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Measurement of the cosmic radiation flux in water as a function of detector depth

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Summary. — 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 the Calabria Region with the collaboration of the INFN researchers (OCRA Collaboration of Cosenza) 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. In those years, studies concentrated on understanding the nature of this radiation and in this regard the contribution of Domenico Pacini [1] was fundamental, together with the studies of Victor Hess, to affirm the extraterrestrial nature of these penetrating radiations. The authors of the MoCRiL project [2] then re-proposed the measurements made in air and water to retrace Pacini's historical-scientific journey and put themselves in his shoes and in those of his contemporary scientists with the aim of understanding the results of his historic experiment. This project saw the participation of dozens of students of the high schools *S. Patrizi* of

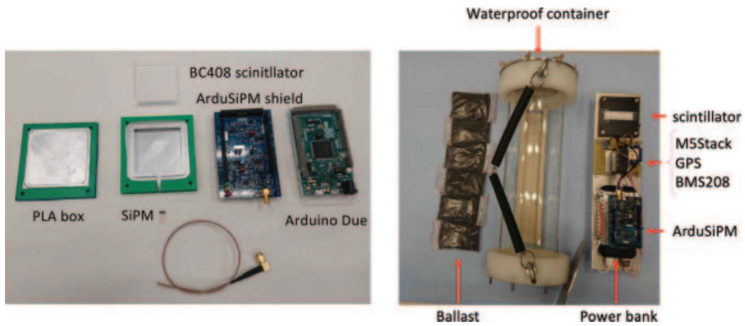

Fig. 1. – The ArduSiPM detector on the left and the water proof container on the right together with the ballast and all the services.

Cariati (CS), *E. Fermi* of Catanzaro, IIS of Tropea (VV), *A. Volta* of Reggio Calabria and the students of the Nuclear and Subnuclear Physics Laboratory of the University of Calabria. Measurements began in the physics laboratories of the schools, and were then completed at Lake Arvo on the Sila plateau (1300 m asl). The project was carried out within the OCRA project of the INFN [3].

2. – Experimental apparatus

The measurement of the rate of ionizing particles was performed with ArduSiPM detectors [4] 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) $50 \times 50 \times 5$ mm size. The instrument is completed with a GPS sensor, a BM208 weather station and a 20000 mAh 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 instrumentation in water, a watertight container was built capable of withstanding the pressure of water up to depths of at least 50 meters. The needed ballast was made up of lead balls, 1 mm diameter, placed on the bottom of the plexiglass tube. Figure 1 shows the ArduSiPM with the scintillator black box on the left and the watertight container on the right. Hereinafter, the waterproof container and the instruments contained inside will be indicated with the name of *submarine*. Five *submarines* were assembled and tested at the INFN laboratories and delivered to the five groups of students many weeks before the meeting at Lake Arvo, with the aim of counting the ionizing radiation in the respective schools to familiarize themselves with the instrumentation to be used, with the data analysis to be carried out and with the procedures to be adopted at Lake Arvo.

3. – The measurements made at Arvo Lake

On May 31, 2022, the 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 early in the morning on the lake shore with the detectors placed directly in contact with

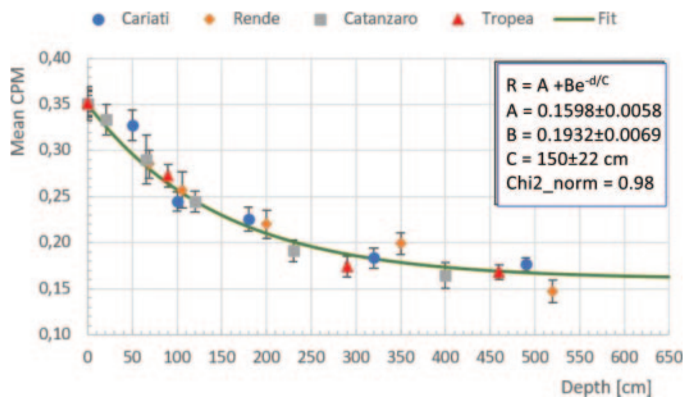

Fig. 2. – Average value of the rate measured by detector "i" at depth "d" normalized to ratio $\Sigma_i R_i^0/4$. The error bars are statistics.

the ground. An hour later, the *submarines* were moved to the surface of the lake about 50 meters from the lake shore to be placed in the water on top of their own raft. Half an hour later, the *submarines* were immersed in water. Due to the limited duration of the measurement campaign and the good thermal shielding of the photosensors, the effects of temperature on the gain have been neglected. To compare the measurements made by the ArduSiPMs with each other, the counts per unit of time were normalized to the average value of the rate measured by all detectors at the lake surface $R_0 = \Sigma_i R_i^0/4$:

$$R_i^{norm}(d) = \frac{R_i(d)}{\epsilon_i} \cdot \frac{R_0}{\frac{R_i^0}{\epsilon_i}}. \tag{1}$$

Quantities d_i and ϵ_i refer to the depth in water and detection efficiency of detector i, respectively. The data acquired by all the detectors as a function of the depth in water follow the same behavior, and therefore they have all been fitted with the same function $R(d) = A + B \cdot e^{-\frac{d}{C}}$. The result is shown in fig. 2. This function describes the attenuation of a radiation coming from above and 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 low energies (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 attenuation length $C = 150 \pm 22\,\text{cm}$.

4. – Didactic impact

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. 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 to the project immediately after the experience. From the analysis of the responses received from the samples, 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 afterwards, 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 and the importance of teamwork.

5. – 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 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 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 [5, 6], 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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REFERENCES

[1] Pacini D., *Nuovo Cimento*, **3** (1912) 93.
[2] Bocci V., Iacoangeli F., Liguori D., Passarelli D., Reino W., Schioppa M. and Tomei C., *G. Fis.*, **LXIII** (2022) 343.
[3] Aramo C. and Hemmer S., on behalf of the OCRA Collaboration *PoS*, **ICRC2019** (2019) 173.
[4] Bocci V., Chiodi G., Iacoangeli F., Nuccetelli M. and Recchia L., *2014 IEEE Nuclear Science Symposium (NSS/MIC)* (IEEE) pp. 1–5, https://doi.org/10.1109/NSSMIC.2014.7431252.
[5] Pacini D., *Rend. Acc. Lincei*, **18** (1909) 123.
[6] Pacini D., Ann. Uff. Centr. Meteor. **XXXII**, parte I; Le Radium **VIII** (1910) 307.