THE FIRST COSMIC RAY MEASUREMENTS FOR FUTURE MCORD PROJECT*

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Multi-Purpose Detector (MPD) is a main detector set for the future Nuclotron-based Ion Collider fAcility (NICA) located in Dubna, Russia. The MPD needs an additional trigger system for off-beam calibration and for the rejection of cosmic ray particles (mainly muons) for full functionality. The prototype Cosmic Ray measurement system for MPD detector is under development. It is called the MPD Cosmic Ray Detector (MCORD). For calibration results of Extended Cosmic Shower (ECS) simulation, we need the real Cosmic Ray (CR) measurement results performed at the NICA location. This article describes the first CR measurements done with the Cosmic Watch simple detectors based on the small 5 cm $\times$ 5 cm plastic scintillators with silicon photomultiplier photodetectors (SiPM).

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1. Introduction

A new accelerator complex is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna to study properties of dense baryonic matter. The main detector set of the Nuclotron-based Ion Collider fAcility (NICA) [1] is called the Multi-Purpose Detector (MPD) [2]. The MPD detector was designed to track products emitted during ion–ion collisions. The cosmic muons from the Extended Cosmic Showers (ECS) are one of the sources of background signals. The prototype Cosmic Ray measurement system is designed for the MPD detector as a calibration and trigger system and additionally as a veto system. It is called the MPD Cosmic Ray Detector (MCORD) [3, 4]. In the past, the similar system at CERN for the ALICE

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detector called ACORDE [5] was built. The main difference between those two detectors is that ALICE is located deep underground (about 60 m), whereas MPD is located on the ground level. The underground location of ALICE gives a natural barrier for filtering low-energy muons. The MPD has the possibility to detect muons coming from all directions between zenith and horizon. Simulations of ECS using CORSIKA code [6] were performed for the MCORD project. We need the Cosmic Ray measurement results performed inside and outside of the MPD building for the calibration results of those simulations. These type measurements were performed for the first time with the use of the small detectors based on the plastic scintillators (5 cm $\times$ 5 cm) with silicon photomultiplier photodetectors (SiPM).

2. Cosmic rays [7]

Cosmic ray particles hit the Earth's atmosphere at the rate of about 1000 per square meter per second. The energies of cosmic rays are comparable to their mass or even greater, being mostly relativistic (10^8–10^{19} eV). It seems that some particles have ultra-relativistic energy of 10^{20} eV and above. Where they come from and how they appear is not understood yet.

There are many sources of cosmic rays: the Sun, other stars, supernovas and active galactic nuclei. Supernovas and active galactic nuclei are sources of high-energy cosmic rays, while the stars emit low-energy ones. In this paper, we will mainly focus on low-energy cosmic rays since the Sun is the main source of cosmic rays.

Primary cosmic rays are those particles which reach Earth's atmosphere (with a thickness of around 40 km) and come directly from the source. The primary cosmic rays consist of many types of particles and nuclei: protons ($\approx 85\%$), alpha particles ($\approx 12\%$) and less common nuclei with a nuclear charge $Z \geq 3$ (only 3%). Since the Earth's atmosphere is very dense, the primary cosmic rays interact with it and create secondary particles, some of them reaching the surface. The most copiously produced secondary particles are pions, which in most cases decay to muons. Muons are the most important for this experiment because the Cosmic Watch detects charged particles that reach the sea level, and muons represent 80% of those particles. This happens because they lose very little energy in the atmosphere (only approximately 1.8 GeV) if they do not decay. Their flux is about one particle per cm^2 per minute.

So far, we only talked about particles coming from vertical directions. There are also muons arriving from an inclined angle and they travel a lot more in the atmosphere. The total muon intensity varies with the angle following the formula: $I_\mu(\theta) = I_\mu(\theta = 0)\cos^n\theta$. The exponent n is known to be 2 (for most of the energies < 10 GeV), which fits perfectly in our experiment.

3. The Cosmic Watch device [8]

Cosmic Watch is a simple, physics-motivated device that can be used for basic measurement, educational purposes by university students, or even in schools (Fig. 1 (top)) because this detector can be battery powered and the total cost of each counter is roughly $100. This self-contained apparatus is easy to build, easy to use and relatively small. Many interesting physics measurements can be performed with the provided software.

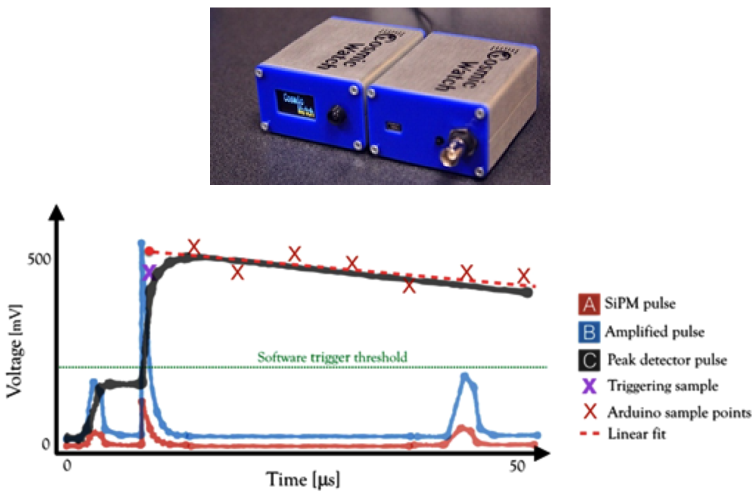

Fig. 1. Top: The Cosmic Watch devices. Bottom: Cosmic Watch signal processing.

One of the main components of the device is a scintillator. This material has luminescent properties, which translates to the re-emission, in the form of photons, of the absorbed energy coming from the interactions of the scintillator with ionizing radiation. Some particles can go through the shell of the device and reach the scintillator, but some cannot (alpha and beta). Muons go through the detector and deposit 1.5–2 MeV/cm in the plastic scintillator. The measured voltage depends on the angle of the muon entering the scintillator.

The photons (light) produced by a scintillator can be measured using a silicone photomultiplier (SiPM). Photo-multipliers absorb the light emitted by the scintillator and re-emit it in the form of electrons (photo-avalanche effect). The more muons interact with the scintillator, the more photons will be emitted, therefore, the measured voltage will be bigger. A photon incident on the SiPM will make a measurable voltage pulse that will be amplified by a non-inverting amplifying circuit by a factor of ~ 6 (Fig. 1 (bottom)). Using a peak detector circuit, the pulse is stretched in time so that even the 16 MHz Arduino Nano is able to measure its amplitude and convert it to a digital signal. This data is used to reproduce the original SiPM pulse amplitude by calculating an average value of these samples. The calculated values are displayed on an OLED (Organic Light-Emitting Diode) screen or written into a file on μSD card in real time. Finally, we receive information about time [ms] from the beginning of a measurement, analog amplitude of signal, digital value of amplitude, dead time of detector, temperature inside the detector and statistical error of received value.

4. Measurement results

The three types of measurements were performed during which the influence of the following factors on the muon flux has been studied: the distance between master and slave detectors, the angular dependence indoor and outdoor, and the impact of filters such as lead, aluminum and copper shielding.

For the first type of measurements, the distance between the master and slave detectors was changed from 5 cm up to 40 cm. In that case, the opening angle (in steradians) from which the muons can pass through both detectors in coincidence mode changes as in Eq. (1)

$$\omega(D) = 4\sin^{-1}\left(\frac{l^2}{l^2+D^2}\right)\,[\mathrm{sr}]\,, \tag{1}$$

where l — is the width of the scintillator (in the case of square shape); D — is the distance between master and slave center.

The time of each measurement varied from 120 to 1200 min. The error for the measured flux is statistical fluctuation. The function fitted for gathered fluxes is

$$y(D) = A + B\omega(D)\,. \tag{2}$$

Variable A can be interpreted as random coincidences in both detectors (*i.e.* background radiation). Parameter B is the muon flux registered by detec-

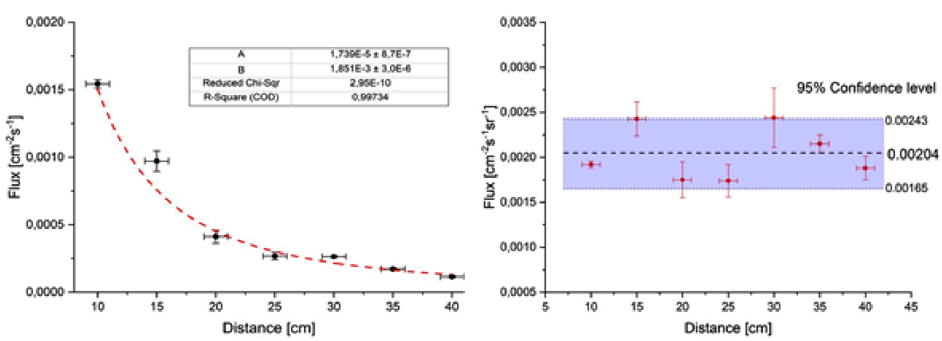

Fig. 2. Left: The measured flux in coincidence mode for the different distance between detectors. Right: The measured flux of muons normalized per steradian.

tors normalized to the opening angle (in steradian). The fitted parameters are shown in Fig. 2 (left) in the inset. The random coincidences of background events are two orders lower than the flux per steradian. The flux per steradian can be found also by normalizing each result by the value of the opening angle what is shown in Fig. 2 (right). The average measured flux is 0.00204(20) $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$, which is consistent with the result obtained by fitting the function (see Eq. (2)).

The flux of muons is highly dependent on a zenith angle, which is the angle between a vector passing through the centers of both detectors and the ground. With increasing the angle, the attenuation from the atmosphere increases, and the flux decreases. The measurements were done for both indoor and outdoor. Inside the building, concrete and structural elements should add additional attenuation factors. By comparison, CORSIKA simulations were performed and results are shown with a red dashed line in Fig. 3 (left). The simulations were done for the altitude and location of the experiment site. The flux was measured for angles between 0° and 90° with 15 cm distance between detectors. The errors for the flux arise from the statistical fluctuation. The angle uncertainties result from the inability to accurately measure the angle for the tested system because of making it by hand.

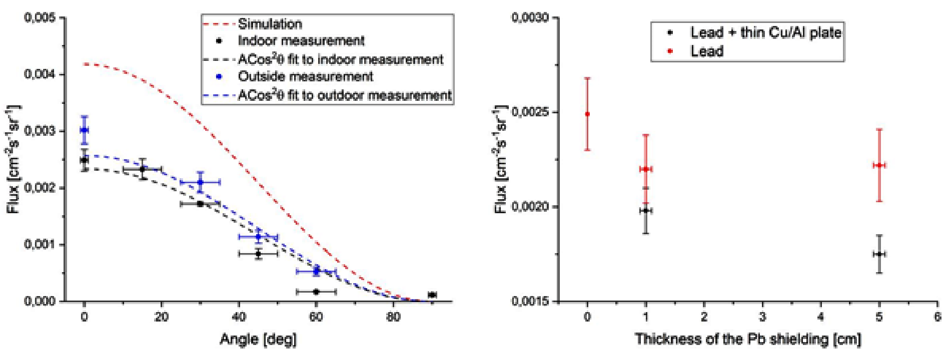

Fig. 3. (Color online) Left: The observed muon flux in coincidence indoor and outdoor. First from the top/red dashed line for CORSIKA simulation. Right: The muon flux for the different lead shielding thickness between master and slave.

The results for each angle measurement are shown in Fig. 3 (left). The rate drops from the maximum value for 0° to nearly 90°. The function $A\cos^2\theta$ was chosen according to CORSIKA simulations. The muon flux has the maximum at 0° and its values are: Indoor: 0.00234(16); Outdoor: 0.00257(21); CORSIKA simulation: 0.00418 $\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$. Indoor flux is lower by around 10% than outside the building due to the attenuation. The difference between simulations and outdoor flux is around 38%. This is a result of low detector efficiency, a dead time of the detectors and differences in ideal parallel location of two detectors. During the last measurement, additional shielding was put between master and slave detectors to eliminate more of the random coincidences (Fig. 3 (right)). The lead brick of width 1 and 5 cm was used. Additionally, the thin aluminum and copper plates were added to reduce the X-rays that can be induced in the lead by muons. The difference between 1 and 5 cm is none. However, the addition of thin aluminum and copper plates allowed to reduce the rate for 10% (in the case of 1 cm lead shielding) and 21% (5 cm of lead). That may prove that a high number of low energetic X-rays trigger a random coincidence event.

5. Conclusion

The Cosmic Watch is a cheap, simple and easy to use device for detection of muons. The number of detected particles drops exponentially with increasing the distance between detectors. No significant rate decrease with up to 5 cm of Pb shielding was observed. Additional thin Cu and Al plates improve the effect of the shielding. Both inside and outside measurements could be fitted using $A\cos^2\theta$, in-line to the theory. Based on the measurements and their analysis, it can be concluded that Cosmic Watch is a suitable tool for performing calibration measurements. In order to refine the system of used lead and copper filters, further measurements should be carried out while ensuring greater repeatability of the measurement conditions (reduction of error values).

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