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Detection of extensive cosmic air showers by small scintillation detectors with wavelength-shifting fibres

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Abstract

A set of three small scintillation detectors was employed to measure correlated events due to the passage of cosmic muons originating from extensive air showers. The coincidence rate between (any) two detectors was extracted as a function of their relative distance. The difference between the arrival times in three non-aligned detectors was used to reconstruct the orientation of the shower axis.

(Some figures may appear in colour only in the online journal)

1. Introduction

Primary cosmic particles—in most cases high-energy protons or light nuclei—interact with the Earth's atmosphere, producing extensive air showers composed of many secondary particles. A large fraction of the most penetrating charged component of air showers, the muons, is able to traverse the atmosphere and arrive at sea level. An extensive air shower may contain a large number of muons, N_μ, depending on the energy E of the primary particle; it scales roughly as $N_\mu \sim E^\alpha$, where the exponent α is slightly smaller than 1. Thus, while for low-energy showers, of the order of 10^{12} eV, the number of muons is about 10, this number may reach several millions for the highest primary energies. These secondary particles are spread over an area that increases with the energy of the primary, exceeding 1 km^2 for the highest-energy events.

While a single detector for cosmic muons is able to measure the arrival of individual particles, the coincident arrival of two or more muons on different detectors, located some distance apart, signal the detection of an extensive air shower. The first evidence for the existence of such showers was reported in the 1930s by Auger and collaborators [1], who observed that even detectors separated by a hundred metres were able to produce coincident events, although with a very low probability. The coincidence rate between two far detectors, normalized to the effective area of the two detectors, as a function of their relative distance, is called a decoherence curve. Its detailed shape depends on the lateral profile of the shower, which in turn is the result of the physical mechanisms (hadronic and electromagnetic processes, decays, etc) which contribute to the development of the shower in the atmosphere.

Large experiments devoted to the study of high-energy cosmic rays are based on the combined use of several detectors, constituting what is called an array. The largest existing experiment is presently—and for years to come—the Pierre Auger Observatory located in Argentina [2]. It is a 'hybrid' detector, since it already includes an array of surface detectors, with about 1600 large Cerenkov water tanks, located at 1.5 km relative distance, and four fluorescence telescopes, able to track the development of air showers by the ultraviolet light emitted in the atmosphere, with several on-going upgrade activities concerning underground muon counters, additional fluorescence telescopes and a prototype radiotelescope array. By a proper trigger selection of the coincident events among several detectors, the experiment is able to reconstruct the highest energy showers ever observed. The study of extensive air showers by large arrays of detectors located worldwide is addressing many of the open problems in this field: the existence of a cut-off energy, the mass distribution of the highest-energy particles and their origin and acceleration mechanisms.

While the investigation of such frontier problems in cosmic-ray physics requires the use of huge arrays, the identification of the arrival of a shower in a set of detectors, or the study of its basic properties, may be carried out even by smaller detection setups, and constitutes an advanced educational activity for high school, undergraduate or postgraduate (master's) physics curricula. Several educational arrays for cosmic rays have been designed and are operational worldwide [3]. Most of them, such as the ALTA [4], SEASA [5], CHICOS [6] or HisPARC [7] projects, make use of small- or medium-sized scintillators, arranged in detection stations which usually include from two to four detectors operated in coincidence. Each station collects data which are time-stamped by a GPS device, so that off-line correlation between the stations may be used to identify the detection of a high energy extensive air shower. More recently, the Extreme Energy Events (EEE) project was started, involving several tens of high-school teams in the construction and operation of cosmic ray telescopes based on the technology of multigap resistive plate chambers [8]. Such telescopes have the advantage of being able to reconstruct the muon orientation with a high angular resolution.

In a previous paper [9] we discussed how to introduce the basic concepts of extensive air showers to undergraduate or high-school students, involving them in simple analyses of simulated data, which were made accessible to the users. In this paper we want to describe some results obtained with a detection setup based on small scintillation detectors with wavelength-shifting (WLS) fibres, operated in coincidence. The properties of such detectors, together with a study of the shielding effects provided by building on the measured angular distributions have already been reported [10]. A set of additional measurements have now been carried out, searching for two- and three-fold coincidence events from the detectors located at various distances. This activity allowed us to measure the coincidence rate as a function of the relative distance between two detectors, the distribution of the time difference between the arrival of individual muons in the detectors, and to reconstruct the orientation of the incoming shower by a triangulation analysis of the arrival times in three non-aligned detectors.

The advantage of using a small setup is that of providing a suitable activity for the undergraduate physics laboratory at a reasonable cost, while giving access to quantitative

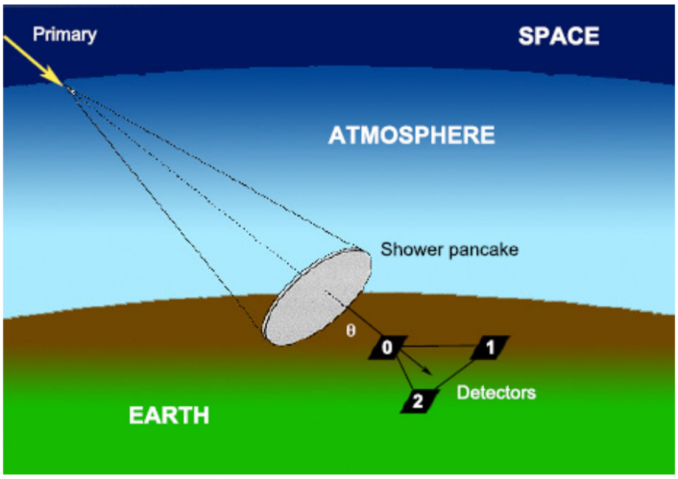

Figure 1. A cosmic shower initiated by a high energy primary particle propagates in the atmosphere reaching two or more detectors located some distance apart at ground. The difference in the arrival times in the detectors allows us to reconstruct, by triangulation, the arrival direction of the shower.

investigations in cosmic-ray physics. The physics outcome and the learning potential are expected to be high, since the students may be involved in understanding the basic properties of extensive air showers, in the installation and operation of the detectors and of the associated electronics and data acquisition, as well as in the data analysis and interpretation. The setup described here may further constitute a basic element for a future array incorporating a few similar stations.

2. Detection setup

The detection setup employed in the present investigation makes use of small plastic scintillator tiles (15 cm $\times$ 15 cm, thickness 1 cm) with a two-coil WLS optical fibre embedded in a circular groove machined in the scintillator. The detailed description of the individual detection modules was reported in a previous paper [10]. To detect coincident events due to the simultaneous passage of cosmic muons in the scintillators, we used two or three such modules, placed on the same horizontal plane and operated in coincidence by means of a Quarknet acquisition card [11]. Such a card may accept up to four signals from photomultipliers or other detectors, and provides discriminator and trigger logic for the four channels. In addition, the relative time between the individual inputs is also available, with 1 ns precision, allowing us to carry out measurements of the rise and fall times of each input signal. The output stream from the card was sent to a PC via a USB and hyperterminal connection, producing a set of ASCII lines which were decoded off-line to extract all the relevant information for the collected events. More details on the performance of these detectors and on the acquisition setup are reported in [10].

3. Experimental results

3.1. Two-fold coincidences

Muons belonging to the same atmospheric shower are predicted to lie in a ‘pancake’ whose thickness in the arrival time is a few hundreds of nanoseconds (figure 1). However, most of

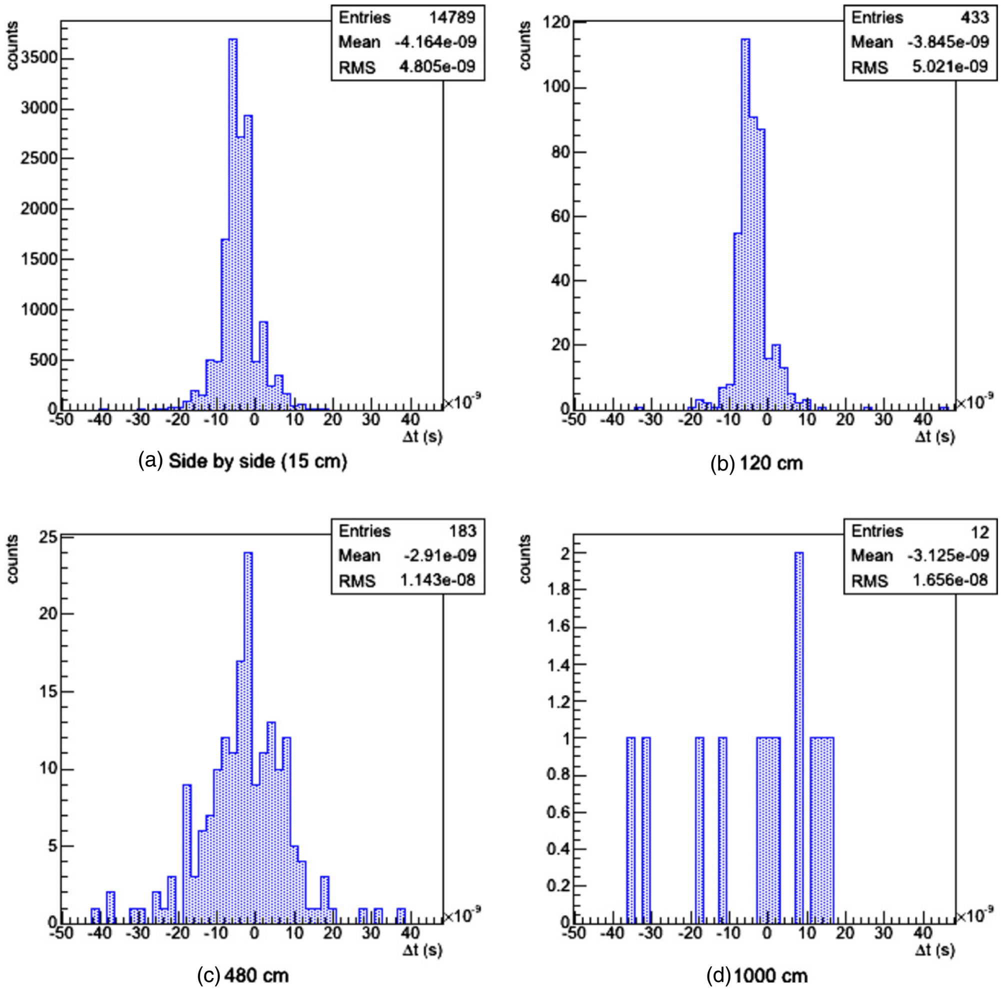

Figure 2. Spectra of the time difference in the arrival times of particles in two detectors separated by 15, 120, 480 and 1000 cm, respectively. The small shift from zero is simply due to a difference in the cable length between the two channels. The RMS of the distributions increases with the separation between the detectors.

them are actually very close to each other (in the order of a few ns), so that the difference in the arrival times in two far detectors is mostly due to the inclination of the shower with respect to the plane in which the detectors lie.

A first set of measurements was carried out by placing two detectors at increasing relative distances, from 15 cm (detectors close to each other) to about 10 m; the coincidence rate as a function of the distance and the spectrum of the time differences between the arrival of the signals in the two detectors were measured. Figure 2 shows the time-difference spectra obtained at various distances. In all cases the centroid of the distribution is shifted a few ns from zero, simply due to the different cable length in the two channels. When the detectors are moved to larger relative distances, an increase in the width of the time distribution is expected, since the spread in the difference in the arrival times to the two detectors, due to shower

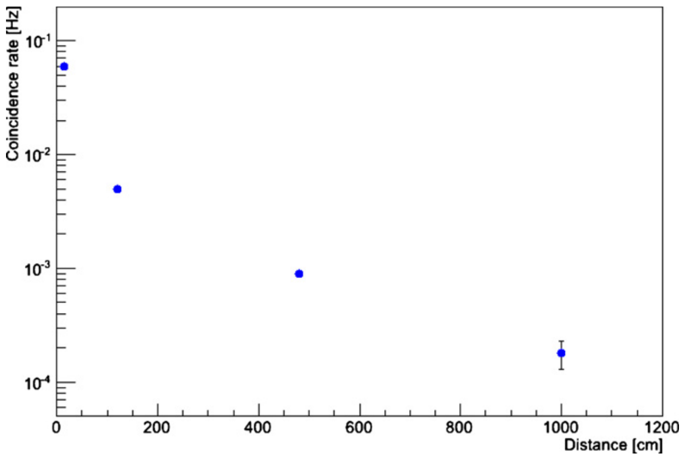

Figure 3. Coincidence rate measured between two detectors as a function of the separation distance.

Table 1. Coincidence rate and approximate number of expected events per day as a function of the relative distance between the two small scintillators.

Relative nominal distance (cm)	Coincidence rate (Hz)	Expected no of events/day
15	$(600 \pm 5) \times 10^{-4}$	5200
120	$(50 \pm 2) \times 10^{-4}$	430
480	$(90 \pm 7) \times 10^{-5}$	75
1000	$(18 \pm 5) \times 10^{-5}$	16

orientation, depends on such distance. It is seen that the RMS of the distribution increases from about 4–5 ns (when the detectors are very close or separated by about 1 m) to about 11 ns at a relative distance of about 5 m and about 17 ns at 10 m. Such values incorporate both the intrinsic time resolution of the detectors and the associated electronics, as well as the spread in the arrival time of the secondary cosmic particles to the two detectors, which increases with the distance.

Table 1 reports the coincidence rate between two detectors as a function of their relative distance. Due to the individual count rate of each detector (less than 10 Hz) and the coincidence time window (50 ns), the expected spurious coincidence rate is smaller than one event per day. Except for the last measurement carried out at 10 m, the spurious rate is almost negligible with respect to the number of true correlated events. In principle it would be possible to go to even larger distances, although this would require very long experimental runs. The data from table 1 are also plotted in figure 3 to show the decreasing trend of the coincidence rate with the separation distance.

This is the result of the convolution of the lateral profile of an extensive air shower, of the relative abundance of the various secondary particles at the sea level (especially electrons and muons), which in turn depends on the energy of the primary particle, and of the specific environment surrounding the detectors. This last aspect is particularly important in our setup, since electrons, although less abundant than muons, and possessing an average energy much smaller with respect to that of muons, may produce electromagnetic cascades in the concrete roofs under which the detectors are located. A small fraction of the particles produced in these cascades may then result in short distance correlations between two particles, thus contributing to the increase of the coincidence rate at very small relative distances. The detailed study of such effects, however, would require the combined use of extensive air shower simulations by professional codes (for instance, CORSIKA [12] or COSMOS [13]), and the propagation of all secondary particles arriving at the sea level in the detailed structure of the building which contains the detectors.

3.2. Three-fold coincidences and the triangulation method

At least three detectors are needed to carry out a simple triangulation measurement. As sketched in figure 1, the difference between the arrival times of muons belonging to the same shower is related to its inclination with respect to the plane determined by the three detectors. Simple mathematical steps are needed to make this relation explicit:

$$A = \frac{d_2 - d_1 \frac{y_2 - y_0}{y_1 - y_0}}{(x_2 - x_0) - (x_1 - x_0)\frac{y_2 - y_0}{y_1 - y_0}},$$

$$B = \frac{d_2 - d_1 \frac{x_2 - x_0}{x_1 - x_0}}{(y_2 - y_0) - (y_1 - y_0)\frac{x_2 - x_0}{x_1 - x_0}},$$

$$A = \cos\vartheta \sin\varphi,$$

$$B = \cos\vartheta \cos\varphi,$$

where (x_i, y_i) are the positions of the ith detector $(i = 0, 1, 2)$, $d_1 = c(t_1 - t_0)$, $d_2 = c(t_2 - t_0)$, t_0, t_1, t_2 are the arrival times of the muon at the ith detector, c is the speed of muons (here assumed to be equal to that of light), and (θ, φ) is the axis direction of the incident shower. With three detectors, two relative time differences, $(t_1 - t_0)$ and $(t_2 - t_0)$, are measured. With four or more detectors redundant information would be available, thus allowing more precise measurements. Different approaches could be used in this latter case, leading, however, to similar formulae.

Three detectors were employed to carry out these measurements. They were placed at the corners of an equilateral triangle of 5 m side. All two- and three-fold coincidence events were stored, while in the analysis procedure only three-fold coincidences were used for triangulation calculations. The three-fold coincidence rate is relatively low, and about 10 days were required to gather approximately 200 events. Figure 4 shows the zenithal and azimuthal distributions of the shower axis, as reconstructed by the triangulation method described above. To take into account the influence of the time resolution on the reconstructed shower orientation, the relative time differences between the detectors were randomized several times around their measured value and the average value of the obtained distribution was used as an estimate of the effective angle. Uncertainties in the reconstructed zenithal angle were evaluated to be around 6°–8°.

The azimuthal distribution of the secondary muons is expected to be flat, apart from a slight east–west asymmetry. An indication for an east–west asymmetry in cosmic rays was found in the 1930s, showing an excess of the intensity from the west, due to an excess of positively charged particles in the primary radiation and to the Earth's magnetic field. The shape of our detectors (in such a case being square) and their relative orientation and shielding effects due to the presence of a concrete building around the detection setup [10] may partly modify the effective angular distribution of the secondary muons, hence the reconstructed distribution of the shower. As seen in figure 4 (right), the azimuthal distribution of the shower axis shows some fluctuations around an average value, which could be due to such effects.

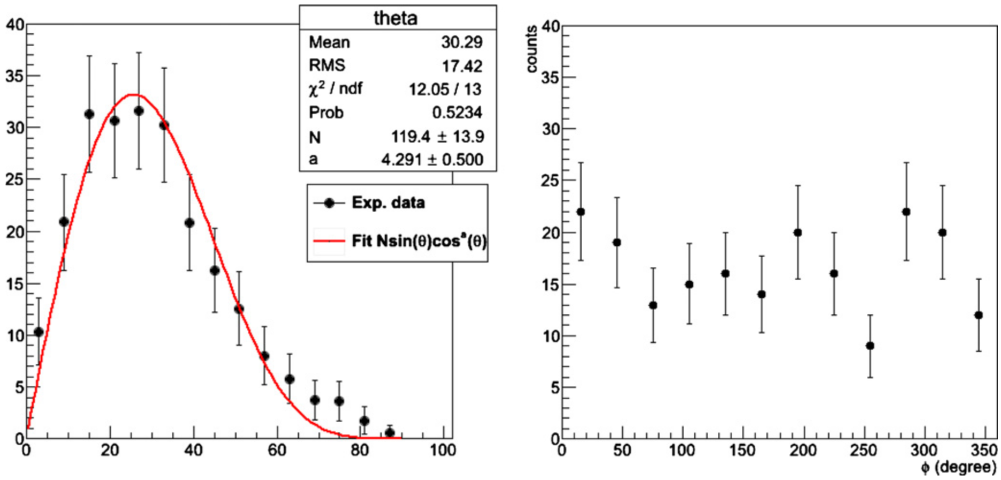

Figure 4. Angular zenithal (left) and azimuthal (right) distributions of the arrival direction of the showers, reconstructed by the time differences between three non-aligned small detectors.

Many more statistics would be required, however, to investigate this effect, which was studied in more detail with single muons in our previous paper [10].

The zenithal angular distribution of secondary muons at sea level has a well-known dependence $dN/d\Omega \sim \cos^2\theta$ (or $dN/d\theta \sim \sin\theta\cos^2\theta$, due to the increase of the solid angle as $\sin\theta$), as a result of the absorption of the particles in the atmosphere, which is more pronounced for larger inclinations, corresponding to a larger thickness to be traversed.

The zenithal and azimuthal angular distributions of the shower axis, however, have a more difficult interpretation, since their measurement requires the simultaneous detection of several (at least three) muons, and depending on the relative distance between the detectors, lower or higher energy showers may be selected. The detailed shape of the angular distributions of extensive air showers is related to the processes involved in their formation. The first measurements of such distributions were carried out more than 50 years ago, with varying results and they are still pursued now under different conditions, with the purpose of understanding the overall detailed properties of the propagation of extensive air showers in the atmosphere [14]. The zenithal angular distribution is expected to increase with the zenithal angle (again due to the factor $\sin\theta$), reaching a maximum around 20°, then falling at higher zenithal angles because of the atmospheric absorption, with an approximate shape $\sin\theta\cos^a\theta$, where the exponent a has large variations over the altitude and detection conditions (typically $a = 5$–10). A fit of the data shown in figure 4 (left) with such a function actually gives a value of the parameter a equal to (4.3 ± 0.5), with $\chi^2/ndf = 0.9$. It is seen that the values at zenithal angles larger than approximately 70° are higher with respect to the assumed shape. It has also been suggested [14] to parametrize the flux dependence $\Phi(\theta)$ as a linear dependence of $\ln\Phi(\theta)$ upon $\sec\theta$, at least for θ not too large, i.e.

$$\ln\Phi(\theta) = C\sec\ \theta + D,$$

after eliminating the solid angle dependence dividing by the factor $\sin\theta$. Figure 5 shows our data reported as a function of $\sec\theta$, which actually exhibit a linear trend, as observed with much higher statistics in experimental investigations carried out with large detector setups [14]. Again, the values obtained at larger zenithal angles, although with large statistical errors, deviate from the trend observed at smaller angles, showing a flattening of the distribution.

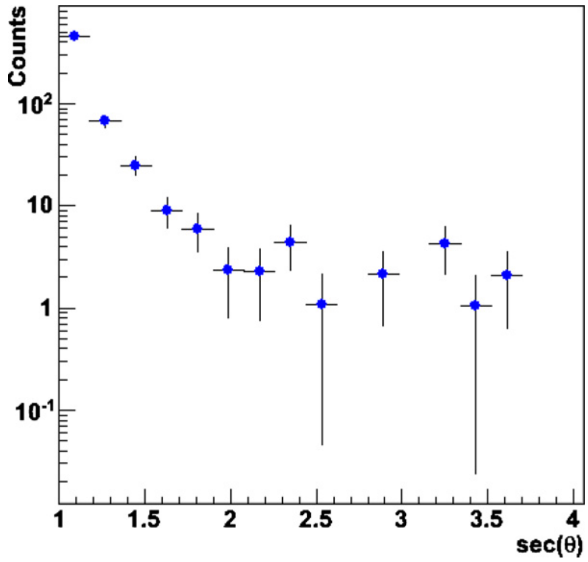

Figure 5. Distribution of the measured flux of primary particles (divided by $\sin\theta$), plotted as a function of $\sec\theta$.

This effect was also observed in the data reported in [14], and it is commonly interpreted as being due to the increasing influence of the muon component in the shower [15].

4. Conclusion

Most of this work was carried out as a result of a bachelor thesis and it is partly used to introduce third-year physics students to the basic knowledge and experimental observation of low-energy extensive air showers. The availability of even small detectors (typically small scintillation detectors), with basic electronics able to measure the time differences between the arrival of coincident particles in at least three detectors, makes it possible to reconstruct the shower axis and measure the (polar and azimuthal) angular distributions. While the use of standard NIM electronics would require, even with a simple three-detector configuration, a rather complicated and relatively expensive setup (discriminators, time-to-amplitude converters, coincidence units, a biparametric acquisition system and possible additional units, such as fan-out or delay lines, etc) the use of a compact Quarknet card proved very successful since it incorporates all the needed electronics (and much more) into a single cheap board. This is also being employed by larger educational networks which aim to detect correlated events from a large number of detectors spread out over large areas, as discussed in the introduction, and could be in our case a first step towards the construction of a larger array.

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