a shower (Chap. 16), provided appropriate detector systems are being used. Simple information on the composition of the particle population in

\(^{12}\) Tracking detectors, though only seldom used, reveal directly the direction of propagation of the shower particles. The claimed angular accuracy of this method is \(\sim 0.3^\circ\).
a shower, such as for instance the approximate determination of the muon fraction, can also be extracted readily with little effort by incorporating comparatively simple (shielded) particle detectors.

Shower parameters and characteristics as listed above can be classified as *directly accessible* since they do not necessarily require complex simulation and analysis procedures. They are discussed in more detail in Sect. 2.10.

On the other hand, to extract information on the hadronic component of a shower (Chap. 13) requires in general the incorporation of a dedicated calorimeter which represents a very significant increase of the instrumental complexity. Such a detector system demands far more sophisticated simulation-based data analysis methods to get at the more subtle specific parameters and distributions. A similar though somewhat less delicate situation exists for the extraction of the relevant shower parameters from measurements of the directly observable atmospheric fluorescence photons recorded with Fly’s Eye type detectors (Chap. 17), and likewise for the interpretation of the data from measurements of the presently not fully understood radio wave emission of air showers (Chap. 18).

The signature of the primary particle, in particular of its nature (type, mass and charge) cannot readily be extracted from basic shower data (except for an approximate estimate of the energy as mentioned before). This is also true for most of the relevant and more fundamental interaction and particle physics properties. These as well as the primary mass effects are heavily masked by the multitude of processes that occur in a shower. Many of the processes manifest similar features in the global picture of a shower and are therefore difficult to isolate from each other. This is particularly true for the effects caused by the energy dependence of the hadronic cross sections, the secondary particle multiplicity and the primary mass (see Chap. 3). They all tend to affect a shower alike.

This category of parameters and data must be classified as *indirectly accessible, derived parameters* as they require sophisticated methods of data analysis. Chapter 10 is dedicated to this topic. Further details concerning the extraction of information on specific shower components and parameters from experimental data are discussed in the corresponding chapters of Part II.

### 2.10 Basic Shower Reconstruction Procedure

In this section we focus the discussion on the basic shower event reconstruction procedure, in particular on the methods that are commonly applied to particle detector arrays. Essentially the same method can be applied to wide-aperture atmospheric Cherenkov detector arrays. Details on optical Cherenkov detection, event reconstruction, results and data interpretation are presented in a separate chapter (Chap. 16). Likewise, event reconstruction based on data from atmospheric fluorescence measurements and radio emission detector (antenna) arrays are discussed in Chaps. 17 and 18, respectively, where a selection of data is presented.
There are many refined procedures to reconstruct the basic shower parameters from timing and particle density measurements acquired with an array (Aglietta et al., 1993). The procedures depend in detail on the array layout, the location of the trigger detectors and the trigger conditions required. Thus, they vary in general from array to array and author to author. For the standard approach see, e.g., Clark et al. (1957, 1961); Tennent (1968); Kakimoto et al. (1996); Ogio et al. (2004).

Usually, before running a full analysis on a recorded shower, certain additional criteria may have to be fulfilled by the raw data beyond the bare trigger condition to accept an event for processing. These may include, for example, the requirement that at least $k$ out of the $n$ array detectors have recorded a predefined minimum number of valid particle density measurements within a given coincidence window. In the following we outline the principle of elementary shower event reconstruction, i.e., the determination of the direction of the shower axis, the axis (core) location at ground impact, and the shower size and age on hand of a simple example (see also Chap. 8 for more details).

Consider an array consisting of $n$ particle detectors and five fast-timing array trigger detectors. One of the latter is placed at the array center, the remaining four are located equidistant from the center at the corners of a square. For simplicity let the square be oriented such that its diagonals run east–west (E–W) and north–south (N–S), as shown in Fig. 2.3, and we label the corner detectors accordingly (E, W, N, and S) and the center detector, C.

![Fig. 2.3 Example of a layout of a simple fast-timing trigger detector arrangement within a shower detection array (not drawn)](image-url)
2.10.1 Arrival Direction

The arrival direction of the shower is perpendicular to the particle disk and given by the zenith angle, $\theta$, and the azimuthal angle, $\varphi$, subtended by the shower axis with respect to a horizontal reference system at the ground. These angles are determined by the arrival time sequence (delay) of the shower front at different locations across the array; in particular, in our example by the arrival of the first particle at each of the 5 fast-timing array trigger detectors. They are obtained using the following relations:

$$\tan \varphi = -\frac{\Delta t_{N,C}}{\Delta t_{W,C}}, \quad (2.13)$$

and

$$\sin \theta = -\frac{c}{d} \frac{\Delta t_{N,C}}{\sin \varphi}, \quad (2.14)$$

where $\Delta t_{i,j}$ is the time difference (delay) [ns] of the arrival signatures between detectors $i$ and $j$ ($i = E, W, N, S; j = C$ in our example), $c$ is the speed of light and $d$ the half-diagonal of the square formed by the 4 outer trigger detectors. In other words, the zenith and azimuthal arrival directions of the axis are determined by an optimized fit of a plane to the particle arrival times recorded by the detectors and taking the perpendicular to this plane.

In more refined procedures and for large showers and arrays the shower front curvature must also be implemented in the reconstruction procedure. Since the thickness of the shower front increases with core distance, the time of the first arriving particle at a detector depends on the density, mainly of electrons, and not on muons at large core distances (Nagano, private communication, 2007). Therefore the particle disc thickness must be taken into account (see Chap. 8).

In this case in a first step the zenith and azimuthal angles, $\theta'$ and $\varphi'$, are determined by the least square method in the so-called plane front approximation where the curvature is ignored, as discussed above, imposing only the condition that

$$l^2 + m^2 + n^2 = 1, \quad (2.15)$$

where $l$, $m$, $n$ are the direction cosines. This leads to a first approximate core position (Aguirre et al., 1973; Nagano, 2007). Subsequently, the radius of curvature, $r_c$, and the disc thickness, $\Delta t$, are introduced as parameters. By successive variation, using these parameters and different sets of timing data, the zenith and azimuthal angles, $\theta$ and $\varphi$, and the core position are calculated anew until finally the errors are reduced to acceptable values. Thus, arrival direction and core location determination are not independent.

---

13 This is also valid for large showers where the particle disk manifests a curved surface.
Angular errors can be evaluated with the following expressions (Baggio et al., 1977),

\[ \delta \theta = \frac{c}{d} \sec \theta \left( \frac{\delta \Delta t_1 (\Delta t_{N,C} + \Delta t_{W,C})}{(\Delta t_{N,C} + \Delta t_{W,C})^{1/2}} \right), \]  

(2.16)

\[ \delta \varphi = \delta \Delta t \left( \frac{1}{\Delta t_{N,C}^2} + \frac{1}{\Delta t_{W,C}^2} \right)^{1/2} \sin \varphi \cos \varphi \]  

(2.17)

and

\[ \delta \sin \alpha = \left[ (\sin \theta_0 \sin \varphi \cos \theta + \cos \theta_0 \sin \theta \sin \theta) \delta \theta \right. \\
+ \left. (\sin \theta_0 \sin \theta \cos \varphi) \delta \theta \right] \cot \alpha. \]  

(2.18)

The errors for the arrival direction range from a few degrees for small arrays to less than one half of a degree for sophisticated installations (Kristiansen, 1980; Antoni et al., 2003a). In Fig. 2.4 we show as a practical example the variation of the angular resolution of the azimuthal and zenith angles of the MAKET-ANI array as a function of zenith angle (Chilingarian et al., 2007).

Depending on the direction of the shower axis with respect to the direction of the geomagnetic field, the latter must be considered to reconstruct the actual direction of initial incidence of the primary accurately.

For special analyses where the geomagnetic field is of particular importance, such as for shower asymmetry or shower radio emission studies, the angle \( \alpha \) between the shower axis and the Earth’s magnetic field direction is the relevant parameter.

**Fig. 2.4** Zenith and azimuthal angular accuracies of the shower axis direction determination as a function of the zenith angle. The example is from the MAKET-ANI experiment on Mt. Aragats, near Yerevan (Armenia). The square symbols apply to the azimuthal angles, the circular symbols to the zenith angles. The open symbols were obtained with the non-parametric method, the filled symbols are simulation results (after Chilingarian et al., 2007).
It is determined as a function of $\theta$, $\theta_0$, $\varphi$ and $\varphi_0$, where $\theta_0$ and $\varphi_0$ are the angles which define the direction of the geomagnetic field and $\theta$ and $\varphi$ the direction of the shower axis. Thus,

$$\cos \alpha = \sin \theta \sin \theta_0 (\cos \varphi \cos \varphi_0 + \sin \varphi \sin \varphi_0) + \cos \theta \cos \theta_0. \quad (2.19)$$

Further details concerning the influence of the geomagnetic field on the shower particle pattern on the ground are discussed in Chap. 8 and radio emission in Chap. 18.

### 2.10.2 Shower Core Location

Several procedures had been developed in the course of time that are all similar. The differences are essentially array related. Often a preliminary core location is determined by assuming a power law for the lateral density distribution function of the shower particles. This core position, that may initially be chosen at the location of the highest measured density, is then moved around in a fitting procedure to obtain the best fit of the particle densities, $\rho_i$, to a simplified Nishimura-Kamata-Greisen (NKG) function or some other, often empirical or experimentally determined distribution function (Greisen, 1956, 1960; Nishimura, 1967), such as

$$\rho(r) = \left( \frac{A}{r} \right) \exp\left( -\frac{r}{B} \right), \quad (2.20)$$

where $A$ and $B$ are obtained by a least-square fit method and $r$ is the distance from the shower axis. In a subsequent procedure the actual NKG function or an array specific lateral distribution function is then used to improve the fit.

Typical errors for the core location amount to a few meters for the more sophisticated particle detector arrays if the air shower core falls within the physical boundaries of the array. For large arrays such as Auger with widely spaced detectors the error can be as much as tens of meters and more.

As a more specific example for large arrays we outline the method which had been used for the Haverah Park array that is also applicable to other large arrays, such as Auger. There an empirical (experimentally measured) density distribution function (Chap. 8) of the form

$$\rho(r) = kr^{-(\eta+r/a)} = k \cdot f(r), \ [\text{ve}\mu\text{m}^{-2}], \quad (2.21)$$

had been used, where $r$ is the radial distance of the detector from the shower axis, $a$ a parameter, $k$ a scale factor, and $\eta$ the slope parameter which is a function of the zenith angle $\theta$. The expression is claimed to be valid for distances $50 \leq r \leq 800$ m from the shower axis. $\eta$ was obtained from simulations and the density $\rho(r)$ depends only weakly on $\eta$ over the relevant radial core distance range where the density had been used to estimate the primary energy ($r \approx 600$ m) (for details see Chaps. 8 and 10).
In this procedure both the core position \((x, y)\) and the shower size are fitted by comparing the measured densities with predictions from simulations, using Eq. (2.21), by minimizing \(\chi^2\) as follows,

\[
\chi^2 = \sum_{i=1}^{n} \frac{1}{\sigma_i^2} (k f(r_i) - \rho(r_i))^2,
\]

(2.22)

where \(\rho(r_i)\) are the measured densities at the location \(i\) and \(\sigma_i\) the uncertainties related to the density measurements and particle fluctuations.

By differentiating Eq. (2.22), \(k\), which minimizes \(\chi^2\), yields

\[
k = \frac{\sum f(r_i)\rho_i/\sigma_i^2}{\sum f(r_i)^2/\sigma_i^2}.
\]

(2.23)

One of the constraints on Eq. (2.22) is that the distribution of the measurement uncertainties is Gaussian. However, for small densities a Poissonian distribution is more appropriate to calculate the likelihood function. The procedure requires some further refinements to account for fluctuations and uncertainties that are array specific. For further details the interested reader is referred to the papers of Armitage et al. (1987), Ave et al. (2003), Coy et al. (1981, 1997), England (1986), and Lawrence et al. (1989, 1991).

### 2.10.3 Shower Size, Energy and Age Determination

In principle, the shower size, \(N\), is obtained by integration of the lateral density distribution. However, this procedure is intimately linked to the shower axis (core) position determination and to the fitting of the measured densities of all detectors to an NKG (or other) function of appropriate age, as outlined above, and usually executed jointly (see Chaps. 4, 8 and 10).

In particular, the shower size is determined by looking for the core position which gives the best fit determined from a minimum in normalized \(\chi^2\) to the Nishimura-Kamata (NK) function (Kamata and Nishimura, 1958) or an approximated NKG function. The calculation is then made for a series of age parameter values, \(s\), defined in Chap. 4, e.g., \(s = 0.4–1.6\) in steps of 0.1 or 0.2, and the size for the best fitted \(s\) is selected. For a reliable evaluation the shower axis must be located within the boundaries of the array.

The primary energy can then be estimated from the size-energy relation or from the energy density deposit of the particle mix in a very specific radial zone of the showers in a deep-water Cherenkov detector tank, expressed in units of vertical equivalent muons per unit area \([ve\mu m^{-2}]\). This latter method is mainly applicable to larger showers. Under appropriate experimental conditions the primary energy can also be estimated on the basis of the muon size or the so-called truncated muon size (Weber, 1997; see also Chaps. 8 and 10).
The size-energy relation was originally based on the photon–electron cascade theory which is summarized in Chap. 4. This theory shows that the shower size at maximum development is nearly proportional to the energy of the shower initiating photon or electron. However, for hadron initiated showers which account for the majority of all events, the parent nuclear cascade must be considered, too, and a full fledged air shower simulations as discussed in Chap. 20 is required to estimate the primary energy from the experimentally determined shower size reliably. This applies even more so to the second method mentioned above, the estimation of the primary energy from the local energy density contents of a shower.

The primary energy determination of air showers is discussed in detail in Chap. 10 (see also Goorevich and Peak, 1975; Takeda et al., 2003; Ave et al., 2003; and Chap. 11). For practical applications a conversion factor is frequently used that is obtained from air shower simulations. This factor depends on the altitude of the observation level where the shower size measurement was made and on the zenith angle of the event. Obviously, different calculations yield somewhat different numerical values, however, the deviations are not very large because the result hinges heavily on the well known photon–electron cascade theory.

As a thumb rule adequate for rough primary energy estimates one can use the following conversion factors: $\approx 1$ GeV per shower particle for near vertical showers at an altitude of 5,000 m, $\approx 3$ GeV per particle at 2,500–3,000 m and $\approx 10$ GeV per particle at sea level (see also Aglietta et al., 1999). These values apply to smaller size showers ($10^{14}$–$10^{15}$ eV). For showers of larger size (higher primary energy) the conversion factor in the lower atmosphere must be reduced by about a factor of two to three because the distance between the observer and the shower maximum is reduced, i.e., because the shower maximum moves to greater atmospheric depth.

Folding the particle density distribution of simulated showers with the detector array and detector response, using the density fluctuations (Chaps. 8 and 19) derived from the lateral distribution of real showers, one can obtain the approximate overestimation of the shower size for an underestimated value of $s$, and vice versa. With the help of simulations one can also estimate the core position error, which depends on the shower size, the number of detectors and the geometry of the array.

### 2.10.4 Array Acceptance and Detection Efficiency

The shower acceptance and the detection efficiency of a particle (or air Cherenkov photon) detector array as a function of shower size, zenith angle and core location depend on many factors and must be carefully explored. This is usually achieved with the help of Monte Carlo simulations of showers, convoluted with the array detector layout and detector response. Cranshaw et al. (1958) and Clark et al. (1961) developed the method initially in connection with the shower size determination (see also the procedures described by Bell et al., 1974; Chiba et al., 1991, 1992; Amenomori et al., 1990, 1993; Chiavassa et al., 2005). Primarily the detection efficiency depends on the array layout, above all on the percentage of detector coverage.
As an example, for the primary energy (or shower size) dependence of the detection efficiency we show in Fig. 2.5 the predicted response of the MAKET-ANI array on Mt. Aragats near Yerevan (Armenia), which is located at an altitude of 3,250 m a.s.l. (695 g cm$^{-2}$), as a function of primary energy from a simulation of Chilingarian et al. (2007).

Another example showing the simulated detection efficiency of the particle detector array of the University of Kiel at Pic du Midi in France (2,860 m a.s.l., 729 g cm$^{-2}$) as a function of radial distance of the shower axis from the designated array center is displayed in Fig. 2.6. This rather small and simple array consisted of 13 scintillation detectors of area 0.25 m$^2$ each. The layout is shown in Fig. A.27.

A very different example is illustrated in Fig. 2.7 which shows the detection efficiency of the far more elaborate and much larger Akeno array as a function of shower age, $s$, for different shower sizes (Nagano et al., 1984). The array configuration to which this efficiency plot applies is illustrated in Fig. A.5.

The errors and uncertainties adhering to the directly measured observables of a shower affect any subsequently derived indirect observable and the interpretation of an individual event as well as the conclusions drawn for an entire set of

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**Fig. 2.5** Predicted detection efficiencies obtained from simulations of the MAKET-ANI shower array on Mt. Aragats (Armenia) for light (p, He) and heavy (Si, Fe) primary initiated air showers as a function of primary energy. The filled symbols apply to a shower selection criterion for shower sizes $N_e \geq 10^5$, and zenith angles $\theta \leq 30^\circ$, the open symbols for $N_e \geq 10^6$, and zenith angles $30^\circ \leq \theta \leq 45^\circ$ (after Chilingaria et al., 2007)

**Fig. 2.6** Example of array shower detection efficiency as a function of core location from the array center of the Pic du Midi array (see Fig. A.27, for layout; Böhm and Steinmann, 1979). The curve labeled $W(r)$ shows the theoretical efficiency whereas curve $G(r)$ represents the efficiency if in addition a core position error is included

**Fig. 2.7** Example of core location from the array center of the Pic du Midi array (see Fig. A.27, for layout; Böhm and Steinmann, 1979). The curve labeled $W(r)$ shows the theoretical efficiency whereas curve $G(r)$ represents the efficiency if in addition a core position error is included.
Fig. 2.7 Trigger efficiency as a function of shower age for different shower sizes calculated for the Akeno array layout shown in Fig. A.5 (after Nagano et al., 1984)

events (e.g., the determination of the primary energy spectrum). Consequently, the accuracy of the shower size reconstruction is of fundamental importance for many subsequent steps and must be investigated carefully for every air shower experiment.

The accuracy of the computed shower size depends above all on the recorded particle densities and the number of measured density samples. This implies that it depends on the shower size itself and the array parameters, such as the number and area of the shower detectors and the array layout. In Fig. 2.8 we show the reconstruction uncertainty as a function of shower size for the KASCADE experiment (Antoni et al., 2003a) as it was evaluated on the basis of simulations using the CORSIKA program system, including the detector responses (Antoni et al., 2003b; for KASCADE-Grande see Glasstetter et al., 2003, 2005).

Fig. 2.8 Reconstruction uncertainty of the shower size determination for the KASCADE array as obtained for showers simulated with the CORSIKA program, including detector response (Antoni et al., 2003b). The array layout is shown in Fig. A.22
2.11 Detector Response to Air Shower Particles and Transition Effects

2.11.1 Introductory Comments

A wide variety of detectors had been used in cosmic ray air shower studies, such as Geiger counters, ionization chambers, proportional counters, solid and liquid scintillation detectors, water and air Cherenkov detectors, spark and discharge chambers, transition radiation detectors, time projection chambers and even cloud chambers. In addition combinations of modern electronic detectors are being used in sophisticated calorimeters to analyze the shower cores as well as optical detectors to record atmospheric Cherenkov radiation and air fluorescence associated with air showers. The different particle detectors do not respond alike in similar applications because of transition effects that may occur within the detector media and enclosures.

Solid plastic and to a lesser extent liquid scintillators are the most frequently used particle detectors in air shower work because of their fast response, relative linearity, wide dynamic range, high signal to noise ratio, long life, low cost, easy handling, dependable and unproblematic operation. They are used primarily as shower detectors in two different modes of operation.

In conjunction with fast timing circuits and operated at a low threshold level scintillation detectors can be used for arrival time and direction determination. On the other hand, if provided with wide dynamic range circuits they can be used for particle density measurements to determine the lateral distribution (or structure) function, shower age, size, core location and other shower characteristics. In addition there are many other applications in more sophisticated apparatuses, such as muon telescopes, hadron calorimeters, etc.

Signal to noise is inferior in very thin scintillators as compared to thick ones. On the other hand transition effects increase with increasing scintillator thickness, particularly near the shower axis, where the average energy of the particles is high. Thick scintillators are more subject to contributions from electron–photon cascades developing within them and from nuclear interactions of hadrons that are abundantly intermixed with the electromagnetic and muonic components in the vicinity of the shower core. As a result, the relationship between the true particle density and the output pulse height of a thick scintillation detector has a stronger dependence on the energy of the traversing particles than a thin detector and, because of the shower properties, also manifests a dependence on core distance and shower age.

Gas filled detectors are much less subject to transition effects because of the much lower density of the detector medium. There, the main concern is the wall thickness of the envelope of the detector which can cause transition effects. In cloud chambers direct observation of the tracks excludes many of the uncertainties but there are other inherent problems that limit the usefulness of this detector type. Thus, the same measurement made with different detectors may yield different results.

In order to compare a specific kind of data acquired by different air shower arrays, instrumental as well as array layout differences must be properly accounted for besides differences in altitude and the geomagnetic location of the various sites.
This is of particular importance when attempting precision measurements or for studying more subtle topics, such as the kink in the primary spectrum and other aspects.

Numerous authors have compared the response of different detectors under similar or identical conditions in air showers at different core distances and altitudes, and have carried out detector calibrations at accelerators. We present a brief summary of some of this work below to illuminate the significance of the problem. For details concerning particle detectors and their properties the reader is referred to the special literature (Allkofer, 1971; Grupen, 1993; Grupen and Schwartz, 2005, 2008; Leo, 1994; Kleinknecht, 1992, 1998; Rao and Sreekantan, 1998; Sokolsky, 1989).

2.11.2 Comparison of Detector Responses

Early work on this topic had been carried out by the Tokyo group at sea level\textsuperscript{14} (Fukui et al., 1960). These authors have made a comparison between a tightly packed thin neon hodoscope consisting of 2 cm diameter cylindrical neon tubes that are oriented with their axis in vertical direction and a 4.5 cm thick scintillator. The result is shown in Fig. 2.9. Saturation effects in a hodoscope with this tube diameter begin to appear at distances of $\leq 1$ m from the shower axis in showers of size $10^6$.

As an example, we show in Fig. 2.10 the photograph of the hodoscope light pattern of a typical single-core shower of size $10^6$ from the work of Fukui et al. (1960).

Similar work was undertaken by the Sydney group, also at sea level, but using different kinds of detectors (Bray et al., 1965). These authors have compared the response of a 10 cm thick \textit{plastic scintillation detector} with that of a \textit{cloud chamber} and a \textit{Geiger counter tray}.

Two sets of data are presented of their work. The first shows the ratio of the particle density in the scintillator as determined from its photomultiplier pulse height to that actually observed in the cloud chamber obtained by track counting, as a function of distance from the shower axis.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{Fig_2.9}
\caption{Ratio of particle densities estimated with a neon hodoscope with 2 cm tube diameter and a 4.5 cm thick scintillation detector in showers of size $10^6$ as a function of distance from the shower axis at sea level (Fukui et al., 1960)}
\end{figure}

\textsuperscript{14} The altitude is relevant because of the energy of the particles.
of scintillator particle density. One set of data applies to the arrangement where the chamber is located directly beneath the scintillator, the other with the chamber on its side, 1 m apart. The results are shown in Fig. 2.11.

The other set of data by the same authors illustrates the core position and shower size dependence of the ratio of scintillator particle density measurements (pulse height) to Geiger tray measurements (number of hits in tray). The Geiger tray had been calibrated separately in earlier measurements. The data are shown in Fig. 2.12 together with results obtained by Kerschenholz et al. (1973) under similar conditions but for a scintillator thickness of only 5 cm.

The increase of the ratio with increasing shower size at a fixed core distance, and the decrease with increasing core distance for a constant shower size are evident. This behavior is in accordance with expectations mentioned above. However, saturation effects in the Geiger tubes, not discussed in this paper, could over emphasize the increase of the ratio at close proximity of the shower axis. The same authors

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**Fig. 2.10** Photograph of a neon tube hodoscope displaying the center of a core of a shower of size $10^6$. The hodoscope measures 2 by 3.5 m and consists of 5,040 tightly packed neon tubes measuring 2 cm in diameter (Fukui et al., 1960)

**Fig. 2.11** Average ratio of charged particle density measured with a 10 cm thick plastic scintillation detector, $\rho_{sc}$, to cloud chamber density, $\rho_{cc}$, at sea level, plotted as a function of scintillator density. The solid curve, 1, is for the cloud chamber placed 1 m from the scintillator, the dashed curve, 2, for the cloud chamber directly beneath the scintillator (Bray et al., 1965)
Fig. 2.12 Average charged particle density ratio of plastic scintillation detectors, $\rho_{sc}$, to Geiger counters, $\rho_{GM}$, versus core distance for showers of different sizes at sea level. The data points of Bray et al. (1965), ◦, •, △ and □, were obtained at Sydney with a 10 cm thick scintillator, those of Kerschenholz et al. (1973), ▽, at Yakutsk with a 5 cm thick scintillator have also studied the effect of lead shielding over the counters and the resulting energy dependence.

Similar measurements comparing scintillators with spark chambers were carried out by Kawaguchi et al. (1971) in Tokyo and Dake et al. (1971) at Mt. Norikura, using scintillators of different thickness. A compilation of their results covering a wide range of core distances and different shower size groups is presented in Fig. 2.13. Additional specifications concerning the measurements are given in the caption.

As an example for a very thick liquid scintillator (30 cm) we present the work of Chudakov et al. (1979), carried out with one of the Baksan detectors. Here the comparison is made with Geiger counters (Fig. 2.14).

A comparison between scintillators only of very different thickness (3 and 50 mm) was made by Hara et al. (1979, 1981) at the Akeno site (Japan). Their measurements at large distances were made with larger showers than those at close proximity, as indicated. The data of Kawaguchi et al. (1971), ◦, •, were obtained in Tokyo (I.N.S.) at sea level with a 5 cm thick scintillator, those of Dake et al. (1971), △, at Mt. Norikura (750 g cm$^{-2}$) with a 3.5 cm thick scintillator. At distances $\geq 10$ m from the axis both scintillator and spark chamber record the same densities up to about 4,000 particles m$^{-2}$
Fig. 2.14 Ratio of particle density determined with a 30 cm thick liquid scintillation detector, \( \rho_{\text{lsc}} \), and Geiger counters, \( \rho_{\text{GM}} \), as a function of core distance, after Chudakov et al. (1979), at Baksan (840 g cm\(^{-2}\)), showing dramatic transition effects in the vicinity of the shower axis.

Results, shown in Fig. 2.15, are compared with theoretical lateral density distributions.

Very comprehensive work was carried out by Blake et al. (1975, 1978a, 1979) and Towers (1971). These authors have compared density measurements made with a liquid paraffin scintillation detector, a tray of unshielded flash tubes, a 1.2 m deep water Cherenkov detector and a muon (shielded scintillation) detector with a threshold of 0.3 GeV as a function of core distance, in a select group of well defined showers (Blake et al., 1978a). The data are presented in Fig. 2.16. Density ratios

Fig. 2.15 Lateral density distribution of electrons measured with a 3 mm, \( \times \), and a 50 mm, \( \circ \), thick plastic scintillation detector at the Akeno site (930 g cm\(^{-2}\)). The transition effects of the electromagnetic component in the thick scintillator are clearly seen within 30 m from the shower axis. The solid (1) and dashed (2) curves represent an NKG-functions with a single age parameter, \( s = 1.0 \) and 1.1, respectively (Hara et al., 1981). The large fluctuations in the thin scintillator are evident. Note that the density along the ordinate is multiplied by the core distance to compress the graph.
are given in Fig. 2.17 (Blake et al., 1975, 1978a; Towers, 1971). Theoretical energy loss distributions for muons passing through a scintillator are shown in Fig. 2.18 and distribution parameters as a function of muon momentum are given in Fig. 2.19 (Blake et al., 1979).

More recently the problem of transition effects in thin absorbers and plastic scintillators had been studies by Asakimori et al. (1979, 1986) and Asakimori (1988). The measurements were carried out with an arrangement of two plastic scintillators, one located above the other and separated by 10 cm. Scintillators of different thicknesses were used, ranging from 0.3, 1 and 3 cm for the upper, and 2 and 5 cm for the lower. The ratio of the particle densities in the two detectors (\( \rho_{\text{lower}}/\rho_{\text{upper}} \)) were measured for different combinations of scintillator thicknesses, for showers of different size groups in the age range \( 0.8 \leq s \leq 1.4 \) and zenith angles less than 30°, as a function of core distance. Typically three measurements were carried out for one set of detectors; (a) no shielding, (b) 1 mm of iron and (c) 5 mm of iron in between the two scintillators. Some of their results are presented in Fig. 2.20.

A comparison between the results of Asakimori et al. (1986) discussed above and those of other authors is shown in Fig. 2.21. Included are the density ratios between

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**Fig. 2.16** Comparison of the response of various detectors to showers with zenith angles \( 0° \leq \theta \leq 25° \) and \( \rho(500) = 1.2 \, \text{ve}\mu \text{m}^{-2} \) at Haverah Park (1.018 g cm\(^{-2}\)), i.e., for showers that yield a signal corresponding to a vertical equivalent muon density (ve\( \mu \)) of 1.2 m\(^{-2} \) in the 1.2 m deep water Cherenkov detector located at a distance of 500 m from the shower axis (Blake et al., 1978a). These showers are initiated by primaries having an energy of approximately \( 4.7 \cdot 10^{17} \text{eV} \). \( \rho_{\text{ls}} \) (○) refers to an unshielded liquid paraffin scintillation detector of thickness 8 g cm\(^{-2} \), \( \rho_{\text{ft}} \) (▲) to unshielded flash tubes, \( \rho_{\text{Ch}} \) (△) to the 1.2 m deep water Cherenkov detector, and \( \rho_{\text{sc}} \) (•) to a plastic muon (shielded) scintillation detector with threshold 0.3 GeV (construction details of the detectors are given in Blake et al., 1978b).
Fig. 2.17 Density ratio versus core distance for two different pairs of detectors, derived from the data presented in the previous figure (Fig. 2.16). (a) Shows the density ratio of an 8 g cm$^{-2}$ liquid scintillation detector, $\rho_{sc}$, to unshielded flash tubes, $\rho_u$, for showers with $\rho(500) = 0.58$ ve$\mu$ m$^{-2}$ (vertical equivalent muons m$^{-2}$) ($E_0 \simeq 2.2 \cdot 10^{17}$ eV) and zenith angles $0^\circ \leq \theta \leq 25^\circ$, $\Delta$ (Blake et al., 1975, 1978a). (b) Shows the ratio between a 1.2 m deep water Cherenkov detector, $\rho_{Ch}$, and the same liquid scintillator as in (a), $\rho_{sc}$, for showers with $\rho(600) = 0.18$ ve$\mu$ m$^{-2}$ ($E_0 \simeq 1.25 \cdot 10^{17}$ eV). The experimental points, $\bullet$ (Blake et al., 1978a) and $\circ$ (Towers, 1971) as well as curve A are for zenith angles $0^\circ \leq \theta \leq 25^\circ$. Curves B, C and D are for $25^\circ \leq \theta < 35^\circ$, $35^\circ \leq \theta < 45^\circ$ and $45^\circ \leq \theta < 55^\circ$, respectively, and $\rho(600) = 0.19$ ve$\mu$ m$^{-2}$, corresponding to a primary energy of $E_0 \simeq 1.3 \cdot 10^{17}$ eV.

10 cm thick scintillators and Geiger-Mueller counters (Bray et al., 1965), two 10 cm thick scintillators, one above the other with a 1/8 inch iron plate in between (Bakich et al., 1970), and spark chambers with unshielded scintillators of different thickness underneath (Shibata et al., 1965, 4.5 cm scintillators; Dake et al., 1971, 3.5 cm; Hara et al., 1970a, 1979, 0.3 and 5 cm).

### 2.11.3 Response of Deep Water Cherenkov Detectors

The response of the so-called Haverah Park type deep water Cherenkov detectors, originally developed at the Imperial College, London (Allan et al., 1960, 1962; Lillicrap et al., 1963), is of some interest because about 1,600 units of this type of detector are now being used in the Auger experiment (Auger Observatory) in Argentina as surface detectors (Suomijärvi, 2007; Ghia, 2007), in an analogous way.
**Fig. 2.18** Energy loss distribution of muons passing through 9.2 g cm\(^{-2}\) of scintillator, according to Monte Carlo calculations by Blake et al. (1979). The distributions (a), (b), (c) and (d) apply to muons having momenta of 0.12, 0.7, 6 and 30 GeV c\(^{-1}\), respectively. The enhanced energy loss of low energy muons and the extent of fluctuations are evident.

**Fig. 2.19** Distribution parameters of energy loss, \(\Delta E\), of muons passing through 9.2 g cm\(^{-2}\) of scintillator versus incident muon momentum, according to calculations of Blake et al. (1979) (cf. Fig. 2.18). In figure (a), curve 1 (○) represents the mean energy, \(\langle \Delta E \rangle\), in MeV, deposited in the scintillator, and curve 2 (●) is the standard deviation, \(\sigma\). In figure (b), curve 3 (▽) is the coefficient of skewness, \(S_3\), and curve 4 (♦) is the coefficient of kurtosis, \(S_4\).
2.11 Detector Response to Air Shower Particles and Transition Effects

Fig. 2.20 Average ratio of the response of two horizontal scintillators of 5 cm thickness (density $1.05 \text{ g cm}^{-3}$) and area $0.25 \text{ m}^2$, located one above the other and separated by 10 cm, as a function of core distance for showers of size $\geq 7 \cdot 10^4$ and zenith angles $\leq 30^\circ$. ●, no absorber; ●, 1 mm of iron and, □, 5 mm of iron in between scintillators (Asakimori et al., 1986)

Fig. 2.21 Comparison of particle density ratios measured with scintillation, $\rho_{\text{scint}}$, and other kinds of detectors, $\rho_{\text{other}}$, as a function of distance from the shower axis: ○ Bray et al. (1965), ● Bakich et al. (1970), ○ Shibata et al. (1965), □ Hara et al. (1970a), ■ Dake et al. (1971), ▼ Asakimori et al. (1986) and Asakimori (1988) (after Asakimori et al., 1986). For details see text

as they had been used decades before at the Haverah Park experiment in England (Wilson et al., 1963).

This kind of detector yields an output signal that is related to the sum of the Cherenkov light produced by the local particle mix in the shower that strikes the water tank. Thus, only those particles whose velocity exceeds the Cherenkov threshold velocity in water contribute to the detector output signal (see Table B.9). The bulk of the electromagnetic component is usually completely absorbed in the first few ten centimeters of the water column unless the shower core happens to hit it directly, which is in general a rare exception. The relative contribution of the different shower constituents, mainly the electromagnetic and muonic components, depends on the radial distance of the detector from the shower axis. At larger distances it is chiefly the muon component that produces the bulk of the signal.

In Fig. 2.22 we show the mean response of such a detector for vertically incident photons, electrons and muons as a function of energy from a simulation of Ave et al. (2003). Very low energy electrons are absorbed in the lid of the tank, whereas energetic muons penetrate the tank and deposit $\approx 240 \text{ MeV}$. The response of this detector, in particular the energy deposit recorded at distances around $600 \text{ m}$ from
the shower core is an approximate measure of the primary energy of large showers ($E_0 \geq 10^{17}$ eV). Simulations show that this observable is relatively independent of primary mass and hadronic interaction model. Further details related to lateral density and timing measurements of shower particle and the relation of the detector response in showers with respect to primary energy estimation are discussed in Chaps. 8 and 10.

### 2.11.4 Response of Plastic Scintillation Detectors

The response of plastic scintillation detectors as they had been used for the Akeno and AGASA experiments in Japan (thickness 5 cm) and at many other sites with respect to the different kinds of particles that are present in air showers had been investigated by the AGASA group (Nagano et al., 1984, 1992, 2000; Yoshida et al., 1994; Hayashida et al., 1994, 1999; Sakaki et al., 2001a, b, Takeda et al., 2003). Their study was based mainly on simulations but was also cross checked by experiment. The more recent work was mainly based on the program package GEANT 3.21.

The results are presented in Figs. 2.23, 2.24 and 2.25. The plots show for a wide range of particle kinetic energies and photon energies and for particles traversing the scintillator under different zenith angles, as specified by sec $\theta$, the detector signal output expressed in equivalent vertically traversing single minimum ionizing particles.
**Fig. 2.23** Simulated distribution of energy deposit in a standard AGASA type scintillation detector by gamma rays incident at different zenith angles, as specified by sec $\theta$. The energy deposit is converted to particle number, using the standard pulse height produced by a single vertically traversing minimum-ionizing particle (Sakaki et al., 2001a)

![Gamma Ray Energy Distribution](image1)

**Fig. 2.24** Simulated distribution of energy deposit in a standard AGASA type scintillation detector by electrons incident at different zenith angles, as specified by sec $\theta$. The energy deposit is converted to particle number, using the standard pulse height produced by a single vertically traversing minimum-ionizing particle (Sakaki et al., 2001a)

![Kinetic Energy Distribution](image2)

**Fig. 2.25** Simulated distribution of energy deposit in a standard AGASA type scintillation detector of muons incident at different zenith angles as specified by sec $\theta$. The energy deposit is converted to particle number, using the standard pulse height produced by a single minimum-ionizing vertically traversing particle (Sakaki et al., 2001a)

![Muons Energy Distribution](image3)
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