MoCRiL: Pacini's experiment in a modern and educational way

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Abstract. The MoCRiL (Measurements of Cosmic Rays in Lake) project has re-proposed, in an educational way and using modern measuring instruments, Domenico Pacini's experiment for determining the origin of the natural ionizing radiation that surrounds us in any instant. The students of 4 different schools from Calabria Region with the collaboration of the INFN researchers (OCRA collaboration of Cosenza [1]) and of the Physics department of UNICAL, performed the measurement of the ionizing particle rate at different depths in the waters of the Arvo Lake in the Sila plateau (1300 m asl). The aim of this project is to let students know and understand the often very difficult way that leads to scientific discovery, sharing ideas and results with other students, from different years and schools, and with teachers and researchers.

1. Introduction

For over a century we have known that ionizing radiation is present in the air, capable of traveling considerable distances before being absorbed and for this characteristic it has earned the nickname of "penetrating". At the beginning of the 20th century, it was believed to be produced by the radioactive chemical elements present in the earth's crust. In particular from the elements present in the minerals of the mainland and to a much lesser extent in the sea water and in the air. The mystery about the nature and origin of this radiation was made even more deeper by the lack of knowledge of the physical mechanisms that regulate the atom. It was known that atoms, in the sense of J.J. Thomson, were capable of emitting ionizing radiation but the physical laws that explain the causes and dynamics of these phenomena were not yet known. The studies conducted in the first 30 years of the last century were fundamental for scientific progress in the atomic and sub atomic universe and in particular for the discovery of the nature of the penetrating ionizing radiation that we now call cosmic-rays. In this regard, the contribution of Domenico Pacini [2] was fundamental, together with the studies of Victor Hess, to affirm the extraterrestrial nature of these penetrating radiations. The authors of the MoCRiL project then reproposed the measurements made in air and in water at different depths to retrace Pacini's historical-scientific path and put themselves in his shoes and those of his contemporary scientists with the aim of understand “in the field” the results of his historic experiment. The schools involved in this project were: Liceo Scientifico "Stefano Patrizi" of Cariati (CS), Liceo Scientifico "E. Fermi" of Catanzaro, Liceo Scientifico of Tropea (VV), Liceo Scientifico "A. Volta” of Reggio Calabria and the students of the physics department of UNICAL (University of Calabria) of Rende. The measurements were first carried out in the schools involved in the project and then completed at Lake Arvo on the Sila plateau (1300 m asl). The project was carried out within the framework of INFN's OCRA project [3].

2. Experimental apparatus

The measurement of the rate of ionizing particles was performed with ArduSiPM detectors [4-8] designed by Valerio Bocci et al. of the INFN of Rome. The ArduSiPM detector, which can be purchased on the internet under the INFN license, consists of an Arduino DUE board, a front-end board, a SiPM (Silicon Photomultiplier) and a plastic scintillator (BC408) 50x50x5 mm size (fig. 1).

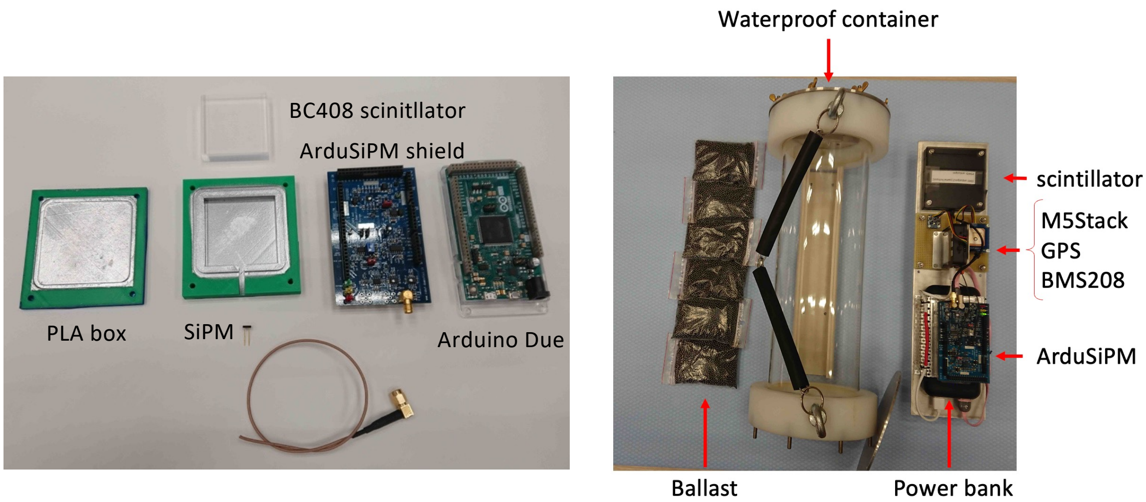

Figure 1 The ArduSiPM detector on the left and the water proof container on the right together with the ballast and all the services.

The SiPM used is HM-S13360-1325CS [9]. It has an active surface of 1.3x1.3 mm, and is composed of 2668 APD diodes each with a size of 25x25 µm operating in Geiger mode. The instrument is completed with a GPS sensor, a BM208 weather station and a 20000mAh power bank. An M5Stack microprocessor is used to read the digital signals provided by the ArduSiPM, to store them on a microSD card and to transmit the last set of signals acquired via wi-fi to a smartphone / tablet / laptop. Having to perform measurements by immersing the instrumentation in water, an airtight plexiglass tube was built capable of withstanding the pressure of water up to depths of at least 50 meters. The needed ballast is made up of lead balls, 1mm diameter, placed on the bottom of the plexiglass tube. Hereinafter the waterproof container and the instruments contained inside will be indicated with the name of "submarine". 5 of these "submarines" have been built, one for each of the groups of Calabrian students who have joined the project. The submarines were delivered to students starting April 1, 2022.

3. The measurements made at school

The students carried out ionizing radiation counts in their respective schools from 1/4/22 to 30/5/22, that is, up to the day before the experience at Arvo Lake. These measures served to gain confidence with the instrumentation, with the data analysis to be carried out and with the procedures that would then be adopted during the measurement campaign at Arvo Lake. Students performed some measurements for each day of the two months preceding the lake measurements: the instant of time provided by the GPS in which the measurement takes place, the counts per minute (CPM), the temperature, the atmospheric pressure and the relative humidity. All the measures were collected in a file shared between all the groups so that everyone could verify the work of others and find reasons for discussion. Students experience a random phenomenon with fluctuations on the order of the square root of the mean CPM value (Poisson distribution). Furthermore, they encounter an example of correlation between two variables and learn that the gain of SiPM transducers - the electrical signal produced for a certain amount of incoming light - is inversely proportional to temperature. They learned how to use histograms as a powerful analysis tool. In particular, they understand that the data are symmetrically dispersed around a central value and that the histogram has the shape of a bell (Gauss curve) typical of the distribution of random events. Last but not least, the students learned that similar detectors give different results and found that the difference is mainly due to the different detection efficiency of the detectors used and, to a lesser extent, to the different natural background radiation in the place where ~~it is used. performed~~ the measurements were performed and at the different temperature in which the detectors operated.

4. The measurements made at Arvo Lake

On May 31, 2022, all five groups of students (in total 120 students and 10 teachers) met at Arvo Lake (1300 m asl) to measure the rate of ionizing particles on the lake shore, on the surface of the lake and underwater, at different depths. The measurements started at 8:00 am on the lakeshore in a tree lined area with the detectors placed directly in contact with the ground. Then the submarines were moved at 9:40 am on the Loricaly boat used for measurements above and below the lake surface. At 10:20 am the boat stopped about 50 meters from the lake shore to put the submarines into the water with its own raft. At around 10:50 am, measurements under the lake's surface began. Due to the limited duration of the measurement campaign and the good thermal shielding of the photosensors, the effects of temperature on the gain and therefore on the CPM have been neglected. The average value of the CPMs acquired by the groups at the different depths are shown in table 2.

Group	Depth 1 (cm)/CPM	Depth 2 (cm)/CPM	Depth 3 (cm)/CPM	Depth 4 (cm)/CPM	Depth 5 (cm)/CPM
Cariati	50±2	100±2	180±2	320±2	490±2
	29.09±0.91	23.13±0.57	18.21±0.53	14.71±0.19	14.56±0.19
Catanzaro	30±2	80±2	140±2	260±2	430±2
	27.72±0.35	30.97±0.65	20.59±0.92	22.53±0.28	13.40±0.28
Rende	60±2	110±2	200±2	350±2	520±2
	38.41±0.65	39.81±0.62	27.84±1.14	28.41±0.25	19.18±0.26
Tropea	40±2	90±2	160±2	290±2	460±2
	- not detected-	23.18±0.35	- not detected -	17.03±0.81	14.19±0.27

Table 1 Mean value and standard deviation of the mean of the CPMs measured at the 5 depths at which the submarines were immersed and acquired data.

Figure 2 shows the normalized rate

$$R_i^{norm}(d) = [R_i(d)/\varepsilon_i]\,(\Sigma R_i^0/4) \,/\, (R_i^0/\varepsilon_i) \quad (1)$$

for 4 detectors. The quantities d_i and ε_i refer to the depth and detection efficiency of the detector i, respectively. The data acquired by the 4 detectors follow the same behavior. The data were then fitted with an exponential plus a constant and the result is shown in figure 2.

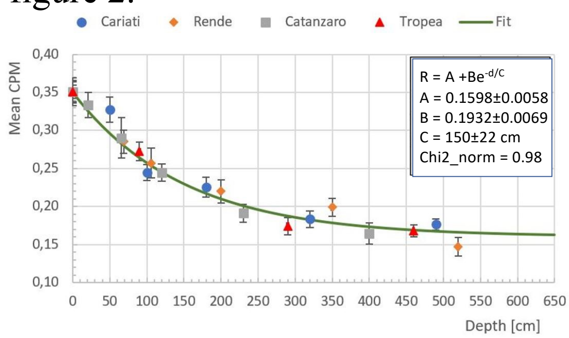

Figure 2 Average value of the rate measured by the detector "i" at depth d normalized to the ratio $\Sigma R_i^0/4$. The suffix 0 indicates the measurement carried out on the surface of the lake. The error bars are statistics.

This function describes the attenuation of a radiation coming from above made up of two components, one not very penetrating and one much more penetrating. The radioactivity component of the seabed is excluded since the radioactive elements present in the earth's crust produce particles with energies comparable to the nuclear binding energy (some MeV) and are strongly attenuated in water, as was well known to Pacini and physicists of his time. The not very penetrating component is characterized by the attenuation length c=150±22cm.

5. Didactic impact

The MoCRiL project is a real scientific experiment made by researchers of University and INFN and students of five different high schools. The primary objective of the project was to bring students closer to the world of science and research, proposing them as protagonists in all phases of the activities. Apart from the undisputed scientific value of the project, particular importance was given to the pedagogical-educational aspect. Participation in all phases of the project allowed the students to become aware of the difficulties that emerged during the setting up of the experiment and also to grasp the less evident but more significant aspects that are an integral part of each experimental activity. Particular attention was paid to the formulation of a questionnaire administered about a month before the implementation of the experience to the students involved in the MoCRiL project (137 pupils of which 46 boys and 91 girls) and to an uninvolved sample (113 pupils of which 76 boys and 37 girls). The same questionnaire was then re-proposed, only to students who participated in the measures immediately after the experience. From the analysis of the responses received from the sample that did not participate in the experience, one of the most dominant weaknesses in teaching experimental subjects was the scarce use of the laboratory. From the analysis of the answers to the questionnaire by the students who participated in the experience, comparing the answers given before with those given after having participated in the MoCRiL experience, however, very evident confirmations emerge on the effectiveness of laboratory teaching in the learning processes, in the perception of physics as a discipline present in our daily life, also useful for the training of future aware citizens. From this analysis it is also evident the awareness, experienced in the field, of the importance of teamwork and collaborations between the school and research institutions and / or universities and above all a significant reduction of many misconceptions related to physics and harmful to university orientation.

6. Conclusions

The aim of the MoCRiL project was to carry out professional measures with students and teachers of higher education institutions, university students and INFN and university researchers. To reproduce the experiment by D. Pacini, the authors of the MoCRiL project chose a scintillation counter, powered and controlled by the ArduSiPM board. The students learned that the rate of radiation present in the air is a random variable with an average value that depends on the place where the measurements are made; the rate decreases moving from the mainland to the surface of the lake, demonstrating that part of the penetrating radiation originates from the radioactive decay of the elements present in the earth's crust; the rate decreases by immersing the detector at different depths with a mathematical law which is the sum of a constant and an exponential.

Domenico Pacini's research represents a turning point in the studies on the origin of what was considered a *mysterious phenomenon*. They marked the beginning of the underwater technique for the study of cosmic rays [10-12], forerunner of the dozens of experiments that have been carried out since then and which will continue to be carried out to better understand the laws of physics that govern our Universe.

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