PROCEEDINGS OF SCIENCE

Status of the ALPACA air shower array to explore sub-PeV gamma-ray sky in the southern hemisphere

T. Sako,[a,*] M. Anzorena,[a] D. Blanco,[b] E. de la Fuente,[c] K. Goto,[d] Y. Hayashi,[e] K. Hibino,[f] N. Hotta,[g] G. Imaizumi,[a] A. Jimenez-Meza,[c] Y. Katayose,[h] C. Kato,[i] S. Kato,[a] T. Kawashima,[a] K. Kawata,[a] T. Koi,[d] H. Kojima,[k] T. Makishima,[h] Y. Masuda,[i] S. Matsuhashi,[h] M. Matsumoto,[i] R. Mayta,[b] P. Miranda,[b] A. Mizuno,[a] K. Munakata,[i] Y. Nakamura,[a] C. Nina,[b] M. Nishizawa,[l] Y. Noguchi,[h] S. Ogio,[a] M. Ohnishi,[a] S. Okukawa,[h] A. Oshima,[d,j] M. Raljevic,[b] H. Rivera,[b] T. Saito,[m] T. K. Sako,[n] J. Salinas,[b] T. Shibasaki,[o] S. Shibata,[k] A. Shiomi,[o] M. Subieta,[b] F. Sugimoto,[a] N. Tajima,[p] W. Takano,[f] M. Takita,[a] Y. Tameda,[q] K. Tanaka,[r] R. Ticona,[b] I. Toledano-Juarez,[c] H. Tsuchiya,[s] Y. Tsunesada,[t,u] S. Udo,[f] R. Usui,[h] R. I. Winkelmann,[b] G. Yamagishi,[h] K. Yamazaki[j] and Y. Yokoe[a]

[a] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[b] *Instituto de Investigaciones Físicas, Universidad Mayor de San Andres, La Paz, La Paz 8635, Bolivia*
[c] *Universidad de Guadalajara, Guadalajara, Jalisco, Mexico*
[d] *College of Engineering, Chubu University, Kasugai, Aichi, Japan*
[e] *Department of Science and Technology, Shinshu University, Matsumoto, Nagano, Japan*
[f] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[g] *Utsunomiya University, Utsunomiya, Tochigi, Japan*
[h] *Graduate School of Engineering Science, Yokohama National University, Yokohama, Kanagawa, Japan*
[i] *Department of Physics, Shinshu University, Matsumoto, Nagano, Japan*
[k] *Chubu Innovative Astronomical Observatory, Chubu University, Kasugai, Aichi, Japan*
[l] *National Institute of Informatics, Chiyoda, Tokyo, Japan*
[m] *Tokyo Metropolitan College of Industrial Technology, Arakawa, Tokyo, Japan*
[n] *Department of Information and Electronics, Nagano Prefectural Institute of Technology, Ueda, Nagano, Japan*
[o] *College of Industrial Technology, Nihon University, Narashino, Chiba, Japan*
[p] *RIKEN, Wako, Saitama, Japan*
[q] *Faculty of Engineering, Osaka Electro-Communication University, Neyagawa, Osaka, Japan*
[r] *Hiroshima City University, Hiroshima, Hiroshima, Japan*
[s] *Japan Atomic Energy Agency, Tokai-mura, Ibaraki, Japan*
[t] *Graduate School of Science, Osaka Metropolitan University, Osaka, Osaka, Japan*
[u] *Nambu Yoichiro Institute for Theoretical and Experimental Physics, Osaka Metropolitan University, Osaka, Osaka, Japan*

E-mail: sako@icrr.u-tokyo.ac.jp

*Speaker

PoS(ICHEP2024)659

To unveil the origin of galactic PeV cosmic rays, observation of sub-PeV gamma rays is crucial. Sub-PeV gamma-ray astronomy is established in the northern hemisphere since the discovery of the Crab nebula above 100 TeV by the TibetASγ collaboration in 2019. ALPACA is a new air shower experiment under construction in Bolivia to explore the sub-PeV gamma-ray sky in the southern hemisphere for the first time. The ALPACA array consists of 401 scintillation counters covering 82,800 m^2 and underground muon detectors (MDs) covering 3,600 m^2 and will start operation in 2025. Prior to the full ALPACA, a prototype array ALPAQUITA with 97 scintillation counters is operating since 2022. The first 900 m^2 MD will be constructed soon. In this contribution, we present the performance of the ALPAQUITA including the detection of the moon's shadow by charged cosmic rays. The plan of the first MD construction and the completion of the full ALPACA array are also presented.

42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic

1. Introduction

The high-energy frontier of astronomy has reached to measure sub-PeV gamma-rays from the space since the successful detection of >100 TeV photons from the Crab nebula by the TibetASγ collaboration in 2019 [1] followed by the HAWC [2] and LHAASO [3] collaborations. Not only the pulsar wind nebula like Crab, Supernova Remnants [4] [5] , Star Forming Region [6] are also known as sub-PeV emitters. Photons above PeV [7] and diffuse photons along the galactic plane [8] are also detected. It is thought that sub-PeV photons are emitted through the inverse Compton process from sub-PeV electrons or decay of neutral pions produced in the hadronic interaction of multi-PeV nucleons and the interstellar matter. If we identify multi-PeV nucleon accelerators, it is extremely important because this energy is known as *knee* in the cosmic-ray energy spectrum, which is thought to be the acceleration limit of proton cosmic rays in our galaxy. For example, the emission from G106.3+2.7 is considered a good candidate of hadronic origin, but its current maximum energy does not reach to the knee [4]. So far there is no definitive evidence of hadron accelerator up to the knee energy, but the existence of sub-PeV diffuse photons assures the existence of multi-PeV nucleons in the galaxy [8]. Because the three experiments introduced above are operating in the northern hemisphere, they have not enough sensitivity in the vicinity of the galactic center region, where many energetic sources are known by the H.E.S.S. galactic plane survey at the TeV energy range [9] .

Andes Large area PArticle detector for Cosmic ray physics and Astronomy (ALPACA) is a new air shower experiment under construction in Bolivia highland. Applying the technique established by the TibetASγ, ALPACA will explore the sub-PeV gamma-ray sky for the first time in the southern hemisphere. Since 2022, a small scale ALPACA called ALPAQUITA has been in operation. In this paper, we present the design and the construction plan of ALPACA and ALPAQUITA, then demonstrate the initial performance of ALPAQUITA.

2. ALPACA and ALPAQUITA

The site of ALPACA is near the Chacartaya mountain at an altitude of 4,740 m above sea level in Bolivia. Fig.1 (left) shows the layout of the ALPACA array. Total 401 plastic scintillating counters of 1 m^2 (5 cm thickness) aligned with a 15 m interval cover the 82,800 m^2 ground area and consists of a surface detector (SD) air shower array. Using the signal size and timing measured by the SD array, arrival direction and energy of the primary particle, respectively, are determined. In addition to this conventional SD array, four underground water Cherenkov muon detector (MD) units are constructed below 2 m soil overburden (Fig.1 (right)). Each MD unit is composed of 16 cells, where a single cell has a 7.5 m×7.5 m area filled with 1.5 m deep water and monitored by a 20" PMT. In the soil layer, most of the electromagnetic particles are absorbed and only muons above 1 GeV can be detected. Using this high-purity muon signal, mu-poor electromagnetic showers produced by gamma-ray primaries are selected from the sea of mu-rich isotropic hadronic showers. This technique was first proposed and established by the TibetASγ collaboration [10] [11] .

In 2022, the area enclosed by the dashed-line octagon in Fig.1 (left) was filled by 97 SDs and it has been operated as ALPAQUITA array, meaning a small ALPACA. After the initial operation and maintenance, the array has been stably operated since April 2023. In Sec.3, initial performance

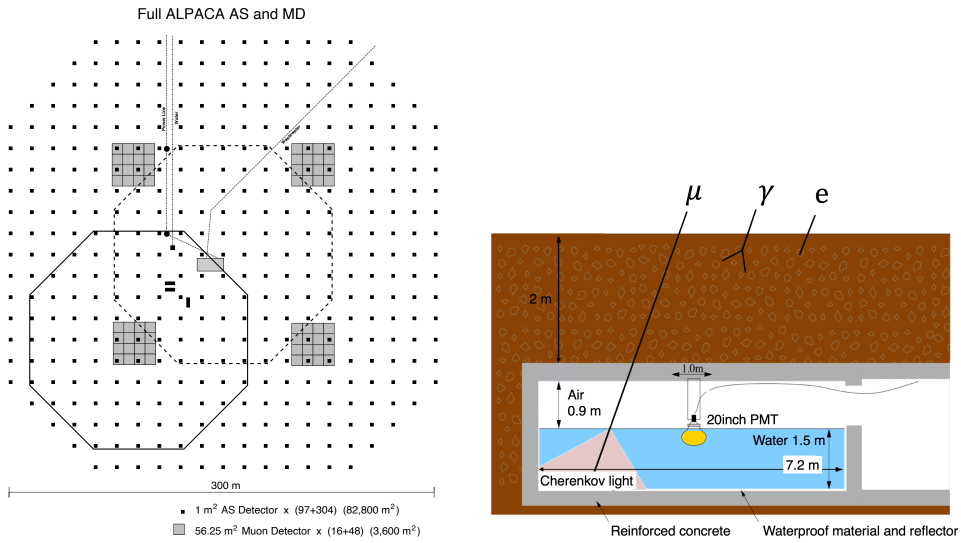

Figure 1: (Left) Layout of the ALPACA array. Small dots indicate SDs and grey hatched areas indicate MDs. The area enclosed by a dashed-line octagon at the center is the ALPAQUITA surface array currently in operation. After the construction of the first MD unit at the left-bottom side, the surface array will be extended as enclosed by the solid-line octagon and will be operated as ALPAQUITA + MD. Full coverage array ALPACA will be eventually achieved. (Right) Schematic view of an MD zooming in a single cell. A reinforced concrete structure is constructed under 2 m soil. MDs are filled with water of 1.5 m depth and Cherenkov lights in each of 56 m^2 cell are monitored by a 20" PMT.

of ALPAQUITA for 1 year is presented. In 2024, the construction of the first MD at the left-bottom side will start. Covering the first MD with additional 70 SDs as enclosed by the solid-line octagon in Fig.1 (left), gamma-ray sensitive operation of ALPAQUITA SD+MD will start in 2025. The sensitivity of ALPAQUITA SD+MD for gamma-ray observation is summarized in [12].

3. Performace of ALPAQUITA

The cumulative number of air shower events recoded by ALPAQUITA since April 2023 is shown in Fig.2. Except two breaks in June 2023 and March 2024 when we had a mass maintenance and a problem of a TDC board, respectively, the events are smoothly recorded.

To test the angular resolution of the array, we applied so-called *even-odd analysis*. In this analysis we first divide the detectors into 2 sub arrays and determined the arrival directions of same shower independently in two sub arrays. The distribution of the angular difference of two directions is shown in Fig.3. Blue crosses show the result of the experimental data while the green hatched histogram show the result of MC simulation assuming the cosmic-ray spectrum and mass composition. The distributions agree well having the median values of 1.95°±0.01° and 1.76°±0.03° for experiment and MC, respectively. The median values are related to the angular resolution of the array but degraded by two factors. One is the division of the data into half and half, and the other is the differentiation of the two reconstructed directions. By considering each term contributes by a factor $\sqrt{2}$, the angular resolution of the ALPAQUITA array is estimated to be

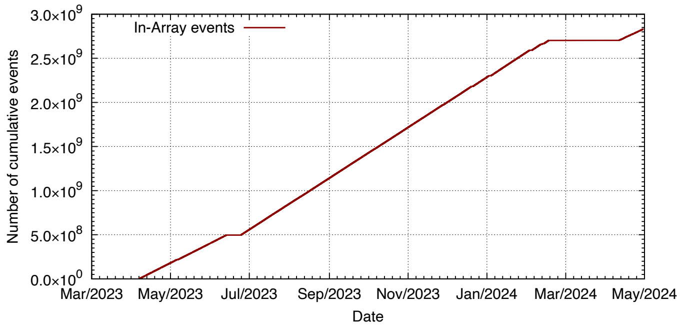

Figure 2: Cumulative number of air shower events recorded by ALPAQUITA. Two breaks correspond to the mass maintenance and a failure of a TDC board.

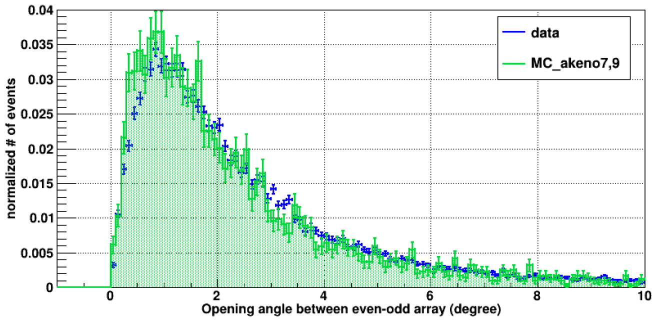

Figure 3: Distributions of the angular difference between two directions determined by the two sub arrays. Blue crosses shows the result of the experimental data while the green hatched histogram show the result of Monte Carlo simulation.

$\sim 1^\circ$. Note that this corresponds to the performance to the hadronic air showers at the mode energy, at a few TeV.

Another test of the array performance is to measure the CR intensity around the moon. While the CR background events arrive isotropically, they are blocked by the moon and a deficit of the CR intensity around the moon, called *the Moon's shadow*, is expected. Fig.4 shows the CR intensity map centered at the direction of the moon observed by ALPAQUITA . As blue color indicates the deficit, a clear shadow of the moon is detected at a statistical significance level of 8σ. A slight offset of the center and a blow into the west (right in the figure) direction, while not yet statistically significant, are consistent if we consider the geomagnetic field and positive electric charge of CRs. The amplitude of the deficit is consistent with the array angular resolution of 1°, which is also consistent with the result of the even-odd analysis.

4. Summary

ALPACA is expected to answer the long-standing problem, the origin of galactic cosmic rays. The prototype array ALPAQUITA is running smoothly and the constructions of the first muon detector and hence the full ALPACA array are scheduled in 2024 and 2025, respectively.

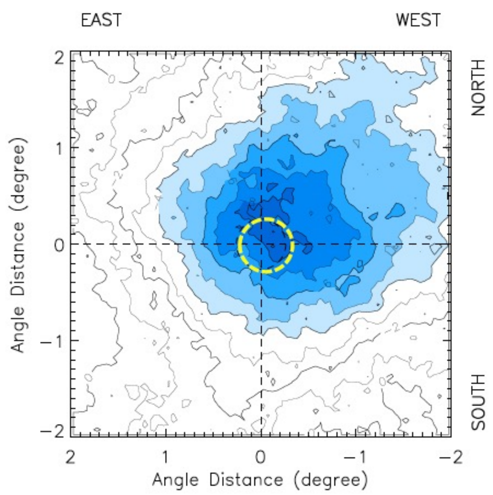

Figure 4: Intensity map around the moon observed by ALPAQUITA. Blue color indicates the deficit of intensity.

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