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First Observational Results of the ALPAQUITA Air Shower Array in Bolivia

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The ALPACA experiment, which consists of a large air shower (AS) array and water-Cherenkov-type muon detectors, is a new project to observe sub-PeV gamma rays in the southern hemisphere. The prototype AS array, named ALPAQUITA (1/4 scale of ALPACA), has been prior operated in the center of the ALPACA site at Chacaltaya plateau (4,740 m a.s.l.) in Bolivia. The ALPAQUITA AS array consists of 97 scintillation detectors each with an area of 1 m^2, deployed with 15 m spacing. Using this AS array, we have successfully observed the cosmic-ray Moon shadow with a statistical significance -6.2σ for 73 live days. The angular resolution is estimated to be 0.9° based on the Moon shadow observation and the even-odd method. In this proceedings, we assess the performance of ALPAQUITA AS array, and outline the future prospects of the sub-PeV gamma-ray observation with the ALPAQUITA AS+MD array.

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1. Introduction

It is widely believed that cosmic rays are accelerated up to a few PeV ('Knee' energy region) in the Galaxy. These cosmic super-accelerators present in our Galaxy are called 'PeVatrons', but their origins are still unknown. Since the charged cosmic rays lose their directions due to the magnetic fields in the universe, it is difficult to directly point back to their sources. On the other hand, high-energy cosmic rays accelerated in the PeVatron interact with the surrounding interstellar medium (ISM) and produce sub-PeV (100-1000 TeV) gamma rays through the neutral pion decay. Therefore, sub-PeV gamma rays unaffected by the magnetic fields enable us to search for their sources.

The gamma-ray air shower experiments, such as the Tibet ASγ, HAWC and LHAASO, currently in operation in the northern hemisphere have good sensitivity above 100 TeV, and have surveyed the northern sky region with a wide field of view, and discovered many sub-PeV gamma-ray sources [1–3]. The Tibet ASγ experiment, in particular, has successfully observed gamma rays above 100 TeV from an astrophysical source [1], and diffuse gamma rays above 400 TeV from the Galactic plane [4]. However, there are currently a lack of gamma-ray detectors with enough sensitivity above 100 TeV in the southern hemisphere. To address this, we have initiated the ALPACA project, which consists of a large air shower (AS) array (83,000 m^2) and underground water-Cherenkov-type muon detectors (MDs, 3,600 m^2 in total) at Chacaltaya plateau (altitude of 4,740 m) in Bolivia, South America [5]. The MD array will enable us to discriminate gamma rays from the background cosmic rays, and will significantly improve sensitivity for the gamma-ray sources [6]. In 2022, the fist prototype air shower array, called the ALPAQUITA, was constructed in Bolivia, South America. In this conference, we will report on the performance of the ALPAQUITA AS array, and outline the future prospects of the sub-PeV gamma-ray observation with the ALPAQUITA AS+MD array.

2. ALPAQUITA Air Shower Array

Figure 1: Panoramic view of the ALPAQUITA AS array located at Chacaltaya plateau (4,740 m a.s.l.) in Bolivia (Photo in September 2022).

The ALPAQUITA air shower (AS) array consists of 97 scintillation detectors deployed with 15 m spacing in a grid pattern, covering a total area of 18,000 m^2. Figure 1 shows a panoramic photo of the ALPAQUITA AS array located at Chacaltaya plateau (16°23′S, 6°08′W, 4,740 m a.s.l.) in Bolivia. Each detector has plastic scintillators with 0.25 $\mathrm{m}^2 \times 4$ (1.0 m^2in total), and is equipped with HAMAMATSU 1.5-inch-in-diameter photomultiplier tube (PMT). The array has been partially operated from September 2022, and reached full ALPAQUITA array in April 2023. An air shower trigger signal is issued when any four fold coincidence appears in all the detectors each of which recordings more than ~0.6 particles within a coincident width of 600 ns. The air shower trigger rate with full-ALPAQUITA AS array is approximately 280 Hz. The detailed Monte Carlo (MC) simulation study of the ALPAQUITA including the detector responses is described in elsewhere [7]. The modal energy of observed cosmic-ray air showers is estimated to be approximately 7 TeV by the MC simulation.

3. Air Shower Reconstruction

The arrival direction and the energy of an air shower are reconstructed using the relative timings and the particle density recorded in scintillation detectors. The relative cable length for each detector is measured every 20 minutes with an inaccuracy of approximately 0.1 ns. The relative PMT transit times for ALPAQUITA detectors are measured by observing cosmic muons simultaneously by each ALPAQUITA detector and a reference small scintillation detector. At each detector, the particle density is obtained from the PMT output charge divided by the charge of the single particle peak.

Figure 2 shows an event display for a typical AS event recorded by the ALPAQUITA AS array. The color circles in this figure indicate the relative timing and the number of particle density measured by each detector. Firstly, we determine the AS core location using hit detector positions weighted by the detected particle densities, then the timings in the AS front are fitted by a conical shape with a core location as the apex to determine an arrival direction of the air shower. In order to evaluate the angular resolution, we divide the ALPAQUITA detectors alternately into even and odd arrays, and check the distribution of the opening angle between the reconstructed directions from the even and odd arrays in Fig. 3. The median value of the opening angles is calculated to be $\Delta\theta_{\mathrm{OP}} = 1.96°$. Therefore, the estimated angular resolution is $\Delta\theta_{\mathrm{OP}}/2 \sim 1°$. The cosmic-ray energy should be proportional to $\Sigma\rho$, which is the sum of the particle density measured by each scintillation detector. The energy of air shower in Fig. 2 is estimated to be approximately 500 TeV. The energy estimation using lateral distribution of the particle density [8] will improve the energy resolution.

4. Moon Shadow Detection

The performance of the AS array, such as pointing accuracy and angular resolution, can be directly checked by monitoring the Moon shadow in the cosmic ray flux [9, 10]. Figure 4 shows the Moon shadow observed by the ALPAQUITA AS array for 73 live days from 2023 April to 2023 July. The peak deficit position of the shadow is observed to shift westward from the apparent Moon position, which is an expected result due to the influence of the geomagnetic field. The statistical significance of the peak deficit position is estimated to be -6.2σ. The angular resolution estimated from the Moon shadow observation is approximately 0.9° which is consistent with the MC simulation. In addition, we will also estimate the systematic uncertainty of the absolute energy

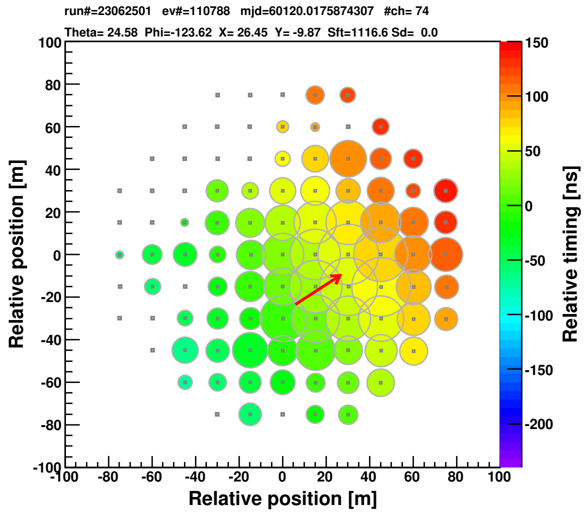

Figure 2: A typical event display of the observed cosmic ray with an energy ~500 TeV. The size and color of each circle represent the particle density and the relative timing in each detector, respectively. The small open squares indicate locations of the plastic scintillation detectors. The arrow head and direction indicate the air shower core position and arrival direction, respectively.

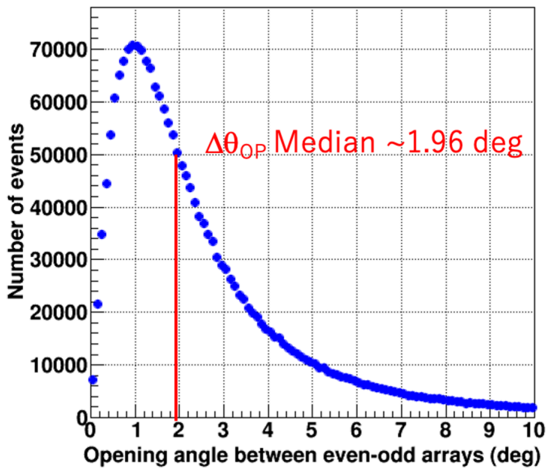

Figure 3: Distribution of the opening angle between the reconstructed directions by the even array and the odd array (even-odd method). The median value of the opening angle is calculated to be 1.96°.

scale using the energy dependence in the east-west displacement of the Moon shadow with more large statistical sample.

5. Summary and Future Prospects

The ALPAQUITA AS array has been successfully operated at Chacaltaya plateau in Bolivia, located at an altitude of 4,740 m. With this array, we have detected the cosmic-ray Moon shadow

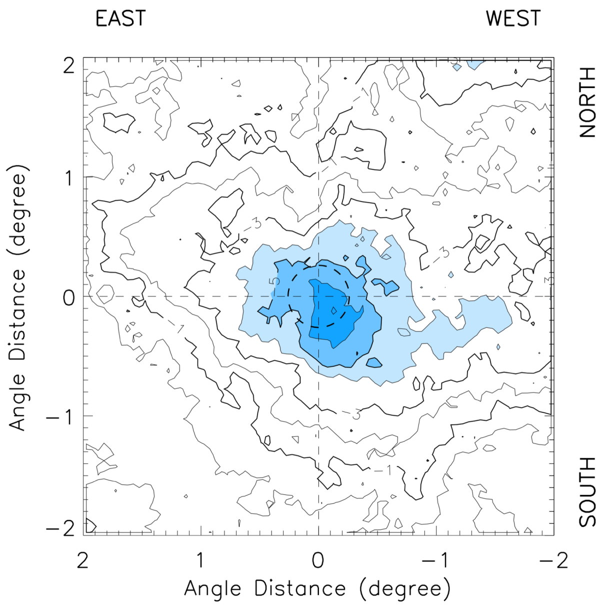

Figure 4: 2D significance map of the Moon shadow observed by the ALPAQUITA air shower array for 73 live days. The map is smoothed by a circle of an angular radius of 0.9°. The maximum significance is estimated to be -6.2σ. A dashed circle in the center of this map shows apparent size of the Moon.

with a statistical significance of -6.2σ. The angular resolution estimated based on the Moon shadow observation is 0.9°, which is consistent with results obtained by the MC simulation. In 2023, we will start construction of an underground MD pool with a detection area of 900 m^2 under the AS array. Furthermore, in 2024, we are planning to start construction of the full-scale ALPACA AS array and three additional underground MD pools. The ALPAQUITA and ALPACA experiments will open new gamma-ray window to the southern sky in the sub-PeV energy range.

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