CORAM (COsmic RAy Mission): an outreach program one century after Pacini and Hess works

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1. Introduction

CORAM (COsmic RAy Mission) is an outreach program carried out by INFN and the University of Salento in close collaboration with high schools. Students and their teachers are involved in the design, construction, test and operation of detectors for the measurement of several properties of the cosmic ray flux. The results of a set of measurements, made with a first detector prototype at different altitudes and underground, will be described.

At the beginning of the 20^{th} century, Domenico Pacini performed several underwater measurements in order to establish the variation of an electroscope discharge velocity, i.e. the radiation intensity, as a function of depth [1]. At the same time, Victor Hess measured a variation of the radiation intensity with the altitude [2], discovering that going up in the atmosphere with a balloon the electroscope discharged more quickly. These and other subsequent works lead to the demonstration that the unknown radiation come from outer space, hence the name "cosmic rays".

Today it is well known that cosmic rays entering the Earth's atmosphere (i.e. the primary cosmic rays) are mainly composed by atomic nuclei and a small amount of photons, electrons and positrons. Their energy varies in a wide interval reaching about 10^{20}eV. Primary cosmic rays interacting in the atmosphere generate extensive air showers (EAS) of secondary particles that reach the ground. The muon flux at sea level is about 300 Hz/m^2 [3]. The dependence of secondary cosmic ray flux on the altitude is then characterized by a maximum followed by an exponential decay (towards sea level). This behaviour is also known as *Pfotzer plot* from the name of the physicist that first performed different measurements with weather balloon and using particle detectors put into coincidence at different altitudes [4]. The position of the maximum in the *Pfotzer plot* depends on different factors, like the considered particle type, the geomagnetic latitude, the detection energy threshold, etc. However all the components show a peak at around 100-150 g/cm^2 of atmospheric depth, corresponding to about 18 km above sea level (a.s.l.).

The goal of CORAM is the dissemination of (astro) particle physics, and related techniques, among high school students, through the measurements of several properties of the *natural particle beam* given by cosmic rays. In a first phase, students and teachers attended several seminars concerning the introduction to particle and cosmic ray physics, covering also the basic concepts related to detection techniques and data acquisition and analysis. Then they were fully involved in the design and building of a *cosmic ray detector*. Some properties of the cosmic ray flux can then be measured and data analyzed and compared with our current knowledge on this topic.

This work describes the results of some measurements taken with a first detector prototype. The dependence of the cosmic ray flux (above a given energy threshold) on the altitude has been investigated by means of a set of measurements done in Lecce and in several places around the Gran Sasso massif in central Italy, up to about 2100 m a.s.l. This approach allowed students to repeat (part of) the same type of investigations made in the summer 1939 by Bruno Rossi and J. Barton Hoag going from Chicago to Mount Evans [5]. In the following sections we will illustrate the experimental setup and the measurement results.

2. The experimental setup

In Fig.1 a prototype of the detector is shown. It is made of four tiles of plastic scintillator interposed with iron absorbers. Each tile has dimensions of $14.3\times14.3\times1.0$ cm^3 and density of 1.032 g/cm^3 (BC-412); iron absorbers have the

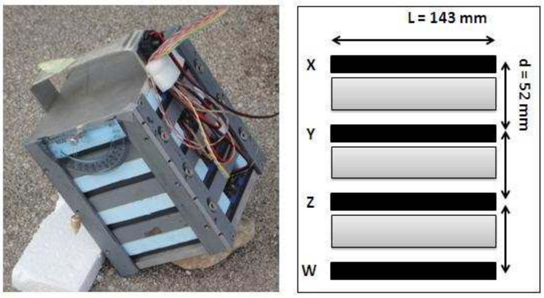

Figure 1. The first detector prototype used in the test campaign (left) and its schematic layout (right) with the names that we assigned to each tile, i.e. X, Y, Z, W starting from the top.

Site	Altitude (m a.s.l.)	Atm. depth (g/cm^2)
Lecce	35	1032
Brecciarola	65	1028
Navelli	684	955
LNGS external lab	990	920
Fonte Cerreto	1120	906
Rocca di Cambio	1270	889
Rocca di Mezzo	1366	879
Monte Cristo	1453	870
Campo Imperatore	2140	799

Table 1
Altitudes above sea level for the various experimental sites. Atmospheric depths, as given from the so called *standard atmosphere* parametrization, are also shown [9].

same size but a 2 cm thickness. Scintillation light is detected by two APDs (Avalanche Photo-Diodes) with 1 mm^2 sensitive area and it is collected through a wavelength-shifting (WLS) optical fiber of 1 mm diameter [6]. The flexibility of the fiber allows packing them in circular coils thus increasing the light collection efficiency over the plastic volume. This setup has been chosen because it allows enough stability and avoids the use of high voltage supply as is the case for photomultipliers. Through the coincidence of four horizontal tiles, it is possible to detect cosmic ray muons with minimum energy of about 150 MeV.

Front-end electronics are placed over each tile, which allows for discriminating signals from the two APDs and for sending the signals to the DAQ system, which comprises an FPGA[1] and a controller[2]. Data are processed from the FPGA in a defined time window through a look-up-table for coincidence counting. The results are sent to the controller that provides the timestamp with the time information from a GPS receiver integrated in the DAQ. Moreover, it also provides the environment temperature records, defines the time window for data acquisition, saves data on a SD-Card and finally sends them serially to a telemetry system or to a computer for test purpose. An appropriate graphical user interface was also developed using the LabView [7] software.

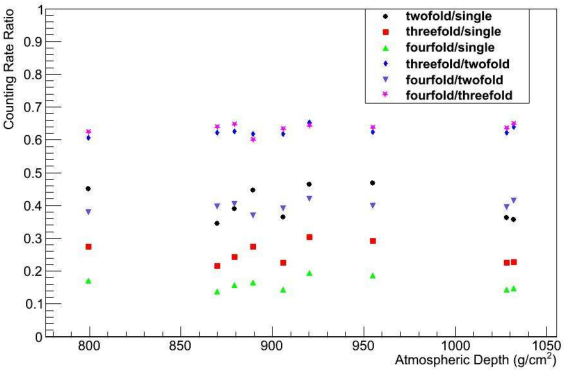

Figure 2. Ratios of coincidence rates measured at different atmospheric depths.

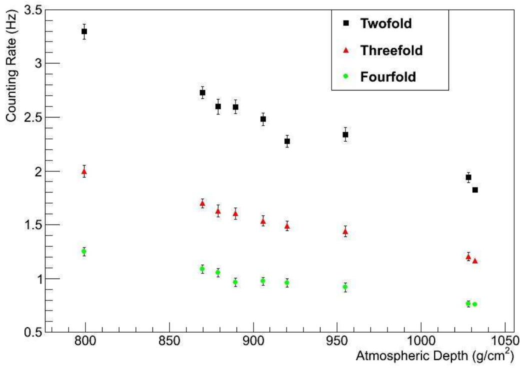

Figure 3. Detected two, three and four-fold coincidence rates as a function of the atmospheric depth.

3. Results of the measurements

Students participating to the project were directly involved in the construction and test of the detector prototype. In small groups, they worked at the Astroparticle Physics laboratory of the University of Salento and INFN Lecce, for assembling and testing the detector. Detailed test

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[1] Xilinx Spartan 3E 500K
[2] MicroChip PIC18F87J50

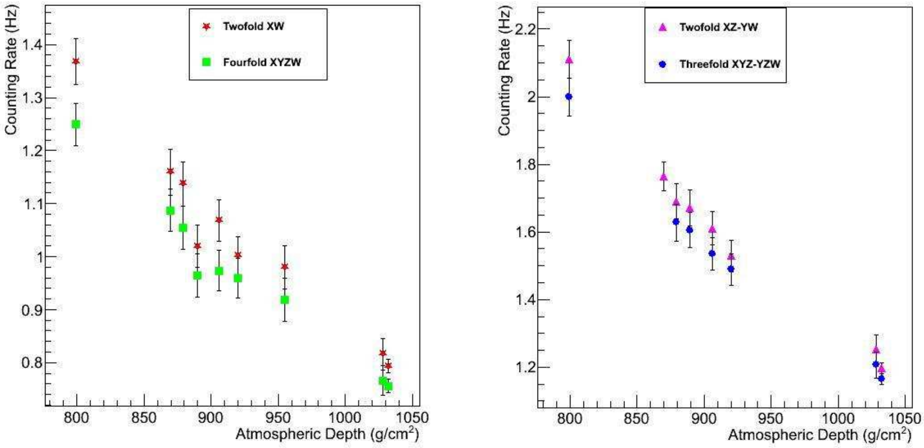

Figure 4. Left: comparison between the twofold coincidence rates for the two outer tiles (X and W) and the fourfols coincidence rate is shown. Right: comparison between the twofold coincidence rate for not-adjacent tiles (XZ and YW) and the threefold coincidence rates. Those plots have been used for a further single layer efficiency measurement (see text).

results can be found in [8]. In March 2012 a first measurement campaign has been organized with students and their teachers, the main goal being the study of the dependence of the detected cosmic ray flux on the atmospheric depth. Measurements were done in differet locations starting from Lecce and going toward the Abruzzo mountains up to Campo Imperatore, a plateau in the Gran Sasso massif at about 2100 m above sea level. The sites together with their altitudes and atmospheric depths are listed in Tab.1.

As a first check, the ratios of several coincidence types (e.g. twofold to threefold, etc.) were studied as a function of the altitude. As expected, those ratios tourned out to be independent from the atmospheric depth (see Fig.2). Moreover their absolute values are in agreement with calcuations taking into account the single detector efficiency measurements made in the Lecce laboratory (see [8]) and simple acceptance estimations.

In Fig.3 the measured rates for two, three and four-fold coincidence, are reported as a function of the atmospheric depth. We can see that the counting rates increase going from sea level ($\sim 1035 g/cm^2$) to Campo Imperatore ($\sim 800 g/cm^2$) as expected. The single tile counting rates, even showing an average encrease with altitude, were affected by the noise of each detector plate and by the different radiation backgrounds at each site.

Further efficiency studies where made by analyzing the ratio of the measured rates for several coincidence configurations. In Fig.4, right panel, the average counting rates of the twofold coincidence of X-Z and Y-W layers are compared with the corresponding quantity related to the threefold coincidence of X-Y-Z and Y-Z-W. The ratio of these two values is a measure of the single layer efficiency [3]. In the left panel the counting rate of the twofold X-W coincidence is shown together with that of the fourfold X-Y-Z-W coincidence. In this case, under the same assumptions given before, the ratio of these quantities gives the square of the single layer efficiency. In both cases the results are in agreement with expected (previously measured in the laboratory) single layer efficiency: about 92% [8].

In Campo Imperatore we also studied the rate dependence on the zenith angle. The counting rates were measured after having tilted the detector vertical axis towards the east and west directions. The results are in agreement with the expectations (see Fig.5) considering the detector wide field of view and shower background for large zenith angles. As expected no east-west effect was detected due to the site location, the energy threshold and detector field of view.

Measurements were also performed during the ascent from Fonte Cerreto to Campo Imperatore (i.e. from 1120 m to 2140 m a.s.l.) with the Gran Sasso cableway. Since the ascent usually lasts about ten minutes, statistical fluctuations in the measured rates are large, due to the small detector acceptance. By the way, a clear raising of the counting rate was observed for each type of

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[3] Of course this does not take into account differences in the efficiency of the various tiles. Anyway measurements made in the laboratory, and in the field, do support this simple hypothesis.

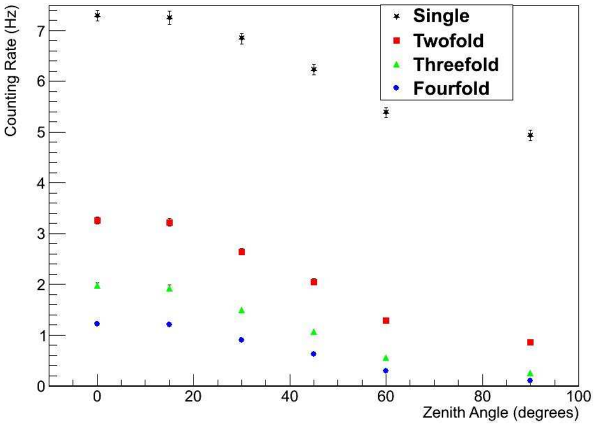

Figure 5. Zenith angle dependence of the coincidence rates measured at Campo Imperatore (2100 m a.s.l.).

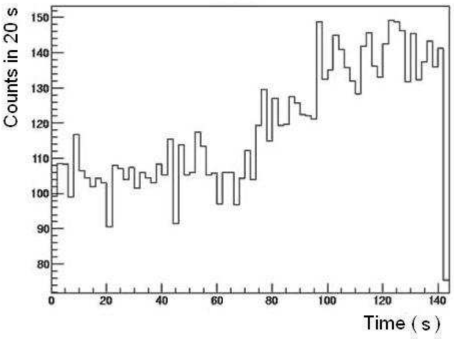

Figure 6. Single rate measured during the cableway riding from Fonte Cerreto to Campo Imperatore (i.e. from 1120m to 2140m a.s.l.).

coincidence, in agreement with the expectations. As an example, the results referring to the single counting rate are shown in Fig.6.

Underground measurements were made in the INFN's Laboratori Nazionali del Gran Sasso (LNGS), where the students also had the possibility to visit the experimental facilities. Because of the rock overburden (about 3000 m water equivalent in the vertical direction) the secondary cosmic ray flux inside the Gran Sasso tunnel is reduced by a factor of about 10^6. This reduces the cosmic ray particles to about one muon per square meter per hour [10]. This flux is below the sensitivity of our detector in the used short time bins. We then expect to have a null result for the coincidence rates, the accidental background being negligible, while the single rates would just give a measure of the electronic noise and the environment radioactivity. This is what we actually observed.

Fig.7 shows the single counting rate measured while travelling to (left panel) and from (right panel) the underground experimental halls. In order to reach the underground laboratory from the L'Aquila side of the mountain (where LNGS offices are located) it is necessary to drive on the highway tunnel crossing the Gran Sasso mountain (about 10 km in length), to get out of the mountain and go back inside toward L'Aquila on the other highway side where the laboratory entrance is located. As can be seen in the upper part of Fig.7, the measured single rates are high in the two highway segments outside the mountain, and drop drastically inside the tunnels, further decreasing inside underground laboratory. The same behaviour is present in the right panel, where the rates measured during the journey towards the L'Aquila side are shown. The lower part shows the four-fold coincidence rate measured during the journey to (left panel) and from (right panel) the experimental underground area. As expected, in this case only in the high-way segments outside the mountain could a rate different from zero be measured. This was true also for the twofold and threefold coincidences (not shown here).

4. Conclusions

High school students (with the help of their teachers) were involved in the design and operation of a small *cosmic ray detector*. Some properties of the cosmic ray flux have been measured and data analyzed and compared with our current knowledge in the field. The dependence of the cosmic ray flux (above a given energy threshold) on the altitude has been investigated by means of a set of measurements done in Lecce and in several places around the Gran Sasso massif in central Italy, up to about 2100 m a.s.l. Underground measurements were also taken inside the INFN Laboratori Nazionali del Gran Sasso. The students were fully involved in detector operation and data analysis. The result of the measurements were in agreement with the expectations.

The next phase of the outreach program includes the building of a larger detector and new measurements at high altitude or even underwater.

5. Acknowledgements

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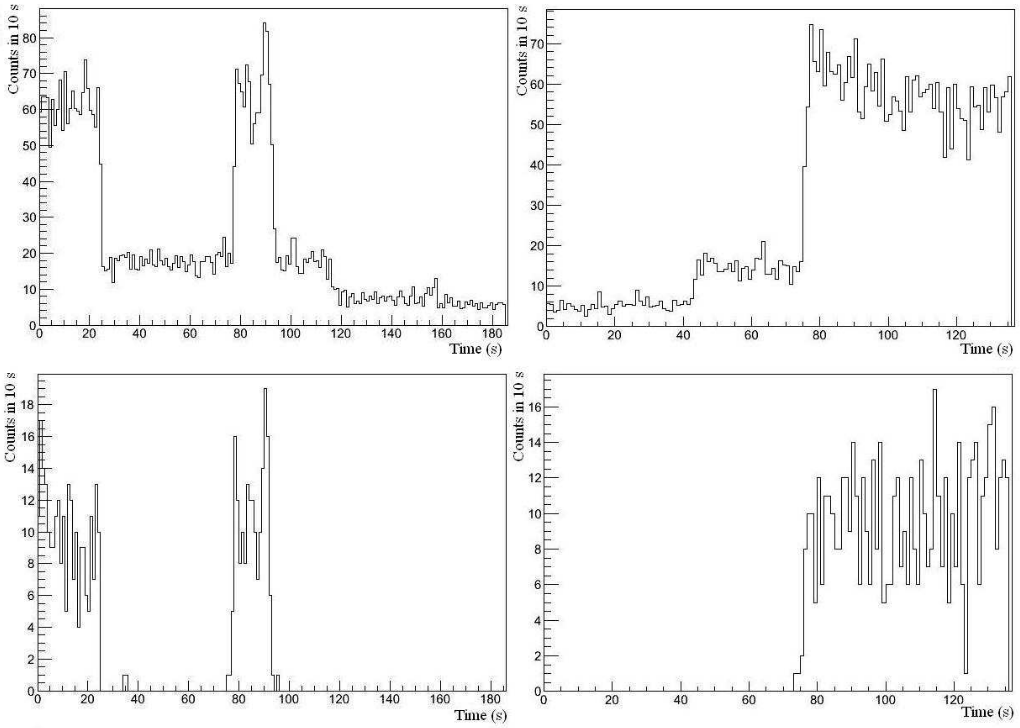

Figure 7. Upper part: single counting rate measured during the journey to (left-plot) and from (right-plot) the underground LNGS halls (see text). Lower part: same as above but referring to the fourfold coincidence rate.

program by funding the detector and the DAQ system. One of the authors, M.S., participated with this activity in the framework of the summer students exchange program 2012 beteewn INFN and the US Department of Energy [11].

REFERENCES

1. D. Pacini *Nuovo Cimento* 3 (1912) 93.
2. V. Hess *Phys. Z.* 13 (1913) 1084.
3. J. Beringer et al. (Particle Data Group), Phys. Rev. D 86 (2012) 010001
4. G. Pfotzer, Zeits. f. Physik, 102 (1936) 23.
5. B. Rossi and J. Barton Hoag, Phys. Rev. 57 (1940) 461
6. A. Akindinov *et al. Nucl. Instrum. Methods* A 539 (2005) 172.
7. *LabVIEW National Instruments*, www.ni.com/labview/.
8. M.R. Coluccia et al., *Nuovo Cimento C* 5 (2012) 35.
9. D. Heck and T.Pierog, Corsika Users guide (2013) http://www-ik.fzk.de/corsika
10. M. Ambrosio et al. (The MACRO coll.), Phys. Rev. D 52 (1995) 3793
11. See http://web2.infn.it/DOE-INFN-SSEP/