SHOWERING FROM HIGH-ENERGY COSMIC RAYS

CAN BE MEASURED IN THE HIGH SCHOOL SCIENCE LAB

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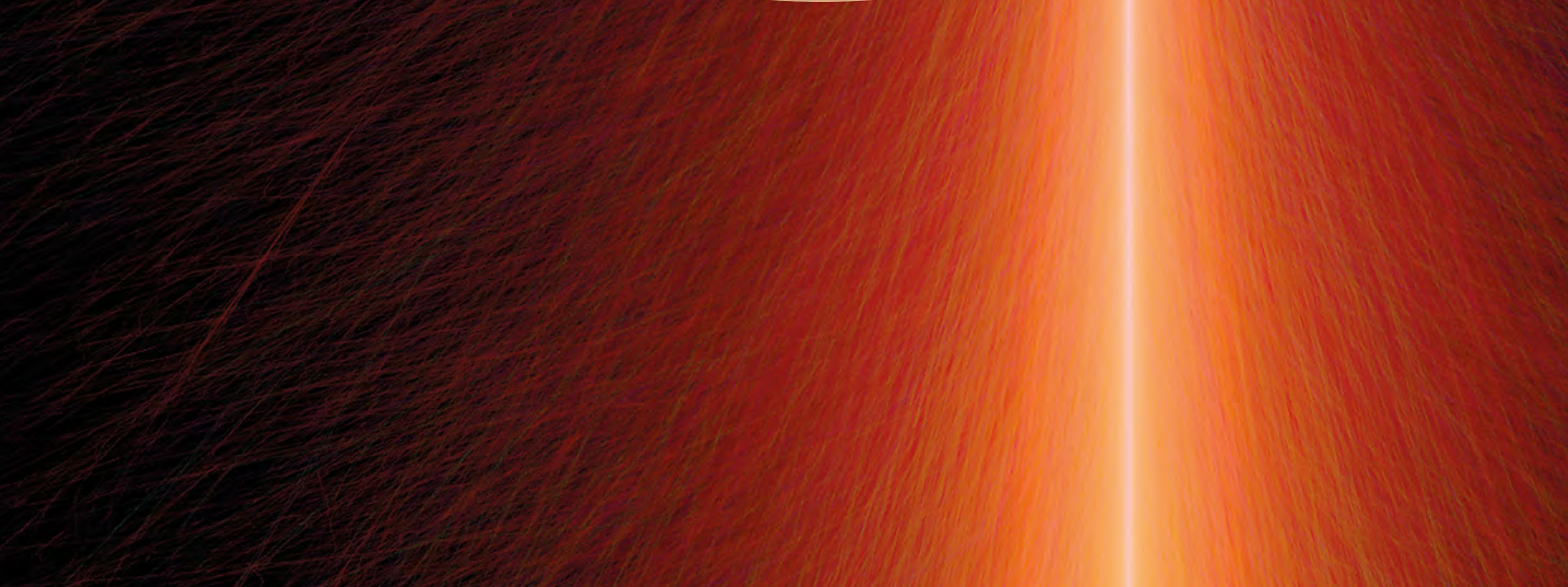
In particle physics a 'shower' is the avalanche of secondary particles produced by an incoming particle with high energy. This production requires the interaction with mass. A shower produced by high-energy cosmic rays usually covers a wide area, on the order of a square kilometer. The secondary particles can be observed by using scintillators. In view of the large area affected and the relatively simple equipment needed, this is an ideal project to involve high-school students and their teachers. Showering can also be observed indoors, on a much smaller scale.



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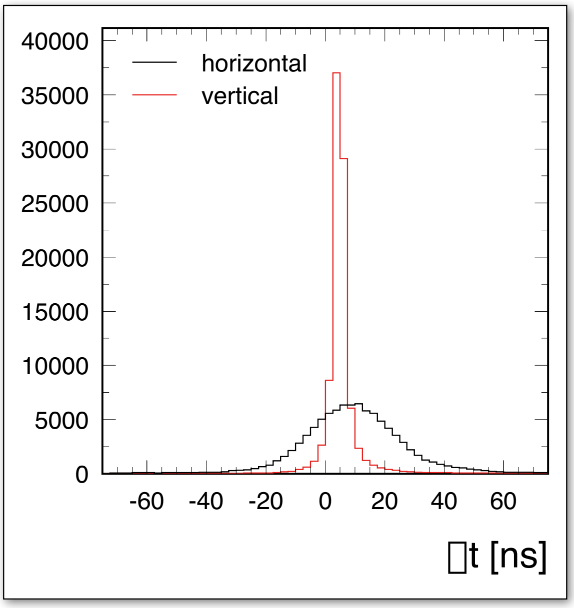
◂ **P.21:** Simulation of an atmospheric air shower induced by a proton (E= 10^{15} eV). The shower starts high in the atmosphere at about 60 km. The shower evolves and wanes in the atmosphere, resulting in a footprint of about 10 km in diameter (simulation Arne de Laat, Nikhef).

When a cosmic particle penetrates the atmosphere, its interaction with the atmospheric gas causes a so-called extensive air shower (EAS). If the energy of the particle is insufficient this shower quenches in the atmosphere. However, with sufficient energy (E >10^{14} eV) the shower can reach the earth's surface. Every square meter of the top of the atmosphere is struck by several dozens of such high-energy cosmic particles per year. Except for neutrinos, which are hard to detect and which are disregarded in this study, these particles are mainly protons (about 75%) and alpha particles (less than 25%). The rest is a small percentage of high-energy electrons, heavier nuclei and photons. The particles of the shower spread out over a surface of 10^4 – 10^7 m^2 when they reach the surface. Since a high-energy cosmic particle produces some 10^6 secondary particles, a detector of 1 m^2 at the surface of the earth is hit by about 0.1-1 particles from air showers every second. In view of the large area covered by a shower two detectors placed several meters apart can detect particles originating from the same shower. By observing coincidences of both detectors, signals originating from one shower can be distinguished from the background.

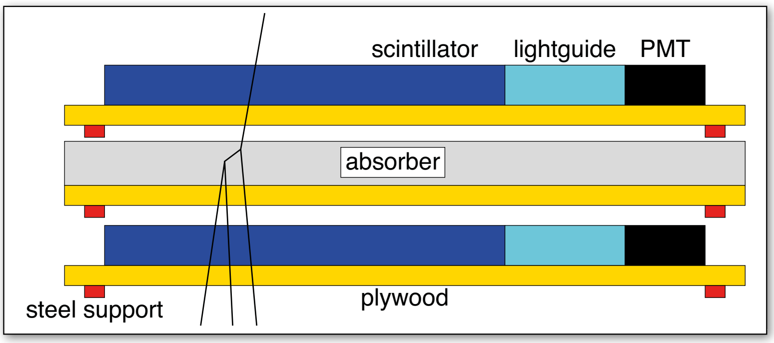


▴ **FIG. 2:** Number of signals from the two detectors as a function of the time differences between the signals of two detectors. In black: time differences between two detectors that are positioned in a horizontal plane about 5 m apart. The width of the distribution is determined by the correlation between two particles in the same EAS. In red: time differences between two detectors placed in vertical alignment, separated by the absorber. The narrower distribution shows that the same particle is measured by the two detectors.

Types of showers

The strong interaction between penetrating particles (protons and α-particles) and the atmospheric gases creates large quantities of charged and neutral pions, plus the fast-moving debris of the projectile and the nucleus being struck. The average distance between two subsequent interactions of an incoming particle with the atmospheric gases is defined as the nuclear *interaction length*. In air this is 90.1 gr cm^{-2}, where gr stands for 10^{-3} kg (nuclear radiation length depends on mass, it is radiation length normalized to the density of the medium). The neutral pions decay almost instantaneously (lifetime 8.4×10^{-17} s) into two photons which start an electromagnetic shower. The charged pions have a larger lifetime (2.6×10^{-8} s). The distance that they can cover before decaying is much larger than the interaction length. Together with the fast debris of the primary interaction these particles are able to induce new interactions. The avalanche extinguishes when the energy per particle is insufficient to produce new particles. The chain of events described above is called *hadronic showering*.

▾ **FIG. 1:** Schematic drawing of the set up. Two detectors are placed in vertical alignment with some spacing for absorber material in which showering can be induced. Both the detectors and the absorbing material are supported by plywood. A third detector is placed at several metres distance. This 'trigger detector' is used to identify Extensive Air Showers (EAS).



When a charged particle penetrates the electric field of an atomic nucleus a photon is emitted (*Bremsstrahlung*). If the energy of the photon is sufficient, pair production of an electron and a positron may occur. In this way the number of particles doubles with each step. This is called *electromagnetic showering*. The average distance between two such interactions is the radiation length (36.6 gr cm^{-2}).

An EAS starts off as a hadronic shower, but the high-energy photons that are produced in the hadronic shower gradually change it into an electromagnetic shower. Therefore, the particles that can be observed at the earth's surface are mainly produced by electromagnetic showers. This explains the composition of detectable particles at ground level: about 80% of the particles are photons, 20% are electrons or positrons, and about 1% are muons [1].

The experiment

To observe showering, we aim to show the production of new particles in an absorber. To this end, we used three scintillators of the type used in the High School Project on Astrophysics Research with Cosmics (HiSPARC, see Box). Two of these, the 'Trigger detectors', are placed several metres apart. The coincidence between events in these two detectors is an indicator of an EAS. Beneath one of these detectors (the 'upper detector') a third detector is installed (the 'lower detector'). Between upper and lower detector, sheets of various materials with varying thickness can be placed (Fig. 1). In this experiment we used sheets of aluminium, steel and lead. Table 1 lists the values of the radiation lengths (X_0) for these materials.

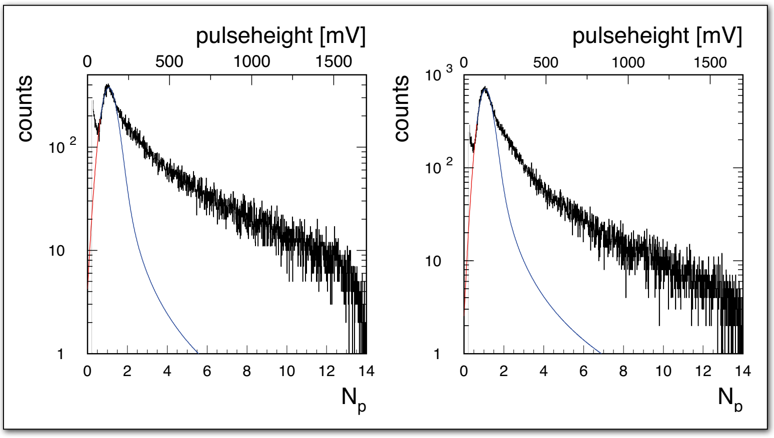
Material	X_0 [cm]
Aluminium	8.9
Steel	1.76
Lead	0.56
Plywood	56.8
BC408	42.5

◂ **TABLE 1:** Value of the radiation length for various materials [2]. The radiation length of plywood was calculated using equation (27.15) in [2]. BC408 is the scintillator material used in the detectors.

The time differences between two signals in detectors at several metres apart follow a normal distribution (Fig. 2) with standard deviation σ (= 14 ns). The time differences between two vertically aligned detectors are, of course, much smaller (σ = 2.2 ns). As described above, the time correlation between the two trigger detectors makes sure that the detectors see particles originating from the same shower. In the vertically aligned detectors either a particle is observed in both detectors, or extra particles that were created in the absorbing material are observed in the lower detector only. These signals originate from the same interaction, which results in a smaller standard deviation.

Figure 3 shows the pulse height spectra of the three detectors. The peak at $N_p = 1$ is identified with the signal caused by the passage of one charged particle. The shape of this peak is determined by the fluctuations in energy loss of this particle during its passage through the scintillator. These are described by a Landau distribution. This is a distribution in which a single parameter describes both the most probable value and the width. The resolution of the experiment is taken into account by taking the convolution of the Landau distribution with a normal distribution, where the standard deviation of the normal distribution equals the resolution of the experimental system. The result of this convolution is fitted to data near the peak. The fit yields an estimate of the horizontal scale of the spectrum in particles per event, as well as the energy resolution of the measurement.

The peak at the onset of the spectrum ($N_p < 0.5$) is ascribed to photons. This part of the spectrum is replaced



▴ **FIG. 3:** Pulse height diagrams from events in the bottom detector. Left panel: with an absorber. In black: data as a function of pulse height (upper scale). In blue: the fit for one charged particle. In red: data without the contribution of gamma photons (at N_p <0.5). Extrapolation to zero charged particles is the result of the fit. The bottom scale indicates the pulse heights in units of Np, the number of charged particles that passes the scintillator. Right panel: same plot in absence of an absorber.

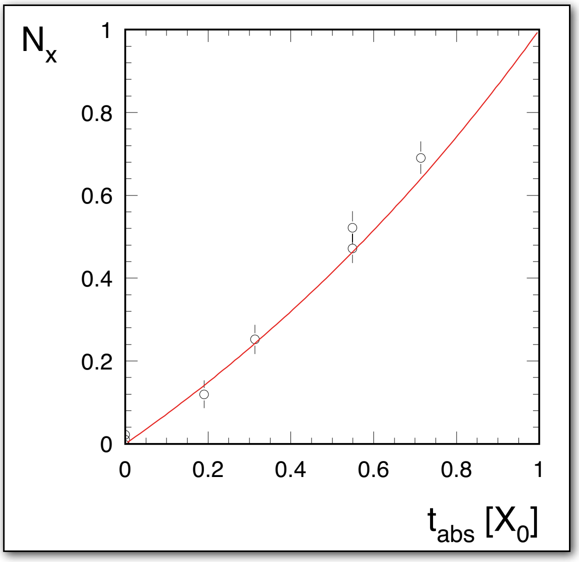
EDUCATION AND RESEARCH IN THE HISPARC PROJECT

HiSPARC (High School Project on Astrophysics Research with Cosmics) is an astrophysics experiment combining high-school education and scientific research. It consists of a physical network of more than a hundred detector stations, covering large parts of The Netherlands. Recently also several detectors in the UK have been installed. Most detectors have been built by high school students, and are installed on their schools (Fig. 5). Together these stations gather data on the interaction of high-energy cosmic particles with the atmosphere, with the aim to learn something about these cosmic particles. Many stations are equipped with a weather station, and a few have a lightning detector. The data of all stations are available for research to schools and scientific institutes.

The HiSPARC experiment achieves results in at least four fields:

1. The construction of detectors and the analysis of the data of this experiment gives pupils a taste of scientific research. After such an introduction many high-school students opt for HiSPARC for their final assignments.
2. For the pre-university level, a high-energy and particle physics course suitable for HiSPARC has been developed. This course can be used in the science and physics curricula.
3. In the 'Teachers in Research programme' (LIO) the Dutch Foundation for Fundamental Research on Matter (FOM) facilitates high school teachers to follow a research programme over the period of one year for one day per week in one of its institutes. Each year, HiSPARC offers five to ten research positions to teachers in this programme.
4. Finally, master and PhD students from various groups at Dutch universities use HiSPARC data for their research.

In the experiment described in this contribution we used a HiSPARC detector in an alternative configuration. We demonstrate the production of showers in matter in doors. It is a variation on the classical experiment by Rossi [4] in which he first demonstrated showering in 1933. This experiment is carried out in the context of the LIO-programme. With some minor changes though, this experiment could be performed or used as data-analysis project in high-schools. The data are available to high schools and the general public.



▸ **FIG. 4:** Average number of extra charged particles (Nx) in the detector under the absorber with respect to the detector above. The thickness of the absorber (t_{abs}) is expressed in radiation lengths (X_0). The red continuous line is a plot of equation 1.

by the extrapolation to zero charged particles as obtained by the fit. The average of this spectrum (without photons) between zero and fourteen particles is used as an estimate for the number of particles that passed the scintillator in each event. Figure 3 shows that the presence of an absorber increases this average for the lower detector.

Various absorbers

The space between the upper and lower detector (fig. 1) is filled with sheets of various absorber materials and of various thicknesses. With the available materials the thickness can be varied between 0.0 and 0.71 radiation lengths. The absorber may consist of several sheets of iron, lead or aluminium, but also sand or other construction material with sufficient mass may be used. The distance between the detectors should not be too large, such that the lower detector does not miss particles that passed through the upper detector.

Fig. 4 shows the average signal in the lower detector as a function of the thickness of the absorber. The extra number of charged particles seen by the lower detector is roughly proportional to the thickness of the absorber.

A simple model by Heitler [3] describes the shower as a sequence of splittings. After each radiation length the particles split into two with each secondary particle taking half the energy. This process continues until the individual particles have insufficient energy to create new ones. In a continuous version of this model the number of particles behind an absorber with thickness *t* is described by

$$N(t) = N(0)2^{t/X_0} - 1 \qquad (1)$$

with X_0 the nuclear radiation length. This curve is plotted in Fig. 4 as the red line, which gives a fair description of the data. ■

▾ **FIG. 5:** High school students installing a detector on a roof nearby their school.

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About the authors

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