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CREDO-Maze Cosmic Ray Mini-Array for Educational Purposes

Tadeusz Wibig * and Michał Karbowiak

Faculty of Physics and Applied Informatics, University of Lodz, Pomorska 149/153, 90-236 Łódź, Poland; michal.karbowiak@fis.uni.lodz.pl

* Correspondence: tadeusz.wibig@fis.uni.lodz.pl

Abstract: In this paper, we present the concept of local networks of small extensive air shower arrays installed mainly in secondary schools. As part of the CREDO-Maze Project, we plan to equip as many schools as possible with sets of detectors capable of detecting extensive air showers and transmitting their data to the central CREDO Project server. The synergy of such a network will make it possible to create a CREDO "global detector" and carry out physical research sensu stricto, e.g., the search for the Gerasimova–Zatsepin effect or the Cosmic Ray Ensemble. The discovery of one or the other would have extremely important consequences for our understanding of the nature of very-high-energy cosmic rays. In this paper, we describe a prototype local mini-array built at our university and some of the results of the exemplary tests performed. The design of the station's electronics and the small size of the detectors allow it to be used to perform, with the simple addition of software, also other tasks within physics circles and student projects. The mini-array consists of four small detectors, with a simple system for triggering, recording, and online communication with the world. The station is designed for autonomous and continuous operation.

Keywords: cosmic rays; extensive air shower; detectors

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1. Introduction

In recent years, we have noticed, in many places around the world, a growing interest in experiments using small-scale air shower arrays to satisfy young people's scientific curiosity. It is difficult to think of ways and opportunities to introduce practical classes in modern high-energy physics, astrophysics, or particle physics into school curricula and after-school activities. Small local EAS array experiments are just such a proposal. As part of the CREDO-Maze project, we plan to equip local high schools with sets of small detectors, with a simple system for triggering, recording, and online communication with the rest of the world. Networked experiments from several schools add significant new educational value to the process of developing good behavior appropriate to scientific communities. Cooperation and competition at the stage of one's own research and information exchange are essential new and valuable values in educating young generation. Small local arrays connected to the global CREDO network [1] will provide additional data and opportunities for important cosmic ray studies, which is an additional benefit of the CREDO-Maze Project. The scale symmetry in this case will result in synergy beyond any doubt.

There is a belief that conducting research and experiments in particle and high-energy physics is reserved only for scientists from scientific centers with powerful research facilities. However, anyone can use cosmic ray particles continuously and uniformly bombarding the Earth's surface to study the properties of high-energy particles (especially muons), to test relativity (e.g., the twin paradox) or to monitor space weather [2–4]. Such experiments can be offered to young people as part of school lessons as well as extracurricular activities. Similar activities are regularly undertaken and reported in the literature:

- "An educational study of the barometric effect of cosmic rays with a Geiger counter" by Famoso, La Rocca and Riggi (2005) [5],
- "Educational cosmic ray experiments with Geiger counters" by F. Blanco et al. (2006) [6],
- "Geiger counters offer powerful way to teach detection methods" by F. Blanco et al. (2006) [7],
- "Educational studies of cosmic rays with telescope of Geiger-Muller counters" by T. Wibig et al. (2006) [8],
- "Cosmic ray measurements by scintillators with metal resistor semiconductor avalanche photo diodes" by F. Blanco et al. (2008) [9],
- "Cosmic rays with portable Geiger counters: From sea level to airplane cruise altitudes" by F. Blanco, P. La Rocca, and F. Riggi (2009) [10],
- "An Inexpensive Cosmic Ray Detector for the Classroom" by Goldader and Choi (2010) [11],
- "The EEE Project: cosmic rays, multigap resistive plate chambers and high school students" by Abbrescia et al. (2012) [12],
- "High energy astroparticle physics for high school students" by Krause et al. (2015) [13],
- "μCosmics: A Low-Cost Educational Cosmic Ray Telescope" by Tsirigotis and Leisos (2019) [14].

Some of these works are experiments performed with single cosmic ray muons, which are very numerous and highly penetrating. However, it would be most attractive to study a phenomenon called Extensive Air Shower (EAS)—a cascade of elementary particles travelling at the speed of light (almost) from the upper layers of the Earth's atmosphere to the surface, where we can observe them. They arrive in a very short instant as a disk of particles in quantities reaching into the millions or even billions. The statement "the source of very high-energy particles that initiated such showers is in general unknown, as is the mechanism of their acceleration in astrophysical sources" is too strong in the way it is stated. While it is true that the phenomenon is not fully understood, there is a lot of research considering the source physics and propagation of ultra-high-energy cosmic rays.

One of those seeking answers is the Cosmic Ray Extremely Distributed Observatory (CREDO) Project [1]. By design, it is a large international enterprise, currently consisting of 20 countries, involving 46 scientific and educational institutions. The main scientific objective of CREDO is the detection of so-called Cosmic Ray Ensembles. These are beams of cosmic rays of very high energy, producing simultaneous extensive air showers across the exposed surface of the Earth. Such a phenomenon has never been seen, but there are several models in which such an event is possible. A system operating on a global scale is needed to observe such events.

We decided to design a local array for EAS recording. We decided to use individual small area detectors. We have carried out appropriate simulation calculations to make sure that they will provide an appropriate registration rate. The energy threshold for primary particles will be less than 10^{15} eV. When designing the EAS station, we must keep in mind the low budget of local groups who might be interested in this activity, mainly schools and educational institutions. We want the EAS detection station to be accessible to students and enthusiasts.

2. The CREDO-Maze Array

2.1. Detector Design

A plastic scintillator that is polystyrene-based, with maximum emission at 418 nm of size 10 cm $\times$ 20 cm, is viewed through two small (1.2 mm diameter) silicon photomultipliers (SiPMs) ASD-NUV1C-P. To maximize the amount of light collected, two 1-mm-diameter optical fibers are mounted in the scintillator and optically connected to the SiPMs. The scintillator, fibers, and SiPMs are wrapped in Tyvek paper and then re-wrapped in thick aluminium foil to shield the detector from visible light.

Each SiPM is integrated with an amplifier and a comparator with an adjustable threshold (specific comparator threshold values will be set individually for each detector and currently they are at a level of 100 mV) to form a logical (+5 V) rectangular signal with the width of 200 µs, which prevents the system from being triggered by unwanted afterpulses. The idea of the detector logic is shown in Figure 1.

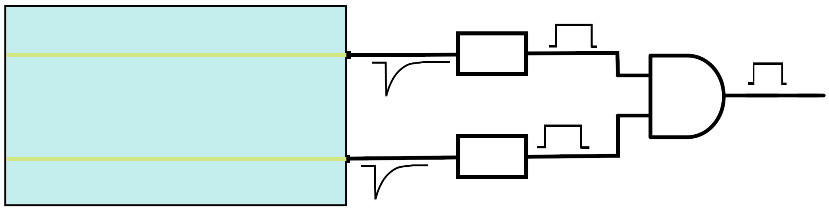

Figure 1. The concept of a single detector.

The rising edge of the comparator output activates the monovibrator, which forms a short (100 ns) logical signal. These signals from both SiPMs are sent to the coincidence gate. The resulting output signal from each of the four detectors goes to the central unit of the local EAS array.

A description of preliminary work on the detector and a concept for its construction with two optical fibers and SiPMs working in coincidence was presented at the 37th International Cosmic Ray Conference, Berlin 2021 [15].

2.2. Central Unit

The central station unit logic is shown in Figure 2. Logical, binary 100 ns signals from the individual detectors are fed to six two-input AND coincidence gates, respectively. If any of these coincidences occurs, a trigger is generated, activating an interrupt in the microcontroller unit and writing the current state of all coincidence outputs to a fast register. The microcontroller reads the register and, together with the current time, sends information about the trigger to the computer, where an appropriate record of the event is created or it is saved directly to the memory card. In the final version, data transmission will be controlled by an Arduino Nano (Arduino Uno) microcomputer with an AVR Atmega328 microcontroller or an Arduino Leonardo with an AVR Atmega32U4 microcontroller.

Data from the card, or from the local school computer, are transmitted at convenient times, or automatically if there is a permanent link between the school computer and the internet, to the CREDO Project database, or another local university database, where they will be preprocessed, archived, and made available for further analysis.

The software for the computer analyzing the collected data has been written in its basic form by us and will be suitably extended, leaving plenty of room for the students, for whom the possibility of programming the experiment will be an additional stimulus for creative activities.

The central unit additionally monitors the counting rate of each station detector. This is of diagnostic interest, but can be used, together with data from other stations, to observe the state of "space weather".

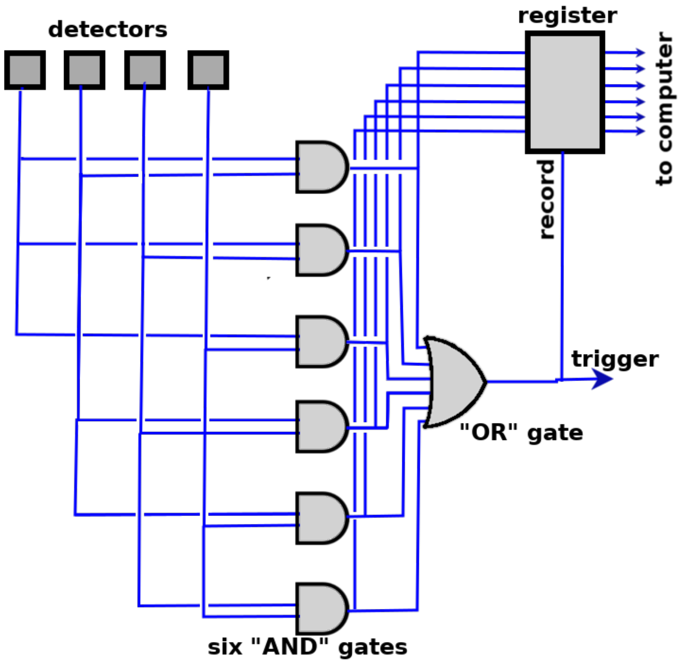

Figure 2. Schematic view of the CREDO-Maze array.

3. Results

3.1. Detector Performance Analysis

It is obvious that after installing a small shower array in a school or another place of its destination, it is necessary to test it comprehensively. The four detectors of the station must work symmetrically and this symmetry is the basic assumption for the correct operation of the array.

The detectors should be identical. Each is equipped with two controls: the first is the setting of the SiPMs' supply voltage and the second is the comparator threshold. These are surely correlated. Higher voltage causes greater amplification of the signal while generating more unwanted noise, which can be cut down by raising the comparator threshold. The detector's design enables these values to be controlled individually for each SiPM. As a result, we should obtain a frequency of signals from the detector of 100 Hz and this frequency should be the same for all detectors, although this requirement should not be treated as fundamental.

3.2. The First Test

The first test of the correct operation of the detectors consists in placing two pairs of detectors, one above the other, and extending such "telescopes" over a certain (∼1 m) distance. Both pairs should register cosmic rays passing through them from above, but we do not expect that the apparatus will register a coincidence of one detector from one pair and one from the other distant pair. Such a test is obvious and quick to implement.

3.3. Quantitative Analysis of the Counting Rate

A slightly more sophisticated experiment, which can be performed by students, consists in verifying the dependence of the count rate on the vertical size of the "telescope".

The solid angle $d\Omega$ at which an element of the upper detector is seen when viewed from a given lower point is by definition equal to (see Figure 3).

$$d\Omega \;=\; dx_g \times dy_g \times \cos(\phi)/r^2 \tag{1}$$

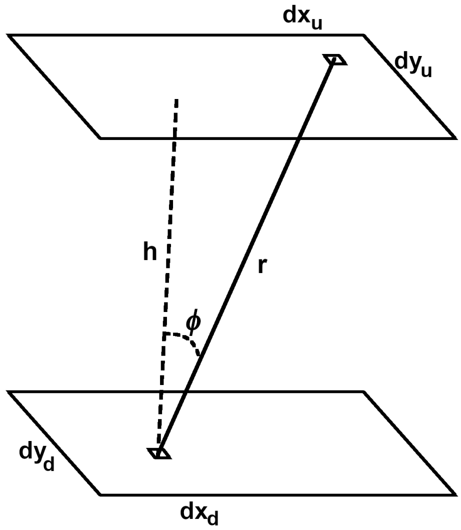

Figure 3. View of the "telescope".

From measurements that others have been making for almost a century, we know that cosmic muons do not come to us uniformly, from every direction in the same amount. Most of them arrive from near-vertical directions, and the angle dependence is not complicated: the flux of cosmic secondary muons (per unit of area and a unit of time) arriving from a given direction in the sky (ϕ) from a unit of the solid angle is

$$f(\phi) \sim \cos^2(\phi) \tag{2}$$

The event rate is thus:

$$\int d\Omega\, dS \times f(\phi) = \int dx_d \int dy_d \int dx_g \int dy_g \left((x_g) - x_d)^2 + (y_g) - y_d)^2 + h^2\right)^{-1} \times \cos(\phi) \times f(\phi) \tag{3}$$

Under certain assumptions, everything under all integral operators can be considered approximately independent of the variables over which we are integrating. Specifically, the positions of each element of the upper and lower detector can be "averaged", and then the integrals reduce to the product of the areas of the upper and lower detectors. These being the same, we have as a result the square of the area of the detector $(x \times y) \times (x \times y)$. Averaging the surface elements leads to some "effective" solid angle where the upper detector is seen by the "average element" of the lower detector. The area of the upper detector S divided by the square of the distance between the detectors h is of course an overestimate of this effective solid angle. The accuracy of this approximation depends on how close the detectors are to each other. The closer they are, the worse the accuracy. If the detectors are very close, a value more representative of the "effective" distance can be entered instead of h.

The exact estimation of the zenith angle value does not matter much, as larger values are truncated by the factor $\cos^2(\phi)$, which means that most often we see particles coming in almost vertically. For almost vertical showers, for angles close to 0°, the cosine function does not change much. We can safely assume that this angle is approximately 15°. In sum, we obtain, instead of the whole integral in Equation (3), a simple formula giving the estimation of the number of coincidences registered per unit time with the telescope of two rectangular 10 cm × 20 cm detectors placed one above the other:

$$n \sim (x \times y) \times (x \times y)/h^2 \cos^2(15^\circ) \tag{4}$$

A comparison of the results of the approximate formula Equation (4) and numerical integration of Equation (3) is shown in Figure 4. The dashed line shows the results of the approximate calculation; the solid line is for the exact one. In addition, we display the relationship $1/h^2$, which we would naively expect looking at the definition of the solid angle (dotted line). One can see, firstly, that our approximate formula is quite accurate, and secondly, that the simple dependence $1/h^2$ does not work too badly either, as long as the distance between the detectors is larger than their sizes, and the larger the better.

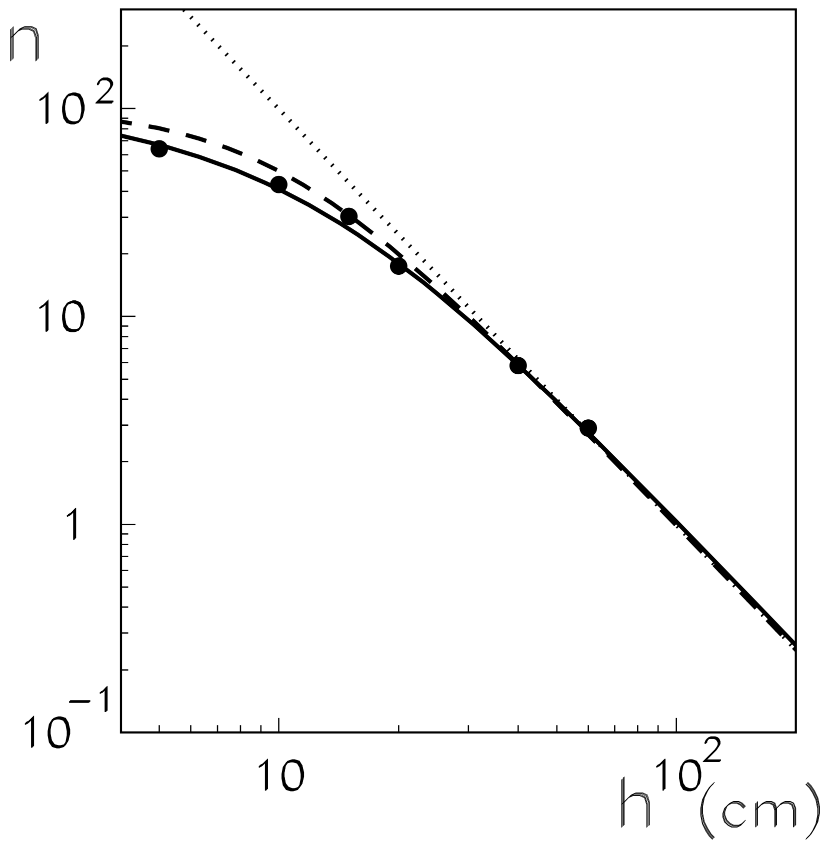

Figure 4. Number of telescopic coincidences calculated exactly from Equation (3), shown by the solid line, determined from the approximate formula Equation (4), shown by the dashed line, compared with the power relation $1/h^2$, showed by the dotted line. Points are results of one of our test measurements. The lines and measurement results were normalized to obtain compatibility for large detector separations.

3.4. Detector Efficiency

The symmetry of the entire local detection system requires the same performance of each of the four detectors. By swapping the detectors in each pair, we expect an identical array response.

The information stored in the computer about which of the four detectors were hit allows the efficiency of the detectors to be determined. By "efficiency", we mean the probability that a particle physically passing through the scintillator gives a signal strong enough to exceed the comparator threshold to be registered by the computer. It may happen that sometimes the signal is too weak; the photons emitted by excited particles from the scintillator are so few that, in an unfavourable geometry, not enough of them will reach the SiPM and such a case will be "lost"; thus, the detector will turn out to be "ineffective". In fact, there are no detectors in the world that are 100% effective. Determining the efficiency of detectors is sometimes even crucial for the success of physics experiments.

With four detectors, we can build them into towers by placing them one above the other. We must first note that the "noise", the coincidence of all four detectors, i.e., the appearance of physically uncorrelated signals "simultaneously" in the four detectors, is virtually impossible:

$$R_{\text{koinc.}} = R_1 \times R_2 \times R_3 \times R_4 \times (\Delta t)^3 \tag{5}$$

With perfect geometry and 100% effective detectors, we should only observe coincidences such as "1234", "123 -", "- 234", "12 - -", "- 23 -" and "- - 34". We assume hereafter that a notation where the numbers 1, 2, 3, and 4 appear in their place means that the detector has recorded a signal and a "-" sign means that no signal has occurred in the detector. Other registrations should not be present at all. The number of instances of the different types of allowed coincidences should be different, but because of the symmetry, there should be the same number of instances of "- - 34" and "12 - -", as well as "123 -" and "- 234". The detailed calculation of how many we should observe is not very complicated. The only modification needed for Equation (3) is to add the efficiency factor of each detector there.

An example is shown in Figure 5a. It shows the predicted histograms of specific patterns obtained assuming 100%, 90%, 80%, 70%, and 60% efficiency for all detectors. Note that all histograms in Figure 5 have been normalized at "12 - -". By comparing the measured results and the predictions, the efficiency of the detectors can be roughly estimated to be close to 90%. The most important aspect to note at this point is that the detectors are indeed not 100% efficient, meaning that sometimes particles are lost. In this case, there may be "impossible", forbidden counts, e.g., "1–34". When interpreting such a registration, we have to conclude that this is the case when a real charged particle has passed through the tower (a random coincidence of the three detectors is, again, almost impossible), and the detector number "2" did not register it, "lost" it, and was ineffective in this case. By conducting measurements with the tower over a longer period of time, as in the example shown in Figure 5, we can find the numbers of cases "1234", "1–34" and determine more precisely the approximate efficiency of detector "2".

$$\epsilon_2 = 1 - \frac{N_{1-34}}{N_{1234} + N_{1-34}} \tag{6}$$

Assuming the symmetry of the system, we determine the efficiency of detector "3" by analogy. Numbers in our example in Figure 5a lead to the efficiency of detector "2" being equal to 87% .The same value is obtained by replacing the number of events "1–34" by the number of events "12 - 4" and determining the efficiency of detector "3". We can, of course, swap detectors "1" and "2" and detectors "3" and "4" and repeat the measurements and determine the effectiveness of detectors "1" and "4".

A more sophisticated and certainly more precise and justifiable way is to minimize the χ^2 value obtained from comparing measurement results with calculations, leaving the effectiveness of individual detectors as free parameters.

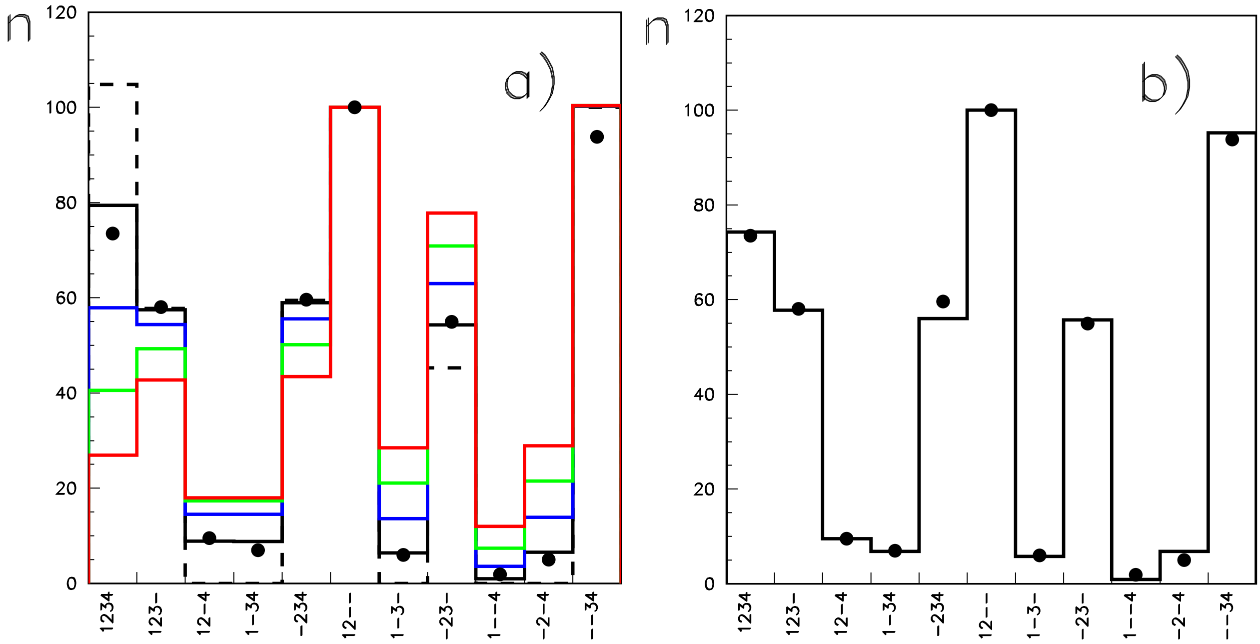

Figure 5. The calculated counting rates of the various recorded patterns: "1–3 -", "1–34", "1–4", etc., are "forbidden" events (for 100% effective detectors), while "12 - -", "123 -", and "- 23 -" are allowed events. The dashed line represents all detectors with 100% effectiveness. The solid black line—90%, blue—80%, green—70%, red—60%. The points are the results of one of our test measurements. All results are normalized to "12 - -" counting rate. The measurement results (black dots) are compared in the left figure (**a**) with the relative counts in cases where the efficiencies of all detectors were equal and listed above. The right figure (**b**) shows the result of the best fit efficiencies of all four detectors. The histograms and measurement results were normalized to a value of 100 for the combination "12 - -".

The final result of such a fitting procedure for our test measurement is shown in Figure 5b. The efficiencies found for all four detectors were 88%, 91%, 89%, and 87%, respectively.

3.5. Single Muon Zenith Angle Distribution

An arrangement of four detectors placed one above the other does not have to be positioned "vertically" as in the previous experiment. It can be turned so that its axis is directed at a certain angle to the zenith. It acts similarly to a telescope: one observes particles that fall in through the upper detector and go out through the lower one, hitting two intermediate detectors along the path. Since cosmic muons, as already mentioned, do not come uniformly, isotropically from all directions, a rotated telescope will measure a different muon flux at different inclination angles. In general, it will be smaller for larger angles. Determining how much smaller it is requires the corresponding integrals analogous to those in Equation (3) to be calculated. The results of these calculations are shown in Figure 6.

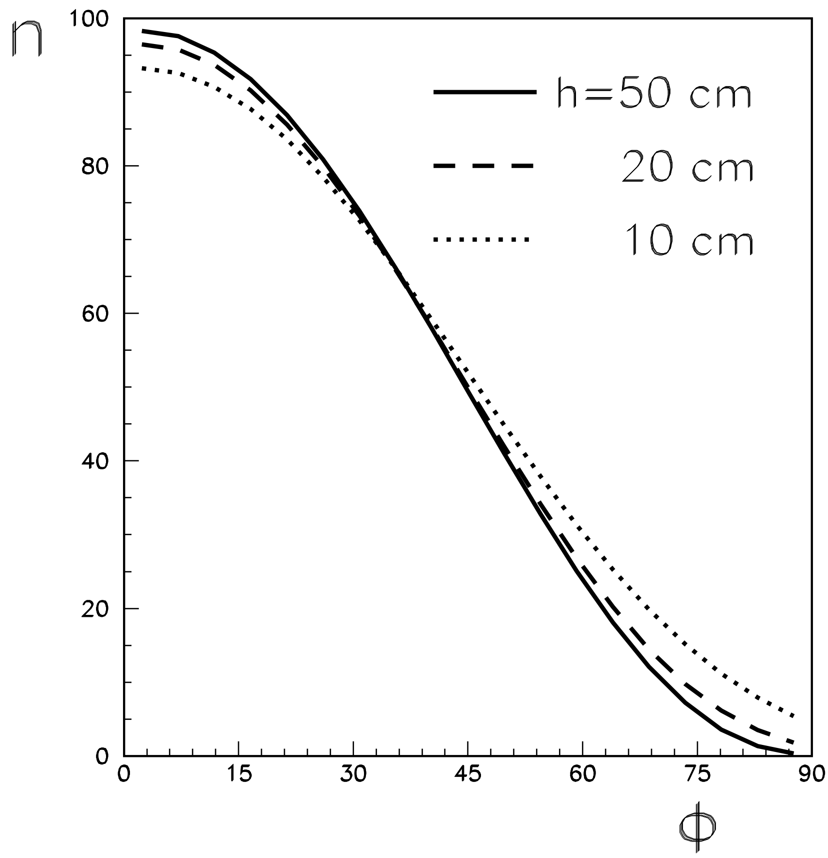

Figure 6. Telescope counting rate as a function of inclination angle. Lines correspond to different telescope sizes: the dotted line for the telescope where the distance between the upper and lower detector is equal to 10 cm; the dashed line for a telescope length of 20 cm and the solid line for a telescope length of 50 cm. The lines have been normalized to a value at an angle of approximately 30°

3.6. Uniformity of Detectors

In order to check the uniformity of the detectors and to verify the correctness of the symmetry of their operation, we set up a telescope with two detectors, one above the other, and then measured the counting rate while moving them relative to each other along the longer and then the shorter side, as is shown in Figure 7.

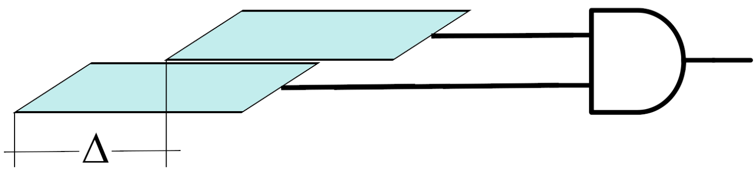

Figure 7. Measurement of the detector homogeneity.

The measurement results are compared in Figure 8 with predictions obtained from the integration of the incoherent muon flux at sea level with the condition that the both detector surfaces of a given geometry are crossed. In these calculations, it has been assumed that the detectors are ideal, which means that every muon crossing the surfaces of both detectors gives a signal to be counted. A comparison of the results of numerical integration and the approximate relation (crossing of detector areas) is also shown in Figure 8. All results have been normalized to 100 for an offset of 0. The thin dashed line shows the linear dependence, showing an overlapping section of both detectors; thick lines represent the results of the numerical calculations for different vertical detector spacing: dashed line for a spacing of 2 cm, solid line 5 cm, and dotted line for the 10 cm spacing.

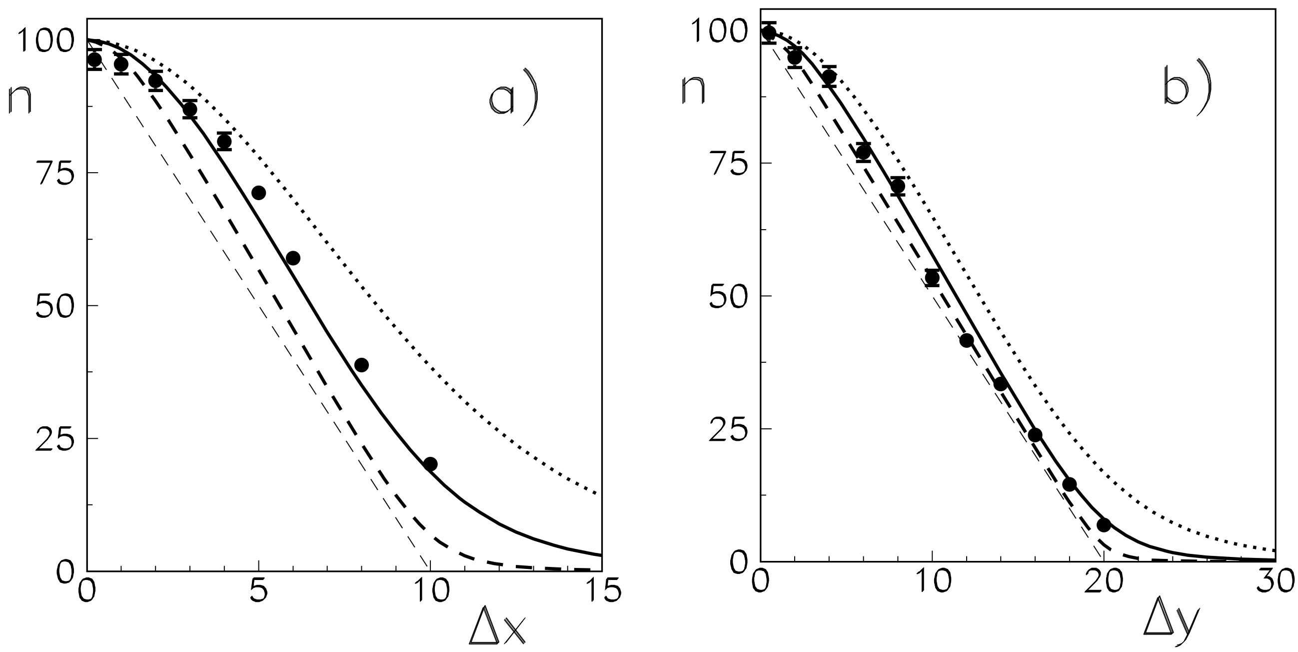

Figure 8. Coincidence rates in a telescope consisting of two detectors, one shifted along the long side (**a**) and the other along the short side (**b**). The lines show the normalized predictions for different detector vertical separation. The points are the results of our test measurements (for a detector spacing of 5 cm). The lines have been normalized to 100 at 0 displacement. Normalization of the measurement results has been achieved by best fit to the appropriate curve.

The transverse uniformity we tested by moving the upper detector along the shorter side, and the results are shown in Figure 8a), as well as the longitudinal uniformity shown in Figure 8b), which do not show significant systematic deviations from the prediction of $\sim$100% efficiency of the two detectors over their entire surface. In particular, no signal fading effect is seen along the optical fibers; see Figure 8b).

3.7. Index of the Cosmic Ray Energy Spectrum

With only four small detectors, we can, however, say something about the physics of cosmic rays. Suppose that a large atmospheric shower containing very many particles reaches our apparatus. Let us assume that there will be an average of 500 particles per square meter in the vicinity of our four detectors. Since our detectors are 10 cm by 20 cm, i.e., with a total area of 0.02 m^2, we expect an average of 10 particles to hit each detector. The Poisson probability that a detector will not be hit is equal to $e^{-10} \approx 0.000045399\ldots$ Thus, we can expect that rather all four will be hit by at least one particle (exactly the probability of such a quadruple hit will be $(1 - e^{-10})^4 \approx 0.9998\ldots$). The probability of only three and exactly three (any three) being hit is $4 \times (1 - e^{-10})^3 \times e^{-10} \approx 0.000182\ldots$ Comparing these two probabilities, one has to conclude that, in this case (with a local density of 500 particles per square meter), virtually all four detectors will always be hit. With 100 particles per square meter, the probabilities will be 0.5590... and 0.3500..., respectively. The ratio of the number of triple coincidence counts to the number of quadruple coincidence counts depends strongly on the incident particle density.

It turned out that nature is very kind and allowed the relevant probabilities to be described very precisely by a simple formula [16–19]:

$$N(\rho) \;=\; N_0\, \rho^{-\gamma} \tag{7}$$

where ρ is the density of particles at the place where our detectors are located. $N(\rho)$ is called the "density (integral) spectrum" and tells us how many events will be registered with a density greater than ρ.

This is the so-called power-law spectrum, and the γ index is one of the most important quantities in cosmic ray physics. Its value can in principle be determined by studying particle acceleration models in the distant space. On the other hand, it can also be estimated by comparing the measured value of the ratio of the number of triple coincidence registrations to the number of quadruple coincidence events with a calculation taking into account the density spectrum with a specific assumed gamma exponent. Detailed calculation results are shown in Figure 9.

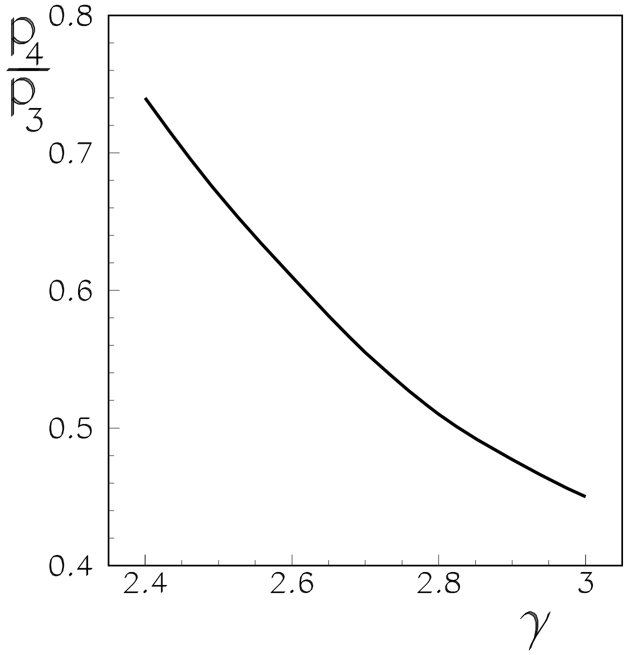

Figure 9. Expected ratio of four-fold to three-fold coincidences as a function of an index in the cosmic ray density spectrum γ.

3.8. Other Significant Cosmic Ray Experiments

With the four detectors and our system for event recording described above, we can, in a simple way, carry out many important historical experiments in cosmic ray as well as particle physics.

One of them is a repetition of Rossi's experiment of 1933, in which he showed that secondary cosmic ray particles form cascades, when passing through matter, providing the experimental basis for Babha and Heitler's theory of electromagnetic cascades (1937) [20].

Two of our detectors are placed directly one on top of the other, and the other two are placed symmetrically below them, side by side. Placing a heavy (large Z) absorbing plate, preferably lead, but iron also works well, between the upper and lower detectors and noting the counting rate when all four detectors simultaneously generate a signal leads to a restoration of the so-called "Rossi curve": the dependence of the number of such registrations on the thickness of the absorbing layer [21]. The original Rossi drawing is shown in Figure 10.

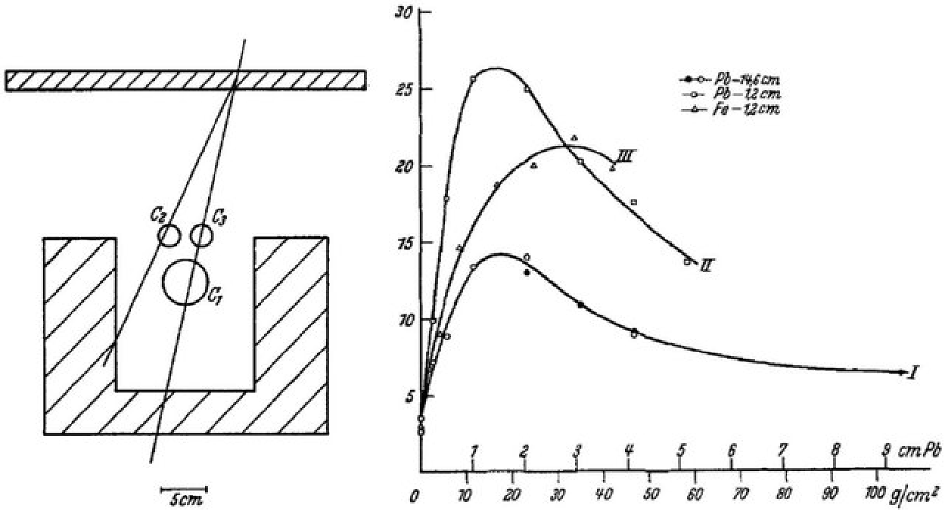

Figure 10. Rossi experiment (**left**) and Rossi curves (**right**) from his original paper.

Another historical experiment that can easily be repeated is the famous Auger and Maze experiment, in which they demonstrated for the first time the existence in nature of elementary particles with energies reaching 10^{15} eV. In order to do so, two telescopes should be built by placing pairs of detectors one above the other, and the rate of fourfold coincidence should be recorded as a function of the distance between them when the telescopes are positioned side by side. This relation is called the "decoherence curve" [22,23]. The original figure is shown in Figure 11.

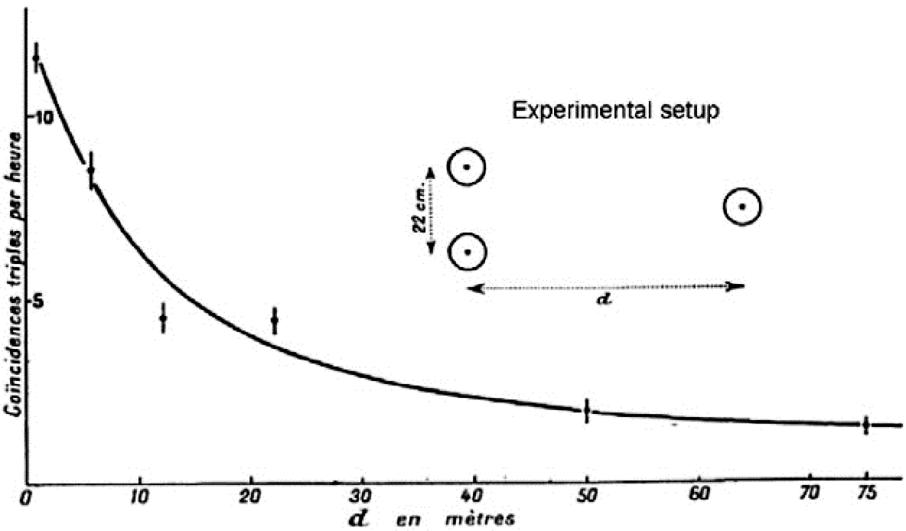

Figure 11. Decoherence curve and Auger and Maze experiment from their original paper.

It should be mentioned that Rossi's cascade curves and Auger's and Maze's extensive air showers are, by their nature, mainly electromagnetic phenomena. Observing muon interactions in lead or muon cascades with our small detectors is extremely unlikely and therefore these experiments should be performed outdoors, or at least under a light roof containing little matter in its vertical cross-section.

4. Summary and Conclusions

In this paper, we presented the design of a local small school EAS apparatus. Our project aims at providing schools in the region—and, in the future, anywhere else—without any restrictions, with the simplest, and thus the cheapest, easy-to-use scientific instruments that can be a real tool for practising physics at a high level of sophistication both from the experimental side and from the side of the interpretation of results and data analysis. The data from the schools will be transmitted to the central database of the CREDO Project, where they will be used by scientists for important physical searches for objects such as Cosmic Ray Ensembles.

The detectors we have proposed and tested exhibit very good detector properties, simple design, and, above all, are inexpensive. The small size of the detectors means that the possible amplitude registration of signals is no longer important. What matters is practically, first of all, the binary information (hit: yes/no). The use in our detectors of light collection from each scintillator symmetrically through two optical fibers and SiPM diodes connected to them, working in coincidence, makes it possible to reduce the noise by a factor of several hundreds, which is not negligible for the realization of other "non-shower" projects and student experiments. The symmetry of the single detector and the electronics used is crucial to our project.

Another symmetry, the symmetry of the local stations, allows for the easy, seamless connection of others to the system and the database as a whole. The development of the network of detection stations is a key element of the project from its scientific aspect. Results obtained at an individual school station may not lead to significant scientific discoveries, but, in conjunction with others, constructing an ever larger network, they automatically strengthen its research potential. The study of cosmic rays of the highest energies in one of its currently developed branches, and it strives to search for new physics, new particles, new phenomena, and a large network of small shower arrays, being a suitable tool for such searches.

In this paper, we have presented the characteristics of prototype detectors. Their homogeneity and efficiency fully meet the requirements that could be set for them. The operation of the central station, allowing one to perform all the experiments described in this paper, is based on simple and inexpensive electronics. Additionally, the power supply for the whole system can be realized by powerbanks, making the apparatus mobile and portable, which gives new possibilities and allows for many interesting works "in the field".

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