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# CREDO-Maze Project: after-school activities in contemporary physics for talented high school students

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We propose to create the global network of small, cheap and simple school Extensive Air Shower mini-arrays. The data registered in each school will be sent to a local database of the city/ region supervised by the nearby universities or research institutes. Each student could use them to create their own (or the student science club) scientific research program, in consultation with scientists. Local databases will be parts of the central CREDO (Cosmic Ray Extremely Distributed Observatory) database system collecting all registration. They could be used, certainly, by each individual student, but also for "professional" research on cosmic rays, searching for sources, determining parameters of particles with the highest energies, but also for searching for the new physic. Our school array network, and particularly the portable single particle detector modules can help teachers to teach elements of modern physics and to extend standard physics curricula. Additionally, they will provide the set of themes for gifted students, for science clubs, to create a student science project for science fairs, and other similar events. Currently, high school students test a prototype version of the station at the University. They perform measurements on their own, albeit under expert supervision, which will eventually form a part of a set of issues we are preparing to help teachers, gifted students, and science clubs create individual student projects for science fairs and other similar events.

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## 1. Introduction

Cosmic rays are a phenomena known for over a hundred years, but so far their origin, acceleration and variability mechanisms are not clear in details. Many questions about, for example, the cosmic weather and the impact of cosmic radiation on humans and human activities have not yet been answered definitively. Extensive Air Showers (EAS)[1] are initiated by a single cosmic ray particle interacting in the upper atmosphere and creating a cascade of elementary particles traveling to the surface of the Earth. They arrive as a disk of millions of particles for one short instance. Recently there has been proposed an even larger shower-like event, so-called Cosmic Ray Ensembles [2], in which bundles of ultra high energy cosmic rays can produce simultaneous showers over the entire exposed surface of the Earth. Such a phenomenon has never been seen, but there are several models under which such an event is a possibility, including the decay/annihilation of superheavy dark matter particles [3]. Searching for such hypothesized Cosmic Ray Ensembles (CRE) is the driving science case behind the CREDO Project [4–6]. It formally commenced operations on Sept. 11, 2019 after approximately three years of network and software infrastructure development [6, 7]. By design it was imagined as a global research endeavor, and currently consists of 20 countries involving 46 scientific and educational institutions [8, 9]. The CREDO infrastructure centers around correlating myriad cosmic ray data from any apparatus around the world, including professional instruments, educational detectors and arrays, and popular devices such as smartphones [6, 10].

## 2. CREDO-Maze Project

The concept of the CREDO-Maze array was developed based on the 20 years old Roland Maze Project [11, 12]. Roland Maze was a co-discoverer of Extensive Air Showers. The apparatus he built on the roof of the École Normale Supérieure in Paris enabled simultaneous recordings of high-energy particles to be observed by two distant (30 m) detectors. His name appeared alongside Pierre Auger's in the headlines of the first papers of 1938 reporting the discovery of radiation of unimaginably high (for those times) energies reaching us from space. Roland Maze was a student of Professor Auger. Today, the largest EAS arrray is located in Argentina and is called the "Pierre Auger Observatory". Comparing the scale and tasks of our project with those of the international and several hundred million dollar ($) Auger Project, it seems quite appropriate to name our venture in tribute to the great scientist that was Roland Maze. It is also worth mentioning that at the beginning of the 1950s, when a cosmic ray physics laboratory was established in Lodz, Roland Maze closely collaborated with Lodz physicists A. Zawadzki, J. Hibner, J. Gawin and J. Wdowczyk. He was a co-author of many publications that strengthened the position of the Lodz centre among the significant high-energy physics institutes in the world.

Technology has evolved a lot since the beginning of the century when we first attempted the Ronald Maze Project, and Linsley's idea of local shower arrays can now be implemented much more easily and, importantly, much more cheaply. Ultimately, we want to equip secondary schools with sets of "professional" cosmic ray detectors linked locally to create a small school EAS array. Once they are all connected, the project will create a global, unique physical apparatus, which will consist of a network of local (school) measuring stations. Some similar attempts were introduced in some locations at the end of previous millennium—the best known example is the

High School Project on Astrophysics Research with Cosmics (HiSPARC) [14] in the Netherlands; as well as WALTA [15], NALTA, ALTA [16], SALTA, CZELTA[17], SKALTA, CHICOS [18], MARIACHI [19] which were made but with no ambitions to expand to a global scale. Some of them are ephemeral; some are in a different phase of realization.

Our method of conducting extracurricular activities consists in creating opportunities for students to conduct scientific research and perform experiments and measurements far beyond the school curriculum. The idea is precisely this ambitious and far-reaching entry into contemporary physics (and other related disciplines, such as electronics, computer science, mathematics, IT). Usually, the activities of school extracurricular circles consist in broadening the knowledge gained during lessons, practicing typical school skills. We offer participation in a serious scientific experiment, which is intended to motivate students right from the start. This different approach allows students to be able to use original equipment (that we give as a gift to the schools), have contact with scientists (important additional motivation!) and have their individual school measurements included in a network connecting other schools in the vicinity, as well as all other participating schools, which are sometimes located in very distant countries. Participation in the "global" project is expected to bring additional motivation absent from the standard extracurricular activities. This is intended to bring additional educational benefits.

The key, basic elements of the CREDO-Maze project are schools. The idea is to build around each centre (University, Research Institute, but also an educational institution, a team of schools, and even a school) a network of geographically related schools in which measurements with groups of interested young people will be carried out. These structures, let's call them "social", will be connected with the exchange of information, results, and presentation of mutual achievements—at the level of schools, local team of schools, but also at a wider forum of the local community, science festivals, fairs and other events.

The creation of local structures with young people involved and organised in research groups (led by teachers/educators), using network communication and relying on research centres such as, for example, colleges and universities, is an important step in the development and institutional activities of research performing organisations, including research funding organisations. The proposed activities open up new areas of innovation in non-formal out-of-school education. The creation of a model system of social communication networks and the demonstration of its effectiveness in the proposed field, which is an element of STEM, will allow for the planning and creation of similar networks implemented in other areas of education. There are no contraindications for such networks to include different groups of young people and research centres.

## 3. The CREDO-Maze array

Our project uses technologically sophisticated measuring equipment in extracurricular activities: detectors of charged relativistic elementary particles will be made of small plastic scintillators. The light pulses will be collected by optical fibers shifting the wavelength from ultraviolet to green, and then light will be converted into electrical signals by Silicone Photomultipliers. Further electronics will be based on high speed digital circuits and microcontrollers to connect to higher-level servers via the Internet and WiFi links.

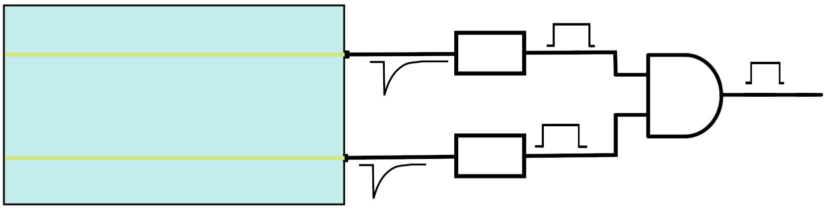

**Figure 1:** The concept of single detector

One of the important parameters of proposed equipment is the cost. It is easy to build an expensive and complicated, 100% effective professional array. We are on the way to building the prototype, which has a cost (including scintillators, SiPMs, trigger electronics, storage and data transmission micro-computer) that is below \$1000 (compared to 3000 EUR per detector for a $\mu$Cosmics detector, which is in [20] or around tens of thousands of euros for four detectors and the necessary electronics from CAEN (SP560x)).

In the current phase of the CREDO-Maze Project, we have obtained funds from the Polish Ministry of Education and Science. They will be sufficient to equip a few (up to 10) schools in the Lodz area and test the Project's principles in real conditions. This stage will end in the first half of 2023. In the second stage, on the basis of experience gained, we want to apply for more funds to expand the project to the scale of several dozen schools. With "mass production" of school shower arrays, prices should decrease significantly.

## 4. Detectors

The detectors we have proposed and tested exhibit very good detector properties, simple design and, above all, are inexpensive. 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 (portable), which gives new possibilities and allows for many interesting works "in the field".

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 below $10^{15}$ eV.

A plastic scintillator of size 10 cm × 20 cm is viewed through two small silicon photomultipliers (SiPMs).To maximise the amount of light collected, two 1 mm diameter optical fibres have been mounted in the scintillator and optically connected to the SiPMs. The scintillator, fibres and SiPMs have been wrapped in Tyvek paper and then re-wrapped in thick aluminium foil to shield the detector from visible light.

The logic of our detector is shown in Fig. 1 and the logic of the CREDO-Maze array consisting of four detectors is shown in Fig. 2.

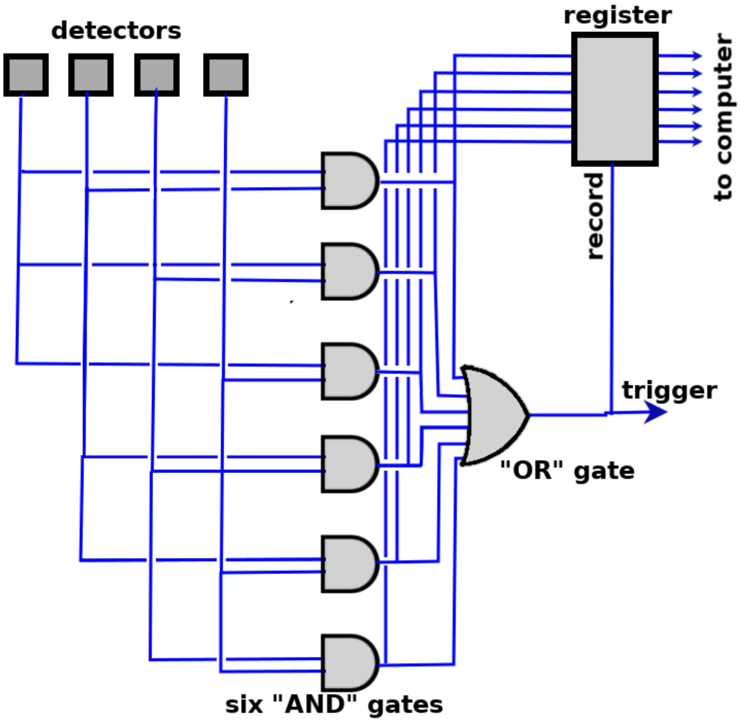

**Figure 2:** CREDO-Maze array logical structure.

### 4.1 Student experimentations

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. 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.

Using this equipment students can perform an interesting and somewhat sophisticated experiment. The information stored in the computer regarding which of the four detectors were hit allows the efficiency of the detectors to be determined. 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. This is not the real case. In Fig.3 we show results of our test measurement.

The final result of a more advanced fitting procedure for our test measurement is shown in Fig. 3b. The efficiencies found for all four detectors were 88%, 91%, 89%, and 87%, respectively.

Students can also check the uniformity of the detectors: 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. The measurement results are compared in Fig. 4, with predictions obtained from the integration of the incoherent muon flux at sea level with

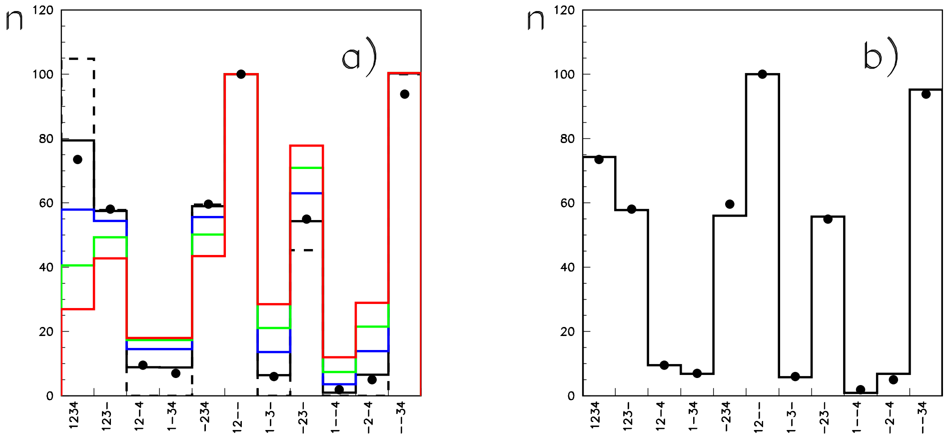

**Figure 3:** Measurement of the detector efficiency. Points represent our test measurements taken by students and the lines show calculation results for assumed 100% (dashed line), 90%(solid black line), 80% (blue), 70% (green) and 60% (red line) efficiency of all defectors; the back line on b) plot is our best fit of detector efficiencies (see text).

the condition that both detector surfaces of a given geometry are crossed. In particular, no signal fading effect is seen along the optical fibers.

Another experiment, which can be performed by students, consists in verifying the dependence of the counting rate on the vertical size of the "telescope". This measurement provides an understanding of quite abstract mathematical concepts such as the solid angle and allows a "semi-empirical" introduction to the processes of numerical integration and applied computer science, in general.

An arrangement of four detectors placed one above the other does not have to be positioned "vertically" as in the previous experiments. It can be turned so that its axis is directed at a certain angle to the zenith. It acts similar 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 do not come uniformly, isotropically from all directions, a rotated telescope will measure a different muon flux at different inclination angles. Its determining requires the corresponding calculation, which can also be done by students under the supervision of an expert.

The four vertically aligned detectors can be separated and layers of different materials can be placed in between. This will make it possible to determine the absorption of radiation in the matter and, with a proper interpretation of the results, it can separate out the gamma, electron-positron and muon components in the secondary cosmic rays. The result of such a measurement made by students is currently in print in the journal "Fizyka w Szkole" (in Polish).

The portable structure of our apparatus offers interesting possibilities. Measurements of muon fluxes at different altitudes above sea level, known from the literature, are waiting to be repeated by enthusiastic groups of students. One could also be tempted to make balloon measurements analogous to the Hess flights in 1912, although this venture requires a considerable logistical effort.

Power supply from powerbanks and local recording of results on memory cards makes it possible to put the entire apparatus in a waterproof container and then attempt to measure the

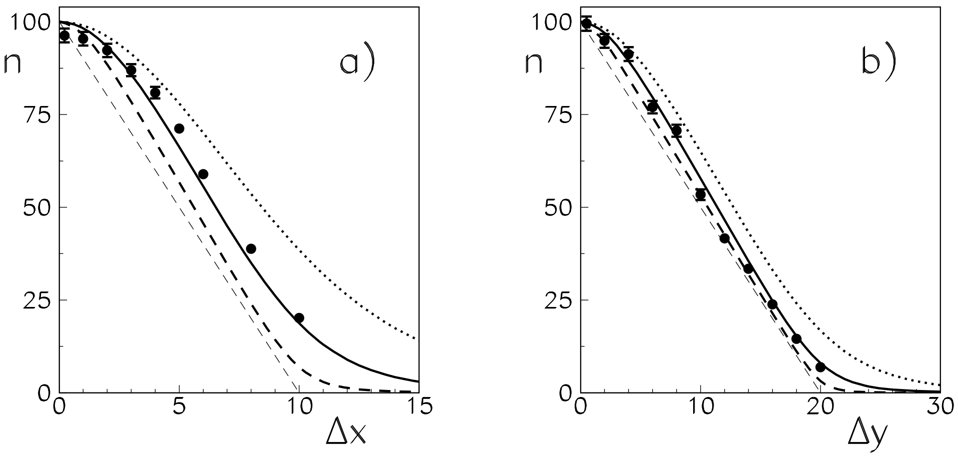

**Figure 4:** Coincidence rates in a telescope consisting of two detectors, one shifted along the long side a) and the other along the short side b). The lines show the normalized predictions. Different lines are for different vertical spacing of detectors. The solid one represents the actual 5 cm spacing and the points measured by the students correspond to this value.

muon (and electron) flux in water at various depths by repeating the measurements of Pacini from the beginning of the 20th century and Regener from the 1930s.

The problem of measuring the cosmic ray flux in natural and artificial underground caves is unexplored and interesting.

The use of muon tomography may also be the subject of research using our equipment.

With the collection of large EAS statistics by a particular school, or using data from many schools, one could attempt to determine the index of the shower size spectrum, which would be a major achievement by the students and the CREDO Maze Project as a whole.

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)[21].

Another historical experiment that can easily be repeated is the famous Auger and Maze experiment on the roof of École Normale Supérieure [22], in which they demonstrated, for the first time, the existence in nature of elementary particles with energies reaching $10^{15}$ eV. In order to conduct this experiment, 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]. The original figure is shown in Fig. 6.

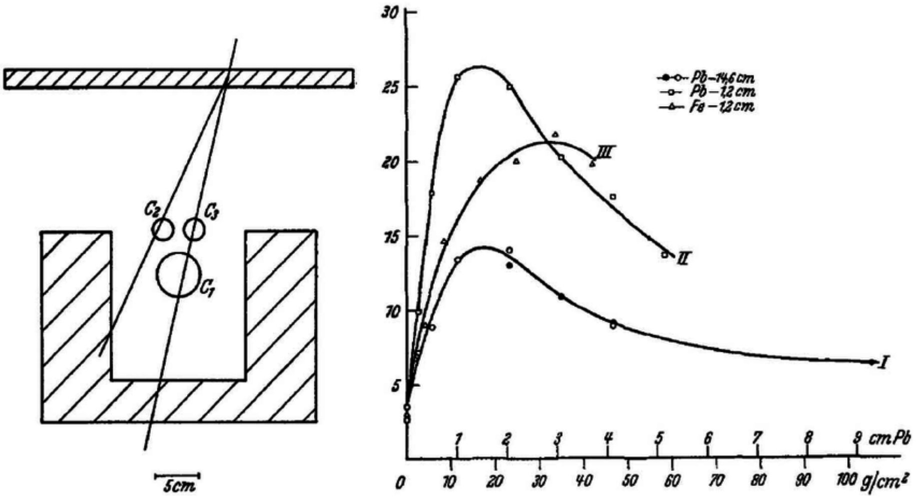

**Figure 5:** Rossi experiment (left) and Rossi curves (right).

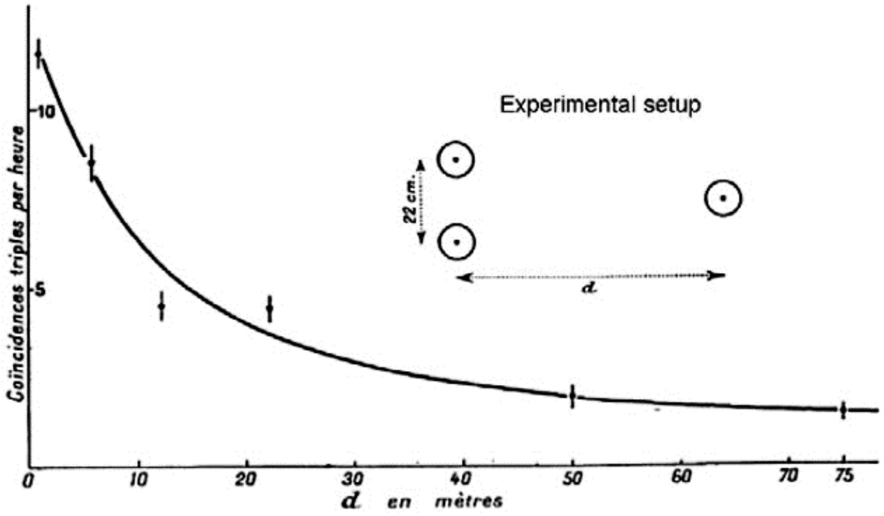

**Figure 6:** Auger and Maze's historic experiment discovering EAS.

## 5. Summary

We presented the design of a local small school EAS array. Our project aims at providing schools in the region, and in the future anywhere else, with the simplest, and thus the cheapest, easy to use scientific instruments that can be a real tool for practicing physics at a high level of sophistication, both for use in experimental physics as well as in the area of interpretation.

Money available to schools in their regular budgets will not provide them with the opportunity to acquire our experimental sets, so it is necessary to subsidize the project both from the central budget and from other sources, which we are counting on in the future.

The range of issues that can be explored in the CREDO-Maze Project is very wide. Proposals for various measurements will be included in the educational materials prepared for this purpose.

Currently, students are making measurements for several issues: angular distribution of cosmic muons, cosmic ray absorption in lead and other materials, homogeneity issues and detector efficiency. Each of these measurements requires many hours of data recording, and the students involved have many other activities and responsibilities. With proper organization of the work, the measurement itself takes a week, up to a month. In addition to the time needed to complete the experiment, there is also the time needed for preparation of the measurement set and theoretical preparation (with our help) for the measurement, as well as the processing of the results, which is the most difficult task and takes a lot of time, meetings and discussions. We have created topics and condensed sets of instructions for doing several more (currently eight) exercises. In summary, this ensures the work of the interest circle for a year or so. In the future, when a number of school stations appear and a central database is created, there will be a list of topics for the search for correlations and dependencies of the distributed registration of showers, which is difficult to determine in time.

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