MINIMUM RESOLUTION OF MCORD AS A CONSEQUENCE OF ASTROPHYSICAL OBSERVATION REQUIREMENTS*

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(Received January 20, 2021)

The Multi-Purpose Detector (MPD) needs an additional trigger system for off-beam calibration and rejection of cosmic ray particles for full functionality. The prototype cosmic ray measurement system for MPD detector is under development and is named MPD Cosmic Ray Detector (MCORD). It can detect muons coming from all directions between zenith and horizon, with information about particle direction vector. Theoretically, it is possible to recognize the extragalactic source of a cosmic particle but only in the case of Ultra-High Energy Cosmic Rays (UHE CR) connected to ECS. We need to use the optimal MCORD position resolution to identify the possible sources on the sky surface.

DOI:10.5506/APhysPolBSupp.14.543

1. Introduction

A new accelerator complex is under construction at the Joint Institute for Nuclear Research (JINR) in Dubna. The first detector set for monitoring collisions at the new Nuclotron-based Ion Collider fAcility (NICA) [1] constructed in Dubna, Russia is called Multi-Purpose Detector (MPD) [2]. 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 additional signals. The prototype Cosmic Ray (CR) measurement system is designed for the MPD detector as an additional trigger and calibration system, and works as a muons veto system. It is called the MPD Cosmic Ray Detector (MCORD)

* Presented at NICA Days 2019 and IV MPD Collaboration Meeting, Warsaw, Poland, October 21–25, 2019.

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(Fig. 1 (left)) [3, 4]. In the past, a similar system at CERN for the ALICE detector called ACORDE was built [5]. The main difference between those two detectors is that ALICE is located deep underground (about 60 m), whereas the MPD is located on the ground level. The underground location of ALICE and other two provided experiments at the similar location with the measurement of ECS (DELPHI [6] and ALEPH [7]) give a natural barrier for filtering low-energy muons ($E < 16$ GeV) and additionally a barrier for muons coming from direction close to horizontal. The MPD has a possibility to detect muons coming from all directions between zenith and horizon [8].

Detectors such as MPD are not created for astrophysical observations. Nevertheless, if they are equipped with an additional detector or one of the sub-detectors is adapted to this, they can become a unique tool for observing cosmic showers. Their uniqueness lies in the fact that they are equipped with a Time Projection Chamber (TPC) detector (Fig. 1 (right)).

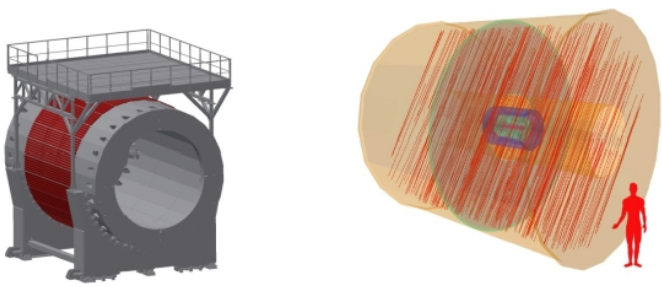

Fig. 1. (Color online) On the left: The MCORD (dark gray/red color) (MPD Cosmic Ray Detector) on the MPD body. On the right: The ALICE TPC detector with the multi-muons event tracks [5].

It was as a result of ECS observations in these three experiments at CERN that a surplus of phenomena coming from the primary Ultra-High Energy Cosmic Rays (UHE CR), inconsistent with theoretical calculations, was noticed and called Multi-muons Events. However, each of these experiments within a few years observed only a few such cases, which is not enough to draw more broad conclusions. However, such events raise reasonable doubts about our knowledge of the interaction between hadrons at extremely high energies. We encounter a similar difficulty when we touch the GZK cut-off problem [9]. According to this theory, it is impossible to observe primary particles with energy greater than 4×10^{19} eV originating from sources with a distance greater than 50 MPc, due to, *inter alia*, interaction with background microwave radiation. One fact is that in many observatories, the presence of such particles was recorded. For this reason, attempts to identify the location of their sources are crucial.

Generally, cosmic ray particles have an isotropic distribution due to their interaction with the magnetic field from stars and galaxies. Anyway, it is theoretically possible that in the case of UHE CR, the impact of these fields will be so small on the particle path that it will be possible to identify their source. Based on data from the ACORDE project, one team was able to determine the location of such a potential source [10]. The high level of uncertainty for this measurement, mainly from very small case statistics, gives us the argument that it is necessary to collect better statistics. Both the MPD and MCORD detectors can become the appropriate tools. The following study shows how to determine the minimum necessary resolution of the MCORD detector system to estimate the location of event sources on the celestial sphere with sufficient accuracy.

2. Calculation of the MCORD angular resolution

The expected accuracy of MCORD resolution is based on the following assumptions:

— The accuracy of determining spherical celestial coordinates depends on the accuracy of the scintillator passage position, related to the particular cosmic rays event.

— Assumed accuracy of the scintillator position determination is about 5–7.5 cm along the X-axis and 7.5 cm along the Y-axis (on the X-axis it depends on detector time resolution, and on the Y-axis — on scintilator width).

— The two layers of scintillators registering a single event are separated up to $D = 6.5$ m. (MCORD layer surrounding the MPD.)

— We assume that the maximum accumulation of measurement errors occurs when the scintillators are located on the opposite directions (Fig. 2). In other cases, the angles of maximum variation are smaller.

— Taking into account the above conditions, we can estimate the maximum errors in the angles measured along the X–Y-axes. (Fig. 2).

With the critical configuration of detecting scintillators (Fig. 2), when the CR event has the direction perpendicular to the detector's axis of symmetry, we can assume that the max. errors in the angles meet the equations

$$\tan(\Delta\alpha_X) = \frac{\Delta X}{D/2} \quad \text{and} \quad \tan(\Delta\alpha_Y) = \frac{\Delta Y}{D/2} \,. \tag{1}$$

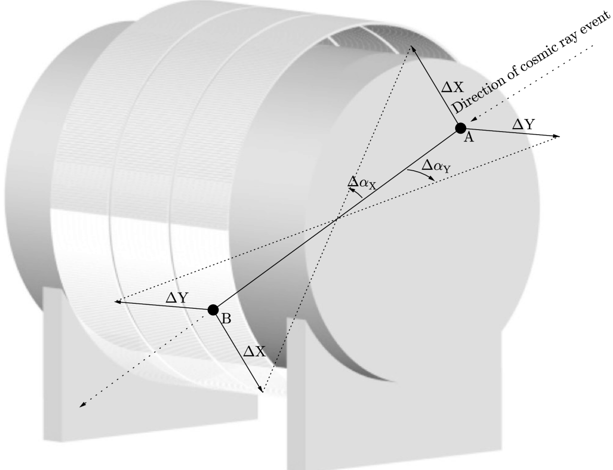

Fig. 2. The example of the geometric configuration, where errors of positional angles on the celestial sphere accumulate (maximize). The error values in X, Y are visually magnified to make the differences more visible.

Therefore, the final maximum errors are

$$\Delta\alpha_X = \arctan\left(\frac{2\,\Delta X}{D}\right) \quad \text{and} \quad \Delta\alpha_Y = \arctan\left(\frac{2\,\Delta Y}{D}\right). \tag{2}$$

If we assume the critical case that the errors accumulate, *i.e.* $\Delta\alpha_X \simeq \Delta\alpha_Y$, the possible total error in determining the angle on the celestial sphere will be

$$\Delta\alpha_{\max} \simeq \sqrt{2}\,\Delta\alpha_X\,. \tag{3}$$

In other individual cases, we can determine the total error from the formula

$$\Delta\alpha = \sqrt{(\Delta\alpha_X)^2 + (\Delta\alpha_Y)^2}\,. \tag{4}$$

Finally, we can receive the total maximum errors in the measured angles (α). By applying a typical error range of position measurement in X and Y on scintillator (up to 5–7.5 cm), the final errors in angles on the celestial sphere can be calculated, as shown in Fig. 3. One can see that for scintillator errors of approximately 5 cm, the accuracy of the position in the sky within a 1-degree limit is always fulfilled. For 7.5 cm errors, the accuracy can be considered as conditionally acceptable. In consequence, we can define MCORD requirements for astrophysical observations. We are able to obtain the estimated position of UHE CR. Typically, we can achieve an accuracy of 1 degree, but with a maximum error on scintillators up to 7.5 cm in X and Y,

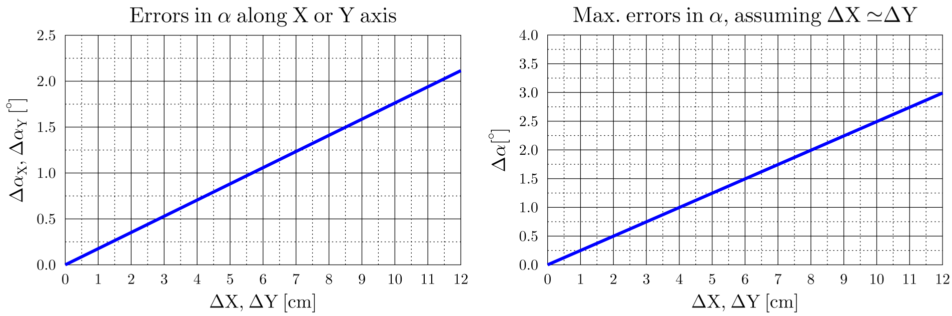

Fig. 3. On the left: Errors in positional angles along axes X and Y. On the right: Maximum error in the positional angle.

slightly degraded but still acceptable. Such a level of accuracy should be sufficient to detect the single source because they are generally well-separated. The most UHE CR, *e.g.* blazars, are generally sufficiently isolated. In order to make progress compared to previous results, we should keep errors within one degree or better. In our previous studies [10], total errors reached a few degrees. Therefore, the critical accuracy of the scintillator should preferably be limited to 5 cm. In the case of a very rich bundle of high-energy muons, the statistics slightly improve the accuracy of the limits. However, as results from other detectors have shown, the dispersion of such a bundle can reach a few degrees. There are other essential measurement factors; one of them is a very rigorous time service. It is preferable to maintain universal time (UTC) rather than local time.

3. Conclusions

We can see that MCORD, along with the entire MPD detector, can contribute to a significant increase in the observational material regarding the identification of ECS created by primary particles from UHECR sources. Therefore, attempts to identify these sources so far have either failed or the results have very high uncertainty. The calculations show that the MCORD detector can meet the requirements for such measurements and allow for the possible identification of such sources. Thanks to the calculations described above, we can estimate the accuracy limit of our system.

In addition, a unique advantage is a fact that the MCORD detector will work in a set with several other MPD detectors like TPC, which will be able to improve the accuracy of the identified position and additionally enable the identification of some particles and their charge.

The proposed observations are extremely important from the point of view of solving the GZK cut-off problem or improving our knowledge of hadron interactions at extremely high energies. Previous observations carried out with the help of similar detectors in the past at CERN raised more questions and doubts than answers, the main reason for which was the very limited statistics of the collected data.

The planned MCORD detector along with the MPD time projection chamber show the unique opportunity of the very precise measurement of atmospheric muon multiplicity distributions as a function of the zenith angle of primary cosmic particle, up to nearly horizontal showers. Until now, such measurements have not been achievable.

This research was supported by the Research Program for the research group at JINR and research centres in Poland by the grant of Polish Plenipotentiary at the Joint Institute for Nuclear Research.

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