PROCEEDINGS OF SCIENCE

ALPACA project to observe sub-PeV gamma-ray sky in the southern hemisphere

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Though the maximum energy of the charged cosmic ray observations exceeds 100 EeV, the energy frontier of the gamma-ray observations is PeV. In the past years, Tibet ASγ, HAWC and LHAASO opened a new window of astronomy in the sub-PeV to PeV range, which is important to unveil yet unknown PeV cosmic accelerators in our galaxy. As these 3 experiments are all located in the northern hemisphere, observations in the southern hemisphere have been awaited. Andes Large area PArticle detector for Cosmic ray physics and Astronomy (ALPACA) is a new air shower array experiment under construction in the Bolivian Andes to explore the southern gamma-ray sky for the first time in this energy range. In this paper, we will provide an overview of the ALPACA project, including the initial observational results from a quarter-sized array named ALPAQUITA, which has been operating since 2023. A successful detection of the shadow of the moon, for example, validates the designed performance of the array. We will also outline the plan for the full-scale construction of ALPACA.

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1. Introduction

Since the discovery of sub-PeV (>100 TeV) gamma-ray emission from the Crab nebula by the Tibet ASγ collaboration in 2019 [1], gamma-ray astronomy entered in a new era also with HAWC and LHAASO [2][3]. To understand the origin and propagation of cosmic rays in our galaxy, the sub-PeV observations in the southern hemisphere is essential. As the first southern sub-PeV observatory, a new air shower array experiment, the Andes Large area PArticle detector for Cosmic ray physics and Astronomy (ALPACA), is under construction near the Chacartaya mountain in Bolivia at the altitude of 4,740 m [4][5].

2. Design of ALPACA and ALPAQUITA

Righthand side of Fig.1 shows the layout of the ALPACA array. A surface array of 401 plastic scintillation counters covers the total area of 82,800 m^2. Four units of the underground muon detectors (MDs) with the total area of 3,600 m^2 will be used as a veto counter to reject hadronic CR background events. With 2 m soil overburden the MDs have energy threshold of 1.2 GeV and a >99.9% BG cosmic ray rejection power at 100 TeV while keeping a 90% gamma-ray survival efficiecny.

Since April 2023, a partial array called ALPAQUITA has been in operation with 97 scintillation counters (red area in Fig.1). A construction of the first MD unit at the left bottom corner of the

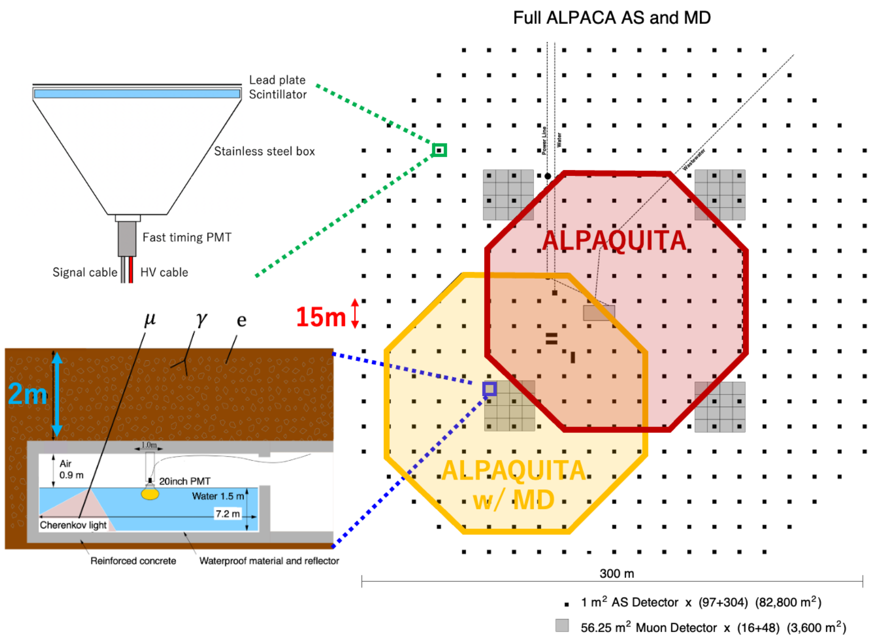

Figure 1: Layout of the ALPACA array (right half) with the currently operating ALPAQUITA surface array (red) and the ALPAQUITA+MD array under construction (yellow). Small black squares indicate the scintillating counters. The design of each counter is shown in the left-top side. The grey hatched area indicates the underground muon detectors. The side view of an MD is shown in the left-bottom side.

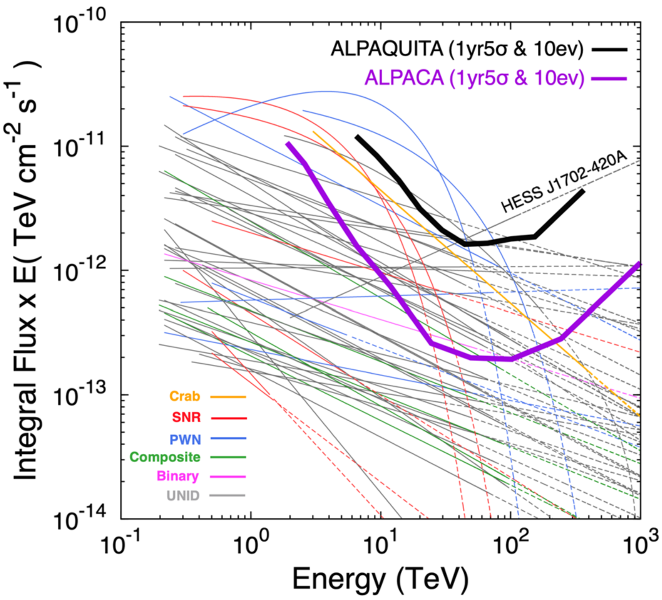

Figure 2: Sensitivities of ALPACA (purple thick curves) and ALPAQUITA (black thick curve) [5]. Thin curves are the fluxes of known southern gamma-ray sources. The solid lines are the measured fluxes while the dashed lines are the extrapolations of the fitting.

ALPAQUITA array will start soon. Surrounding the first MD unit with additional 60 counters, the ALPAQUITA+MD array (yellow area) will start a gamma-ray sensitive observations in 2025.

3. Source Sensitivity

The flux sensitivity of ALPACA and ALPAQUITA (+MD) was reported by [5] as shown in Fig.2. The thin lines are the energy spectra of known sources based on the H.E.S.S. galactic plane survey [6] within the field of view of ALPACA. The solid lines are the best fit spectra in the measured energy range while the dashed lines are the extrapolations. Extrapolations of half of the known sources are within the reach of the ALPACA sensitivity (1yr, 5σ). It is also important that about five sources are within the sensitivity of ALPAQUITA around 100 TeV. The energy spectrum of a peculiar hard source discovered by H.E.S.S., HESS J1702-420A [7], can be tested by the initial observation of ALPAQUITA.

4. Initial Performance of ALPAQUITA

The deployment of the ALPAQUITA surface detectors were completed in 2022 August as shown in Fig.3. After a half year of a pilot operation, a stable operation started in 2023 April.

The first test of the array performance is to analyze the directional intensity of the air shower events around the direction of the moon. Because the trajectories of cosmic rays are blocked by the moon, a deficit of the intensity, called 'shadow of the moon,' is expected [8]. Figure 4 shows the intensity map around the moon (left) and the time evolution of the deficit amplitude (right). A clear

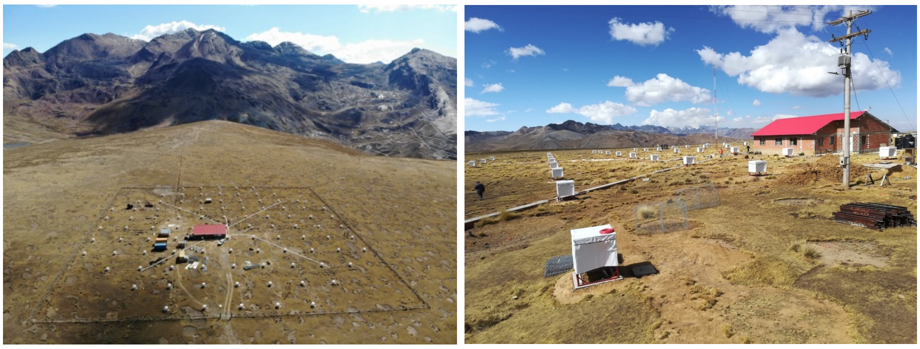

Figure 3: Photographs of the ALPAQUITA array in Bolivia. In the left photograph, the mountain found in the back is Mt. Chacaltaya. The right photograph shows the ground view of the array. Each scintillating counter is protected by a water-proof white cover. The cables for signal and HV are connected to the central hut through the underground cable path.

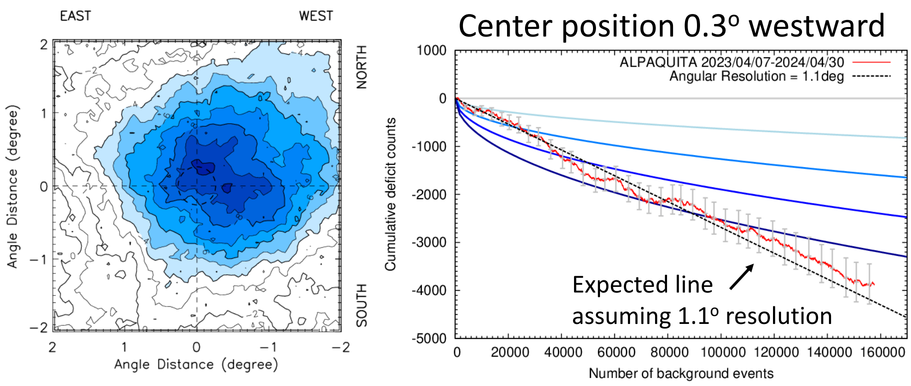

Figure 4: (Left) Distribution of the cosmic-ray intensity around the direction of the moon. The blue color indicates the deficit of the intensity indicating a clear detection of the shadow of the moon by the ALPAQUITA surface array. (Right) Time evolution of the deficit of the shadow of the moon. The blue curved lines indicate the statistical significance of the deficit in order of 0σ, 2σ, 4σ, 6σ, 8σ from top to bottom. The straight dotted line indicates the expected amplitude of deficit when the angular resolution of the array is 1.1°.

shadow of the moon is detected and it assures the pointing accuracy of the array. A slight blur into the western direction is as expected due to the geomagnetic effect between the moon and the earth. A linear evolution of the amplitude indicates a stable operation of the array. The slope is consistent with the angular resolution of 1.1°, which is the expected value at the mode energy of the observed cosmic-ray events (several TeV).

Another test called 'even-odd analysis' was applied. The counters are alternatively grouped into two arrays, and the arrival directions are independently reconstructed. Figure 5 shows the distribution of the opening angles between two reconstructed directions. It is found that the distributions of the experimental data (blue; median 1.95°) and the MC simulation (green; median 1.76°) agree well. Considering the division of the data into two arrays and the calculation of the difference between two measurements, half of the median value, $\sim 1^\circ$, indicates the 50% angular

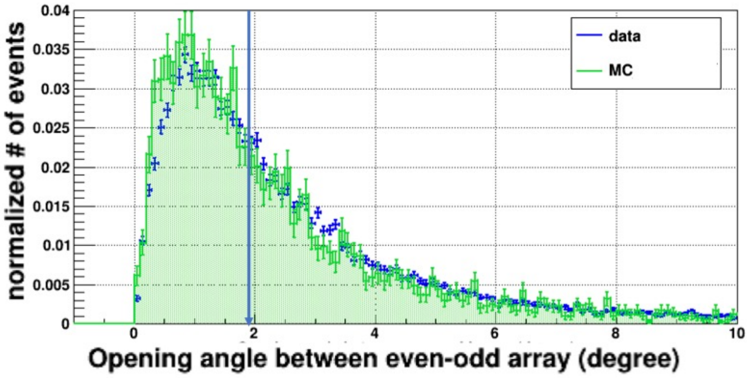

Figure 5: Distribution of the opening angles reconstructed by the divided arrays. Blue shows the experimental result of ALPAQUITA and green shows Monte Carlo calculation.

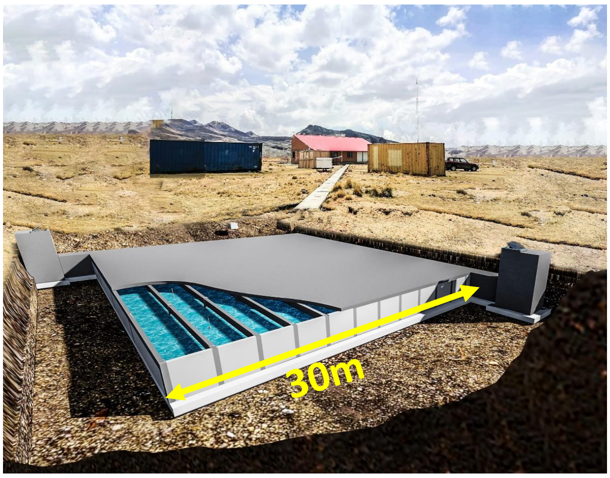

Figure 6: Artistic view of the first MD unit.

resolution and it is consistent with the result of the moon's shadow.

5. Summary

ALPACA will open a new window of the southern sub-PeV sky. A partial array ALPAQUITA has been stably operating since 2023 and shows expected performance in the CR shower observations. With the first MD, whose construction will start soon as illustrated in Fig.6, ALPAQUITA will start gamma-ray sensitive operation in 2025. The extension to the full ALPACA follows it and will reveal the PeV accelerators in our galaxy. As a next generation observatory, Mega ALPACA is also proposed [9] as well as SWGO [10] to observe PeV gamma rays in the southern hemiphere with 1 km^2 scale air shower array.

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