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# THE FIRST COSMIC RAY MEASUREMENTS FOR FUTURE **MCORD** PROJECT

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Кордун К.-М. и др. E1-2020-38

Первые измерения космических лучей для будущего проекта MCORD

Многоцелевой детектор (MPD) — это основной детектор для будущего ионного коллайдера на базе нуклотрона (NICA), расположенного в Дубне. Для полной функциональности MPD требуется дополнительная система, работающая вне пучка, для калибровки и подавления частиц космических лучей (в основном мюонов). Прототип такой системы для детектора MPD находится в стадии разработки. Он называется детектором космических лучей MPD (MCORD). Для калибровки результатов моделирования расширенного космического ливня (ECS) нужны результаты измерений реальных космических лучей, выполненных в месте расположения комплекса NICA. Описываются первые измерения космических лучей, выполненные с помощью простых детекторов CosmicWatch на основе небольших пластиковых сцинтилляторов размером $5 \times 5$ см с кремниевыми фотоумножителями (SiPM).

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The First Cosmic Ray Measurements for Future MCORD Project

Multi-Purpose Detector (MPD) is the 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 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 paper describes the first CR measurements done with the CosmicWatch simple detectors based on the small $5 \times 5$ cm plastic scintillators with silicon photomultiplier (SiPM) photodetectors.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energy Physics, JINR.

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## 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 main role of the MPD is to provide information necessary for reconstructing each event and particle tracks. 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 veto system and additional calibration and trigger system. It is called the MPD Cosmic Ray Detector (MCORD) [3, 4]. In the past, the similar system at CERN for the ALICE 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 ground level. The underground location of ALICE gives a natural barrier for filtering low energy muons. The MPD located on ground level has possibility to detect muons coming from all directions between zenith and horizon. Simulations of ECS using the 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 measurements were performed for the first time with use of the small CosmicWatch [7] devices based on the plastic scintillators ($5 \times 5$ cm) with silicon photomultiplier (SiPM) photodetectors. For the reason that the MPD hall was not ready, the measurements were performed inside and outside of other JINR's laboratory building.

## 1. COSMIC RAYS

Cosmic ray particles hit the Earth's atmosphere at the rate of about $1000\ \mathrm{m}^{-2}\cdot\mathrm{s}^{-1}$. They mostly consist of elementary particles (mainly protons) and partly of heavier ions. There are two types of cosmic rays: charged particles and neutral ones [8–10]. It is easier to detect charged particles because they interact much more with the environment than the neutral ones, but there is a big disadvantage: unless their energy is very high, one cannot determine their origin because they change their trajectories when interacting with the intergalactic and interstellar magnetic field. Therefore, in order to determine the source of these particles, one needs devices which can detect neutral particles, especially neutrinos. However, in our experiment, we focus on determination of charged particles, especially muons, because we use a plastic scintillator. The process will be described in more detail in Sec. 2 devoted to the CosmicWatch.

The energies of cosmic rays are comparable to their mass or even greater, most are relativistic, beginning from about $10^8$–$10^9$ eV. The ultrarelativistic energies have only small part, reaching up to $10^{20}$ eV (about 20 J — this is eleven orders of magnitude greater than the equivalent rest mass energy of a proton). There appears to be some particles with the energy of $10^{20}$ eV and above. Where they come from and how they appear is not yet clear.

There are many sources of cosmic rays: the Sun, other stars, supernovas, and active galactic nuclei. Supernovas and active galactic nuclei are the sources of high energy cosmic rays, while the stars emit the low energy ones. In this paper, we will talk more about the Sun as a source, since we mostly detect low energy cosmic rays. Primary cosmic rays are those particles which reach the Earth's atmosphere and come directly from the source, without interacting with the galactic and extragalactic environment. The atmosphere does not have a well-defined top, but it is considered to be at around 40 km above the surface of the Earth. The primary cosmic rays consist of many types of particles and nuclei, but some are more abundant than others. Protons are the dominant ones ($\approx 85\%$), then the alpha particles ($\approx 12\%$), and the less common are the nuclei with a nuclear charge $Z \geqslant 3$ (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. Because of this, it is impossible to study primary cosmic rays at the sea level. Protons are the most common to be the primary particles. The most copiously produced secondary particles are pions. Most of them decay to muons. Muons are the most important for this experiment because the CosmicWatch detects charged particles which reach the sea level, and muons are 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. Most of these particles originate from pion decays and their flux is about one particle $\mathrm{cm}^{-2} \cdot \mathrm{min}^{-1}$. We have only talked about particles coming from vertical directions so far. 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 the most particles energies), which fits perfectly in our experiment as well.

## 2. THE COSMICWATCH DEVICE

The CosmicWatch is a simple, physics-motivated device that can be used for basic measurement, educational purposes by university students, or even at schools. This detector can be battery-powered, and the total cost of each counter is roughly \$100 (Fig. 1) [7]. This self-contained apparatus is easy to build, easy to use, and it is relatively small. Many interesting physics measurements can be performed with the provided software.

One of the main components of the device is a scintillator. The used 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. There are multiple types of radiation that interact with the detector. Some particles can go through the shell of the device and reach the scintillator, but some cannot. Alpha and beta particles are captured (except those coming directly on the surface of the scintillator), but gamma radiation will penetrate through the detector. Muons will also 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. If a muon hits the scintillator perpendicularly, it will cross a distance $d$ (1 cm) — the thickness of the scintillator. But if a muon enters the scintillator under an angle, the distance $d'$ crossed in this case will be bigger than $d$.

Fig. 1. The front and backside of CosmicWatch devices

The more muons interact with the scintillator, the more photons will be emitted, therefore the measured voltage will be bigger. The photons (light) produced by a scintillator can be measured using a silicon photomultiplier (SiPM). Photomultipliers absorb the light emitted by the scintillator and re-emit it in the form of electrons with the photo-avalanche effect. Thus, a photon incident on the SiPM will make a measurable voltage pulse that will be amplified by a noninverting amplifying circuit by a factor of $\sim 6$ (Fig. 2). This pulse can be analyzed and yields meaningful information about the particle that originally struck the plastic scintillator. 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. The Arduino samples an analog waveform produced by the peak detector circuit several times and converts it to digital. Those values are used to reproduce the original SiPM pulse amplitude by calculating an average value of these samples. In other words, Arduino transforms the analog signal coming from the SiPM into a digital

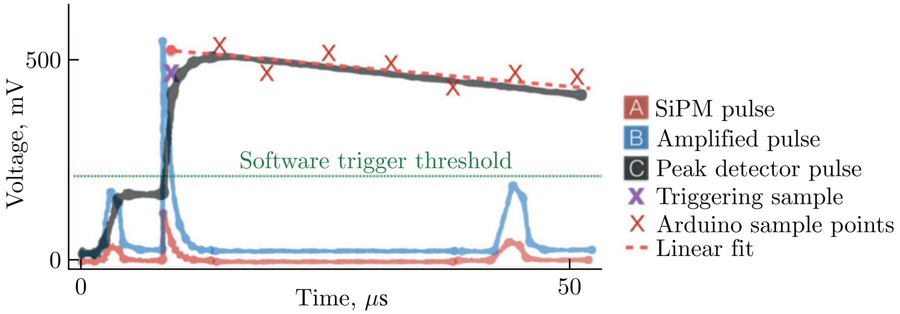


Fig. 2. CosmicWatch signal processing

one. The calculated values are displayed on an OLED (Organic Light-Emitting Diode) screen or written into a file on $\mu$ SD card in real time. Finally, we received 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 the received value.

## 3. 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 the master and slave detectors;
- the angular dependence indoors and outdoors;
- the impact of filters: Pb, Al and Cu shielding.

For the first type of measurements, the distance between the master and slave detectors was changed from 5 up to 40 cm. In that case, the opening angle [sr] 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) and $D$ is the distance between the master and slave centers.

The time of each measurement varied from 120 to 1200 min. Figure 4 shows the results. 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, different muons passing through both detectors, etc.). Parameter $B$ is the muon flux registered by detectors normalized to the opening angle [sr]. The fitted parameters are shown in Fig. 3, *a* (in the table). 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 that is shown in Fig. 3, *b*. The average measured flux is 0.00204(20) $\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}\cdot\mathrm{sr}^{-1}$, which is consistent with the result obtained by fitting the function (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 both indoors and outdoors. Inside the building, concrete and structural elements should add additional attenuation factors. For comparison, CORSIKA simulations were performed, the results of which are shown by a red dashed line in Fig. 4, *a*. The simulations were done for the altitude and location of the experiment site. The flux was measured for angles between 0° and 90° with a 15-cm distance

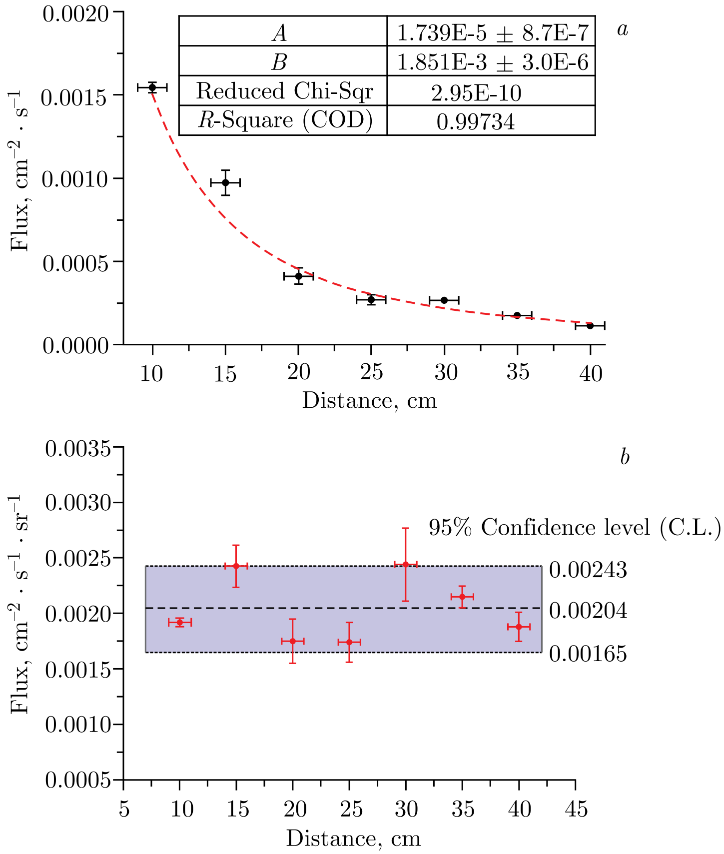


Fig. 3. *a*) The measured flux in coincidence mode for the different distance between detectors; *b*) the measured flux of muons normalized per steradian with an average value and C.L. at 95%

between detectors. The errors for the flux arise from statistical fluctuation. The angle uncertainties result from the inability to accurately measure the angle for the tested system because of making it by hand.

The results for each angle measurement are shown in Fig. 4, *a*. The rate drops from the maximum value for 0° to nearly 0 for 90°. The function $A\cos^2\theta$, which was chosen according to CORSIKA simulations, was fitted for indoors and outdoors. The muon flux for indoor and outdoor measurements (from fitted function $A\cos^2\theta$) and from CORSIKA simulations and the fitted parameter $A$ is the maximum registered flux for 0°, and its values are as follows:

- indoor: 0.00234(16) $\mathrm{cm^{-2}\cdot s^{-1}\cdot sr^{-1}}$;
- outdoor: 0.00257(21) $\mathrm{cm^{-2}\cdot s^{-1}\cdot sr^{-1}}$;
- CORSIKA simulation: 0.00418 $\mathrm{cm^{-2}\cdot s^{-1}\cdot sr^{-1}}$.

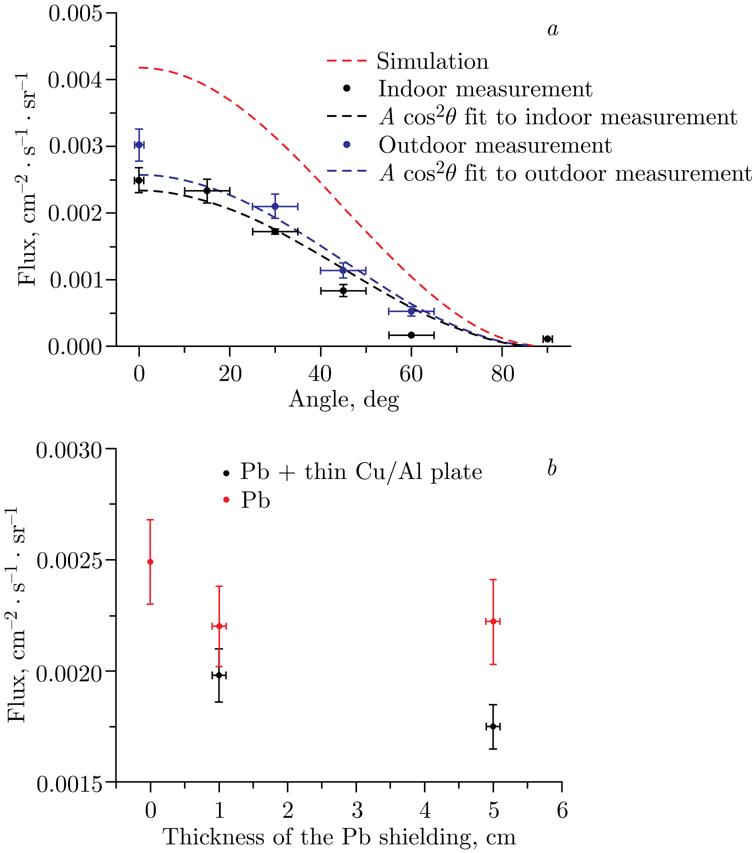


Fig. 4. *a*) The observed muon flux in coincidence indoors and outdoors. For the results, the $A\cos^2\theta$ function is fitted with a dashed line. The red dashed line stands for the CORSIKA simulation; *b*) the muon flux for the different Pb shielding thickness and with/without thin Cu and Al plates between the master and slave detectors

Indoor flux is lower by around 10% than that outside the building because of the attenuation. The difference between simulations and outdoor flux is around 38%. This is a result of low detector efficiency (small scintillator sizes), a dead time of the detectors, and differences in ideal parallel location of two detectors. Moreover, the muon flux naturally fluctuates as a result of changing atmosphere pressure, air humidity, temperature, and so on.

During the last measurement, additional shielding was put between the master and slave detectors to eliminate more of the random coincidences. The Pb brick of width of 1 and 5 cm was used. Additionally, thin Al and Cu plates were added to reduce the X-rays that can be induced in Pb by muons. The reduction of events through the Pb shielding is negligible (Fig. 4, *b*). Moreover, the difference between 1 and 5 cm is none. However, the addition of thin Al and Cu plates allowed reducing the rate for 10% (in case of 1-cm Pb shielding) and 21% (in case of 5 cm of Pb). That may prove that a high number of low energetic X-rays trigger a random coincidence event.

## CONCLUSIONS

The CosmicWatch is cheap, simple and easy to use device for detection of muons. The number of detected particles drops exponentially with increasing the distance between detectors. There is no significant rate decrease with up to 5 cm of the Pb shielding. Additional thin Cu and Al plates improve the effect of the shielding. Both indoor and outdoor measurements could be fitted using $A\cos^2\theta$, in line with the theory. The flux that we measured outdoors was bigger than the one measured indoors, but the shape of the curve remained the same, like we expected.

Based on the measurements and their analysis, it can be concluded that the CosmicWatch is a suitable tool for performing calibration measurements. In order to refine the system of the used Pb and Cu filters, further measurements should be carried out while ensuring greater repeatability of the measurement conditions (reduction of error values).

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## REFERENCES

1. http://nica.jinr.ru/complex.php
2. *Golovatyuk V., Kekelidze V., Kolesnikov V., Rogachevsky O., Sorin A.* The Multi-Purpose Detector (MPD) of the Collider Experiment // Eur. Phys. J. A. 2016. V. 52. P. 212.
3. *Bielewicz M. et al.* MCORD — MPD COsmic Ray Detector a New Features // Eur. Phys. J. Web. Conf. 2019. V. 204. P. 07016.
4. *Bielewicz M. et al.* MCORD — MPD Cosmic Ray Detector for NICA // Proc. of Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2018 (SPIE 2018). 1080847; doi: 10.1117/12.2501720.
5. *Fernandez A., Kartal S., Pagliarone C.* ACORDE, a Cosmic Ray Detector for ALICE. arXiv:physics/0612051 [physics.ins-det].
6. *Heck D., Schatz G., Thouw T., Knapp J., Capdevielle J.* CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers. Tech. Rep. FZKA-6019, Forschungszentrum Karlsruhe, 1998.
7. *Axani S. N., Frankiewicz K., Conrad J. M.* CosmicWatch: The Desktop Muon Detector // J. Instrum. 2018. No. 13(03).
8. *Stanev T.* High Energy Cosmic Rays. Springer, 2010.
9. *Grupen C.* Astroparticle Physics. Springer, 2005.
10. *Gaisser T. K.* Cosmic Rays and Particle Physics. Cambridge Univ. Press, 1990.

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