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Article

First Results of the CREDO-Maze Cosmic Ray Project

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Abstract: The CREDO-Maze project is the concept for a network of stations recording local, extensive cosmic ray air showers. Each station consists of four small scintillation detectors and a control unit that monitors the cosmic ray flux 24 h a day and transmits the results to the central server. The modular design of each array allows the results to be used in educational classes on nuclear radiation, relativistic physics, and particle physics and as a teaching aid in regular school classrooms and more. As an example, we present here some preliminary results from the CREDO-Maze muon telescope missions to the Arctic and down into a deep salt mine, as well as the first shower-particle correlation measurements from a table-top experiment at Walailak University. These experiments show that the different geometric configurations of the CREDO-Maze detector set can be used for projects beyond the scope of the secondary school curriculum, and they can form the basis of student theses and dissertations at universities.

Keywords: cosmic ray ensemble; extensive air shower; incoherent muon flux; shower particle correlation; CREDO

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1. Introduction

Cosmic rays, high-energy particles primarily originating from outside the solar system, pose significant questions regarding their origins and properties; see, e.g., refs. [1–3]. These particles offer a unique perspective on high-energy astrophysical processes, and they are a vital component of the natural radiation environment on Earth. The CREDO-Maze project aims to extend the reach of cosmic ray research into the educational sector, providing practical scientific opportunities to students worldwide. CREDO-Maze emphasizes extensive global collaboration and educational integration, offering insights into cosmic ray phenomena through an accessible and inclusive approach. Projects with similar goals can be found at the state, national, and international levels, benefitting from the cooperation between science and secondary- and upper secondary-level educational institutions.

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 the cosmic ray particles continuously and uniformly bombarding the Earth's surface to study the properties of high-energy particles (especially muons), test relativity (e.g., the twin paradox), or monitor space weather [4–6]. Such experiments can be offered to young people as part of school lessons, as well as extracurricular activities.

Qualitatively new and potentially extremely important results will come from the CREDO (Cosmic Ray Extremely Distributed Observatory) proposal [7] concerning the idea of cosmic ray ensembles [8]. They occur as a result of ultra-high-energy cosmic rays entering the Solar System and its magnetic fields. They simultaneously cause extensive air showers (EASs) [9] over the whole of the Earth's exposed surface. Such a phenomenon has never been seen before. However, there are several models for such an event, including the decay/annihilation of superheavy dark matter particles [10]. The CREDO project [11] is dedicated to the search for such hypothetical cosmic ray ensembles. It was officially launched on 11 September 2019; by design, it was conceived as a global research endeavor, and it currently involves now 52 institutions from 20 countries [12,13].

The CREDO-Maze project is a modular addition to the CREDO project, allowing the geographical distribution of cosmic ray detectors to temporal and even mobile locations. Currently, it is being implemented on a limited scale within a national context, being the first step in complementing the global networks of school-based cosmic ray recording stations. Data from our CREDO Maze project will automatically be part of CREDO.

1.1. Objectives of the CREDO-Maze Project

The concept behind the CREDO-Maze project, originating in the 1980s with the ideas of Linsley [14], involves networking numerous small shower arrays composed of local, dedicated instruments designed to record EASs. Ideally positioned within schools and other educational institutions, these arrays leverage the existing technical and human infrastructure alike. The primary operators are students, who not only gain hands-on experience with particle physics, quantum physics, relativistic physics, astronomy, and astrophysics—fields typically underrepresented in standard curricula—but also actively participate in a global scientific endeavor. This project allows them to learn the methodology of scientific work firsthand. Furthermore, their interaction with scientists and peers worldwide, exchanging information and solving problems, forms a crucial and enriching part of their educational experience. This aspect of CREDO-Maze, focusing on collaboration and practical engagement, is arguably as significant as its scientific objectives.

1.2. Integration into Educational Frameworks

CREDO-Maze profoundly integrates into both school curricula and after-school programs, giving students a unique chance to participate in bona fide scientific research. This project differentiates itself from standard extracurricular activities by enabling students to use actual scientific equipment and data, thereby immersing them in a global scientific endeavor. Such engagement not only boosts their interest and expertise in physics but also nurtures skills in mathematics, computer science, and related technologies. Participating schools serve as nodes within a comprehensive data collection network, overseen by local universities or research institutes. This arrangement provides a framework for students to conduct individual or collaborative research projects under expert guidance, enhancing their educational experience and contributing to significant scientific goals. By involving students in sophisticated research and equipping them with advanced scientific tools, CREDO-Maze not only enhances educational practices but also prepares students for advanced scientific pursuits. Furthermore, by integrating data into the expansive CREDO network, the project extends its scientific reach, opening up possibilities for new insights and breakthroughs in the study of cosmic rays and other phenomena [15].

1.3. Comparison with Other Educational Cosmic Ray Projects

Several projects across the globe have demonstrated the feasibility and educational value of integrating cosmic ray detection into school curricula:

- Extreme Energy Events (EEEs) [16] has been a trailblazer in embedding cosmic ray detectors within schools across Italy, fostering scientific curiosity and hands-on research among students. The EEE project serves as a significant influence and benchmark for CREDO-Maze in terms of its scale and educational integration.

- ADA (Astroparticle Detector Array) [17] emphasizes collaboration across European schools, using cosmic ray detection to enhance student engagement with science.
- ALTA [18] and CHICOS [19] showcase North American contributions to cosmic ray education, engaging students in hands-on research and data analysis.
- HiSPARC [20] and QuarkNet [21] provide extensive networks of detectors, offering models for scalability and depth in educational content.
- CROP, CZELTA [22], and WALTA [23] contribute unique regional insights and methodologies, enriching the global data pool on cosmic rays.

2. Technical Specifications of the CREDO-Maze Detectors

The CREDO-Maze project aims to provide a large number of schools with state-of-the-art EAS arrays; so, of necessity, the instrumentation must meet several (apparently) contradictory assumptions:

- It must fulfill the basic task of detecting showers of sizes corresponding to primary particles with energies of the order of 10^{15}–10^{16} eV.
- It must be relatively simple in order to ensure its reliability and continuous operation without interference, recalibration, or potential future modifications.
- It must be based on modern but proven technology.
- It must be cheap,
- It should be potentially multifunctional and suitable for non-standard measurements of an educational nature.

In particular, fulfilling the final two requirements necessitated the applied solution, rather than the other possible ones.

In the initial design work, we decided not to use timing. Therefore, we did not try to determine the direction of arrival of the showers or analyze the amplitude of the signals. Due to the small area of the counters in most cases, we do not expect to obtain significant information about the number of particles recorded via the detectors.

An important factor that affects the cost of the detection station is the scintillators themselves. Their final surface area of (20 cm $\times$ 10 cm) was determined through simulation calculations. We used a specially developed semi-analytical model for this purpose based on the CORSIKA program, which is described in more detail in [24].

The choice of light detectors was another element. A plastic, polystyrene-based scintillator with a 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 (Mouser Electronics, Inc., Mansfield, TX, USA). To maximize the amount of light collected, two Y-11(200), 1.0-mm, round, single-cladding, non-S-type Kuraray optical fibers (incorporating a wavelength shifter from ultraviolet to green, Kuraray, Chiyoda City, Japan) were mounted in the scintillator and optically connected to the SiPMs.

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 a width of 200 µs, which prevents the system from being triggered by unwanted afterpulses. The rising edge of the comparator signal activates 1/2 of the UCY74123 monovibrators, which forms a logical signal with a width of 200 ns, and sends them to the coincidence circuit. The narrow width of the monovibrator outputs (200 ns) practically eliminates any accidental overlapping of signals that come from both detector SiPMs.

The idea of the detector logic is shown in Figure 1.

The resulting outgoing signal from the detector goes to the central unit of the local EAS array.

The logic of the entire detection station is shown in Figure 2. It shows four detectors, physically spaced as a standard EAS array at certain distances (here estimated at 5–10 m, depending on local capabilities), at the registration level. Each of their pairs is connected to a logical AND gate. The outputs of these six gates enter the logical OR gate, which works out the trigger for the logical register, and the Arduino controller. The arrow indicates the transmission from Arduino to the memory card. In addition, the controller's connection with the GPS receiver, used for the absolute time synchronization of events, is marked. The report on the operation of the prototype-measuring station was presented, e.g., at the Vysehrad meeting in Opava, and also published in [15].

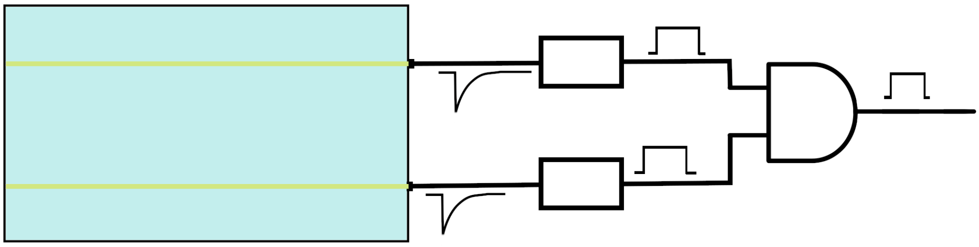

Figure 1. The concept of a single detector.

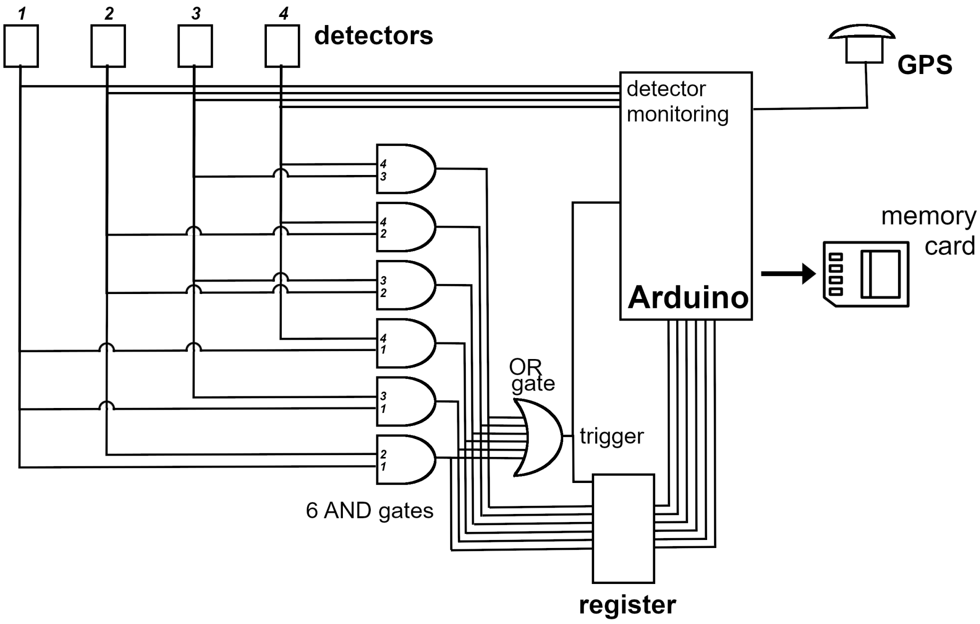

Figure 2. Schematic representation and operating logic of the entire detecting station.

We will try to develop the station measurement kits to ensure that they can be duplicated and distributed to end users as "self-assembly kits" with the different degrees of sophistication of the finished components. As potential business projects, they will be able, together with educational-material pledges and software, to provide a ready-made market product. With positive recommendations based on our research results, the potential market and the demand from educational institutions seem to be quite considerable.

3. Three Example Studies Made with the CREDO-Maze System

3.1. Mobile CREDO-Maze Traveling through the Arctic and Beyond

An example of a nonstandard application of the CREDO-Maze project's cosmic ray station is an expedition to Lofoten and beyond the Arctic Circle, organized by the Radiation and Nuclear Safety Authority in Finland at the end of 2023. For this measurement, the standard CREDO-Maze array was used, but its four detectors were arranged one above the other to form the geometry of a telescope. In such a setting, all triple and quadruple coincidences are the result of a secondary cosmic muon passing through the telescope, and when we talk about measuring the muon flux, we are really talking about the rate at which such coincidences are recorded. The team started by car from Oulu, Finland (latitude 65), and traveled all the way to the Lofoten islands, Norway (latitude 68). The mobile setup consisted of a CREDO-Maze base with a modified electrical input, allowing the car's 12VDC power system to be powered. The apparatus continuously monitored the cosmic ray muon flux and the time and position of the setup using an integrated GNSS data receiver. This allowed us to potentially investigate the muon flux dependencies with geomagnetic latitudes and altitudes, using external online data sources and correlations with atmospheric pressure and magnetic field values. The preliminary analysis of the mobile CREDO-Maze system focused on the muon flux changes while driven along Highway E10 through the Lofoten islands. More data, including mobile measurements, are currently being analyzed in detail and will be published later.

Here, in Figure 3, we present the geocoded muon flux data measured over 10-s time intervals. The discernible (systematic) difference between the two measurements taken four days apart (back and forth—the blue and red lines in Figure 3) can be mostly explained by the changing weather conditions, namely the atmospheric pressure, between sampling days. During the three days between the drive and the return from the Lofoten islands, few shorter trips were made at the end of the chain of islands. These trips are represented with a red line.

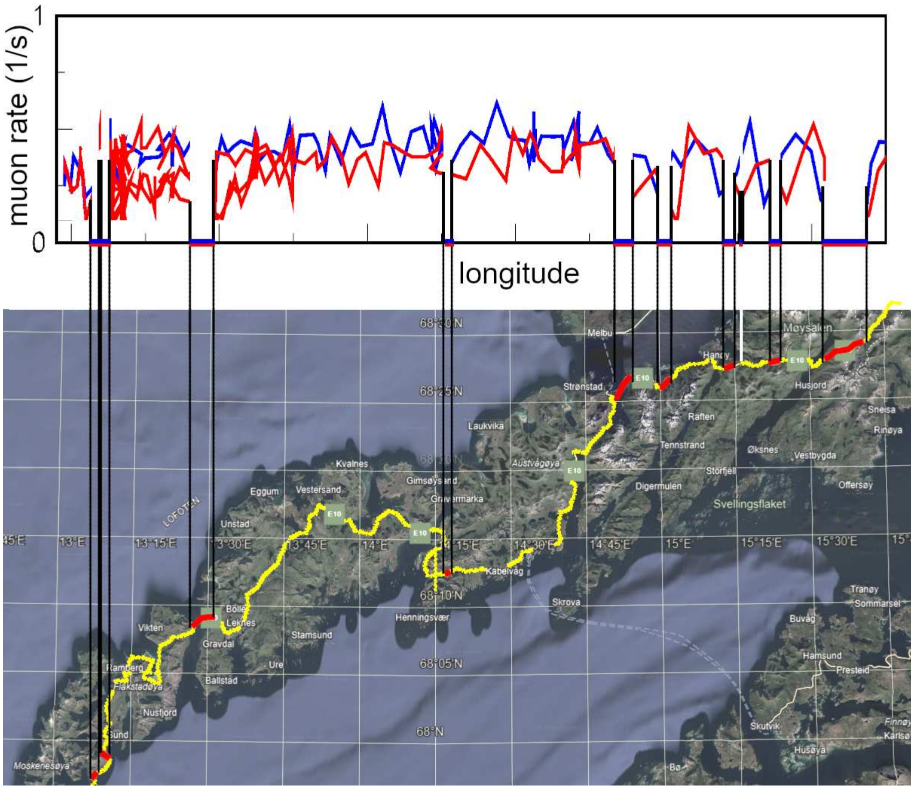

Figure 3. Map of the Lofoten islands showing the route followed. The upper part shows the results of the cosmic ray muon-counting rate along this path (in units of 1/s) measured over 10-s time intervals. The journey had to follow the same road in two directions, and colors (blue and red) were used to indicate the results for both directions. Tunnels on Highway E10, where the counts dropped to zero, are marked on the map in red. The map is provided courtesy of Google Maps.

What is most important to us here and what is not in doubt is that, during the passage through the tunnels, the number of the counts dropped to zero. This was expected, as the tunnels' overburden can range from a few meters to tens of meters (from tens to hundreds of m.w.e.), and it is well known that the vast majority of muons have energies too low to penetrate a layer of earth several meters thick. The results also validate that the system does indeed record cosmic ray muons.

3.2. Deep Underground Muon Flux Measurements

In June 2023, an underground detector test was performed in a salt mine in Poland. For this measurement, the standard CREDO-Maze array setup was again used with a muon telescope geometry. This arrangement makes it possible to count muons efficiently even when their flux is very low (e.g., in a mine): a true muon is able to penetrate the entire telescope, so it will trigger the coincidence of four, and sometimes, for more inclined particle tracks, three detectors, while random noise will only trigger one detector, and very rarely two detectors, so it will not be mistaken for a muon.

The entire measurement setup (including the battery) fit into a suitcase-sized protective box and could be carried easily into the mine.

The setup was brought down to a depth of about 350 m ($\tilde{1}$ km of water equivalent) and left there for 6 h, and then it was brought back up to the surface without shutting down. During the underground measurement, the count rate was very low but exactly as expected. There were three coincidences with four detectors and two coincidences with three detectors; i.e., five muons were observed, while the expected muon count at a depth of 1 km w.e. was nine [25]. According to the previously performed detector efficiency tests and the estimated average effective efficiency of about 90%, the expected number of muons that passed all four detectors but were detected as "1-34" or "12-4" should have been less than 1, or of the order of 1 for detector efficiencies closer to 80%. It can also be assumed that muons detected at a larger angle and passing only three detectors, ideally detected as "123-" and "-234", could not have been included in our timeline as double-coincidence detections. We expected less than 0.5 such cases. Taking detector efficiency into account reduces the expected number of muons in our measurement from nine to eight or even seven, and thus, our measurement (five muon detections) becomes even more consistent with these predictions. After the device was pulled out of the mine, the number of coincidences increased by about 1000 times to the standard number that the telescope recorded on the surface. The timeline of the measurements is shown in Figure 4.

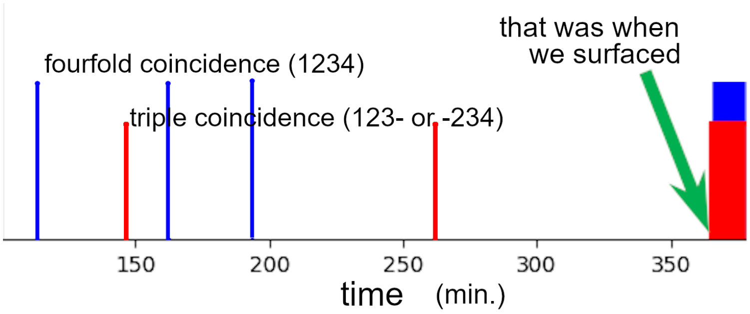

Figure 4. Timeline of underground measurements. The high (blue) bars indicate events in which all four detectors of the telescope were hit. The low (red) bars indicate triple-coincidence events in which the first detector from either the top or the bottom of the telescope was not hit. The moment of departure to the surface is marked, and one can see a very large increase in the number of detections since then.

This test proved that the device works efficiently and does not generate false coincidences.

3.3. Study of Short-Range EAS Particle Correlations Using Horizontal Displacement of CREDO-Maze Detectors

The existence of short-range correlations between particles in the EASs does not come as a surprise; see, e.g., ref. [26], although these effects have not been well documented in experimental studies. Our set of four small detectors is well suited for such measurements.

A pilot measurement was conducted at the University of Walailak, Thailand, by placing these detectors 5 cm apart horizontally (which corresponds to 15 cm between their centers) and studying the number of coincidences between them as a function of their mutual separation. The very preliminary results are shown in Figure 5. We present here the raw data, i.e., the counts of the individual coincidence types, not corrected for the roughly estimated efficiency of the individual detectors. As can be seen in Figure 5, the detectors did not work exactly identically. In part, this may have been an effect of the extreme temperatures that prevailed during the measurements, when the air temperature reached 40 °C, and it is known that the behavior of electronics, especially SiPMs, is very sensitive to their temperature. For cost reasons, our detectors do not contain any cooling elements. An additional effect may be related to absorption and also to the regeneration of the soft component of the large bundle in the walls and ceiling, the homogeneity of which we could not guarantee. Taking into account all the effects that led to unexplained differences in the number of coincidences, which at first sight should be identical, (e.g., "12- -" and "- -34"), is the subject of work currently in progress.

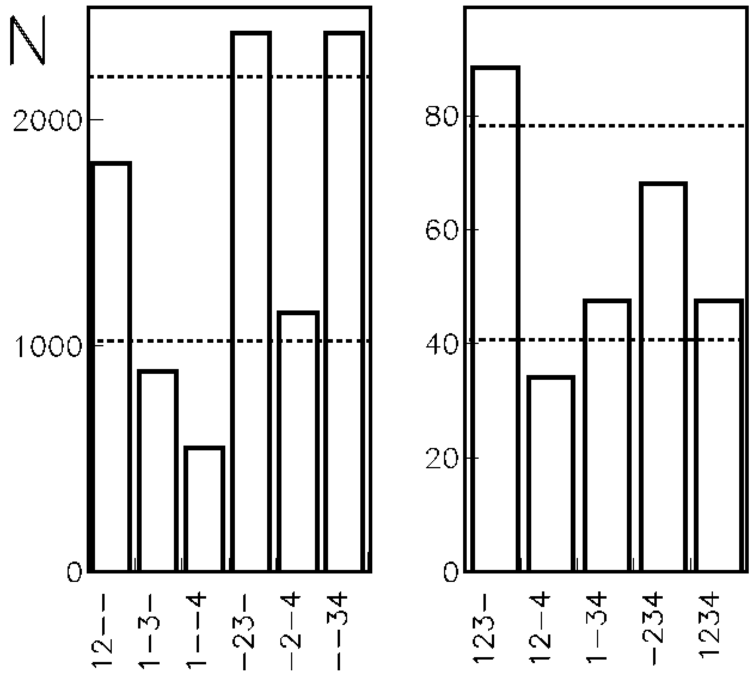

Figure 5. Counts recorded from 2 February to 6 March for different configurations of double- and triple-coincidence hit detectors. Lines show respective averages; see text for details.

In Figure 5, it can be seen that, in the case of a double coincidence, when the detectors are closer together, i.e., at a distance of 15 cm ("12-", "-23 -", or "- -34"), there are significantly higher counts than when the detectors are a further 30 cm apart ("1-3-", "-2-4"). A further increase to 45 cm in distance ("1- -4") results in a further decrease in count rates. A similar behavior was observed for the triple coincidence shown on the right side of Figure 5. There are more cases of coincidences between detectors that are right next to each other ("123-" and "-234") than between detectors that are far away from each other ("1-34" and "12-4"). The average counting rates that we are talking about are shown in Figure 5 using the respective dashed lines.

4. Educational Effect

The three examples shown above are excellent examples of how our CREDO-Maze station can be used in a variety of scientific projects beyond the scope of a high school, and with their complexity and the level of analysis of the results, the station is perfectly suited even to the theses of students at universities.

CREDO-Maze introduces a novel approach to extracurricular activities by leveraging technologically advanced yet conceptually simple measuring instruments. These instruments have undergone extensive testing at the University of Lodz, ensuring their effectiveness and reliability.

Groups of students from nearby schools visited the university on weekends and carried out measurements using the CREDO-Maze array. These activities sometimes lasted several hours and often continued for many sessions. Under our guidance, students who were more interested in programming ran a program to calculate the count rate, i.e., a de facto four-dimensional integral of a geometric element, while learning plane and spherical trigonometry. It should be emphasized that the ability to calculate integrals, and the concept itself, is beyond the standard curriculum, and yet the students did surprisingly well. Before the students started measuring muon fluxes in different configurations, they carried out tests of the detectors' uniformity and efficiency.

By measuring the change in the count rates of two detectors positioned one above the other as they are moved relative to each other along the long and short sides, and comparing this with the results of the integration program modified accordingly, it is possible to see a lack of deviation from uniformity. By stacking the three (as well as the four) detectors and recording instances in which a detector that was placed between other detectors that recorded a muon passage failed to register this passage, it is possible to determine the efficiency of the detectors. The results presented in [15] allowed us to estimate that the efficiencies of all four detectors were around 90% (from 87% to 91%). The other detectors tested had efficiencies above 80%.

It is also interesting to measure the change in count rates as a function of the vertical distance between the top and bottom detectors.

The students measured the properties of secondary cosmic ray particles (mainly, therefore, incoherent muons) in an attempt to determine their angular distribution. This measurement is difficult in that it takes time to collect the right statistics, and ultimately, a series of measurements from different weekends, which differ fundamentally in the intensity of the muon flux caused (for example, due to changes in atmospheric pressure), must be properly merged. A separate class of measurements is that of muon absorption, which the students measured by covering the lower detectors with layers of lead in different thicknesses. Outdoor measurements showed that, when the lead layer was of the order of one to several cascade units, the effect of radiation "regeneration", i.e., the conversion of secondary gamma quanta into electron–positron pairs, was evident. With a thicker layer, the soft component was cut off, and a very weak absorption of cosmic muons in the matter was observed. Additional absorption measurements were made when the position was changed from one story to another.

The tests of the detectors in the telescope setup, in which the detectors are stacked on top of each other, show, on the one hand, the correct operation of the whole system and, on the other hand, the possibilities for active use in school and extracurricular activities. The above examples of experiments do not exhaust the possibilities that we suggest for teachers and students, but they show the flexibility of the set, inviting the participants in the CREDO-Maze project to show their own ingenuity.

The technology for the large-scale production of these devices is now being implemented. High school students are actively involved in the assembly and testing of kits for their educational institutions.

Involving students directly in the construction and operationalization of their monitoring stations serves as a powerful motivational tool. Supervised by scientific staff, students construct and manage fully functional monitoring stations within their school environments. This hands-on experience enhances students' engagement and fosters a deeper interest in scientific pursuits among peers and the broader school community. Previous initiatives of a similar nature (Quarknet, HiSPARC [20], CZELTA [22], ADA [17], and EEEs [16]) have shown positive outcomes, reinforcing the value of practical scientific work in education.

The monitoring stations are ideally placed in educational settings such as schools, where they are most effective. Suitable educational levels for this type of integration include the eighth or ninth grade and upper secondary school (or gymnasia or high schools in certain countries), where curriculum goals align well with the project's objectives.

For instance, Finnish secondary and upper secondary curricula provide a framework for integrating such projects into the existing educational structure (Finnish National Agency for Education Curriculum, 2014 and 2019) [27,28]. Subject teachers at these educational levels guide students through complex projects that include detector assembly and testing (technical work starts in the eighth grade), programming (starts as soon as the third grade), data analysis (starting from the eighth and ninth grades), and multidisciplinary projects (starts from the first grade). Science and scientific research (what it means in real life) and scientific literacy are key learning goals for secondary school levels. From the physics side, although the structure of an atom is already introduced at the secondary level, more in-depth coverage of radiation, and especially cosmic radiation, is introduced at the upper secondary levels. Depending on a course's time resources, cosmic radiation is included or left to additional activities. However, if extra physics courses are available (school-dependent), cosmic radiation and further in-depth experimentation could be an option.

Implementing the CREDO-Maze project in schools advances scientific knowledge and enriches educational experiences through its alignment with STEM education goals. The projects can be conducted on a school-based level or as part of a larger global scientific endeavor. This contributes to local educational goals and broader scientific research.

5. Conclusions

The CREDO-Maze project operates at the intersection of physics and astronomy, addressing complex questions within these disciplines. As a pioneering effort, it has established a global network of local cosmic ray extensive air shower recording stations situated (primarily) at educational institutions. And it is this global character of the CREDO-Maze project that is essential and decisive for CREDO's main task: the search for cosmic ray ensembles. This project exemplifies the innovative integration of scientific research with educational outreach. By introducing advanced scientific research into classroom settings, the CREDO-Maze project enhances our understanding of cosmic ray phenomena, and it also enriches educational experiences. It provides students with practical contexts for learning advanced physics and other STEM subjects, such as mathematics, data analysis, and programming.

As a cost-effective and engaging educational tool, CREDO-Maze introduces students to scientific concepts that are often absent from standard curricula. It facilitates the creation of local research groups in schools, organized by educators and linked to major scientific centers. This approach fosters a deeper institutional engagement in research and innovation in informal education.

In the future, a critical task for all educational cosmic ray detector projects, including CREDO-Maze, will be facilitating global data sharing and standardizing data formats. This will enhance cooperation among researchers and students worldwide and enable the development of a comprehensive, global-scale muon detection network. These collaborative efforts are essential to maximizing the scientific and educational potential of distributed cosmic ray detection projects.

Ultimately, the CREDO-Maze Project aims to clarify the relationships among space, fundamental particles, and the universe. The engagement of students and communities in this exploration, it is hoped, will lead not only to an increase in specific scientific knowledge but also to a general improvement in scientific literacy. This project enriches the lives of participants and their communities, promoting more informed engagement with the world around them.

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