Sub-PeV to PeV Photon Observations Using the New Air Shower Array in Bolivia

T. Sako,[1] M. Anzorena,[1] E. de la Fuente,[2,3] K. Goto,[4] Y. Hayashi,[5] K. Hibino,[6] N. Hotta,[7] A. Jimenez-Meza,[8] Y. Katayose,[9] C. Kato,[5] S. Kato,[1] I. Kawahara,[9] T. Kawashima,[1] K. Kawata,[1] T. Koi,[10] H. Kojima,[11] T. Makishima,[9] Y. Masuda,[5] S. Matsuhashi,[9] M. Matsumoto,[5] R. Mayta,[12,13] P. Miranda,[14] A. Mizuno,[1] K. Munakata,[5] Y. Nakamura,[1] M. Nishizawa,[15] R. Noguchi,[9] S. Ogio,[1] M. Ohnishi,[1] S. Okukawa,[9] A. Oshima,[4,10] M. Raljevich,[14] T. Saito,[16] T. K. Sako,[1] T. Sasaki,[6] T. Shibasaki,[17] S. Shibata,[11] A. Shiomi,[17] M. A. Subieta Vasquez,[14] N. Tajima,[18] W. Takano,[6] M. Takita,[1] Y. Tameda,[19] K. Tanaka,[20] R. Ticona,[14] I. Toledano-Juarez,[21,22] H. Tsuchiya,[23] Y. Tsunesada,[12,13] S. Udo,[6] R. Usui,[9] K. Yamazaki,[10] and Y. Yokoe[1]

[1] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa 277-8582, Japan*
[2] *Instituto de Investigaciones Físicas, Universidad Mayor de San Andrés, La Paz 8635, Bolivia*
[3] *Departamento de Física, CUCEI, Universidad de Guadalajara, Guadalajara, México*
[4] *Doctorado en Tecnologías de la Información, CUCEA, Universidad de Guadalajara, Zapopan, México*
[5] *College of Engineering, Chubu University, Kasugai 487-8501, Japan*
[6] *Department of Physics, Shinshu University, Matsumoto 390-8621, Japan*
[7] *Faculty of Engineering, Kanagawa University, Yokohama 221-8686, Japan*
[8] *Faculty of Education, Utsunomiya University, Utsunomiya 321-8505, Japan*
[9] *Departamento de Tecnologías de la Información, CUCEA, Universidad de Guadalajara, Zapopan, México*
[10] *Faculty of Engineering, Yokohama National University, Yokohama 240-8501, Japan*
[11] *College of Science and Engineering, Chubu University, Kasugai 487-8501, Japan*
[12] *Chubu Innovative Astronomical Observatory, Chubu University, Kasugai 487-8501, Japan*
[13] *Graduate School of Science, Osaka Metropolitan University, Osaka 558-8585, Japan*
[14] *Nambu Yoichiro Institute for Theoretical and Experimental Physics, Osaka Metropolitan University, Osaka 558-8585, Japan*
[15] *National Institute of Informatics, Tokyo 101-8430, Japan*
[16] *Tokyo Metropolitan College of Industrial Technology, Tokyo 116-8523, Japan*
[17] *College of Industrial Technology, Nihon University, Narashino 275-8575, Japan*
[18] *RIKEN, Wako 351-0198, Japan*
[19] *Faculty of Engineering, Osaka Electro-Communication University, Neyagawa 572-8530, Japan*
[20] *Graduate School of Information Sciences, Hiroshima City University, Hiroshima 731-3194, Japan*
[21] *Doctorado en Ciencias Físicas, CUCEI, Universidad de Guadalajara, Guadalajara, México*
[22] *Maestría en Ciencia de Datos, Departamento de Métodos Cuantitativos, CUCEA, Universidad de Guadalajara, Zapopan, México*
[23] *Japan Atomic Energy Agency, Tokai-mura 319-1195, Japan*

Abstract

Physics at the TeV scale is explored by colliders, while astrophysical PeV photons are now detected by the air shower array experiments. After the first discovery of $>$100 TeV emission from the Crab nebula in 2019 by the Tibet ASγ group, recently 43 celestial objects are reported $>$100 TeV by the LHAASO group in the northern hemisphere. In this contribution, a new air shower experiment called ALPACA, under construction in the Bolivian Andes to explore the southern sky for the first time in the sub-PeV to PeV energy range, is introduced. The prime motivation of ALPACA is to reveal the PeV cosmic hadron accelerators. At the same time, ALPACA is sensitive to astrophysical signals from phenomena beyond the standard model. Possible topics include photons from decaying heavy dark matter surrounding the galactic center, attenuation of PeV photons with starlight, and searches for axion-like particles. We would like to discuss the synergy between the high-energy frontier of astrophysics and physics beyond the standard model.

Keywords: PeV photons, comic rays, air shower array
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1. INTRODUCTION

The photon is one of the most important particles for proving fundamental physics and even physics beyond the standard model. Currently, the highest-energy photons available in laboratories are produced at the Large Hadron Collider. The production cross section of photons with energy almost close to the beam energy, 6.5 TeV, is reported by the LHCf collaboration located very forward region of the ATLAS interaction point [1]. The energy frontier of photon observation from space now reaches beyond PeV, and the astrophysics of the highest-energy photons, gamma-ray astronomy, provides unique opportunities of testing fundamental physics at the energy unreachable by laboratory experiments.

One of the most important goals of gamma-ray astronomy is to identify the sources of galactic cosmic rays. It is known that the energy spectrum of cosmic rays has a break or a rapid steepening at around 3 PeV, known as the *knee*. This is usually explained as the acceleration limit of protons at yet unknown accelerators in our Milky Way galaxy. Cosmic rays with energies above the knee are considered to be heavier nuclei up to 10^{17} eV or from extragalactic origins up to 10^{20} eV. Although this standard model of cosmic-ray origin is well recognized, there is no direct evidence of the existence of the PeV hadron accelerator. To search for PeV accelerating objects, the observation of sub-PeV photons, which are produced through $p + p \rightarrow X + \pi^0$ interaction and a subsequent decay of π^0 into photons, is crucial. As the photons produced in this process typically have 10% of energy of the parent proton, observations of $>$100 TeV (sub-PeV) photons are target to search for the PeV hadron accelerators.

In 2019, the Tibet ASγ collaboration reported the first firm detection of sub-PeV gamma rays from the Crab nebula [2]. Followed by the HAWC [3] and the LHAASO [4] collaborations, the sub-PeV gamma-ray astronomy was established very quickly. The Tibet ASγ collaboration reported the detection of diffuse galactic photons $>$400 TeV [5], which proves that PeV cosmic rays are produced in our galaxy and emit such high-energy photons through interaction with the interstellar medium when they are wandering in the galaxy. LHAASO, thanks to its large experimental area, published a catalog of gamma-ray sources, which contains 43 objects above 100 TeV [6]. Although many objects are identified as sub-PeV photon emitters, detailed analyses of the energy spectra and multi-wavelengths analyses do not show clear evidence of hadron acceleration up to the knee energy without break.

Next important step of this field is to build an observatory in the southern hemisphere, where we can observe the inner galactic plane, including the galactic center. The inner galactic plane is known to have many energetic objects, such as supernova remnants, pulsars and notably the supermassive black hole at the center of the galaxy. The H.E.S.S. collaboration reported 78 sources from the southern hemisphere around the TeV energy range [7]. Andes Large area PArticle detector for Cosmic ray physics and Astronomy (ALPACA) is a new air shower experiment launching in the Bolivian Andes based on the design of the Tibet experiment. In this paper, we describe the design, status, and the plan of the ALPACA experiment in Section 2. We briefly discuss the connection between the gamma-ray astronomy and the physics beyond the standard model in Section 3, then summarize in Section 4.

2. ALPACA EXPERIMENT

2.1. *Design of ALPACA*

ALPACA is a collaboration of scientists from Bolivia, Mexico, and Japan. The experimental site is at a plateau of 4,740 m altitude near the Chacaltaya mountain in Bolivia. A conventional ground air shower array consisting of 401 plastic scintillating counters, each with a 1 m^2 area, covers 82,800 m^2 as shown in Figure 1 (enclosed area by the green line). The signal size and timing measured by the detectors are used to determine the energy and arrival direction of individual air shower and hence the primary particle. To eliminate the events dominated by isotropic hadronic cosmic rays, muon detectors (MDs) are constructed. Four muon detectors shown in Figure 1 as shaded squares, each one composed of 900 m^2 water Cherenkov detector employed with 16 20$''$ PMTs, are constructed under 2 m soil overburden. The electromagnetic component in air shower is absorbed in the soil, and muons with energy above 1 GeV can arrive at the MD. By selecting mu-less or mu-poor showers, we can eliminate the hadronic BG showers down to 0.1% while keeping the gamma-ray (electromagnetic) showers at 80% above 100 TeV. The basic specifications of ALPACA are summarized in Table 1.

Location	Chacaltaya plateau, Bolivia
Longitude and Latitude	$68°08'$ W, $16°23'$ S
Altitude	4,740 m a.s.l. (572 $\mathrm{g/cm^2}$)
Surface area	82,800 m^2
Underground muon detector area	3,700 m^2
Number of surface detector	401 (1 $\mathrm{m}^2 \times 5\,\mathrm{cm}^t$ each)
Energy resolution (100 TeV)	20%
Angular resolution (100 TeV)	0.2°
Duty cycle	100%
Instantaneous field of view	π steradian

TABLE 1: Specifications of the ALPACA design. Details in the different construction stages are summarized in Table 2.

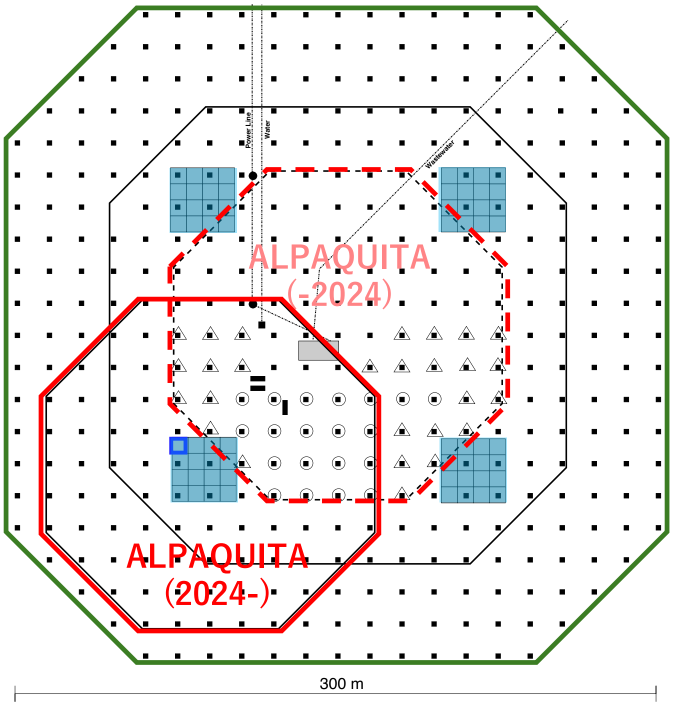

FIGURE 1: Layout of the ALPACA and ALPQAUITA arrays.

2.2. *Status of ALPACA*

In the end of 2023, a part of the ALPACA array with 97 scintillating detectors shown in Figure 1 enclosed by the red dashed line is in operation (photograph in Figure 2). The first MD will be constructed in 2024, and 70 more scintillating counters will be deployed to surround the MD. This partial array of ALPACA enclosed by the red dashed or solid lines in Figure 1 is called ALPAQUITA, meaning a small ALPACA. Although ALPAQUITA has only 25% of the size of the full ALPACA, it has a sensitivity to detect some bright gamma-ray sources within one year operation [8].

Figure 3 demostrates some initial performance of the ALPAQUITA ground array. The left panel shows an example of air shower events with the energy above 100 TeV. Each point indicates the position of a scintillating counter, and the size of the circle represents the particle density observed by that counter, while the color indicates the relative timing of the signal. The red arrow indicates the reconstructed arrival direction, which is from the southwest direction. Because ALPAQUITA does not have an MD yet, we cannot identify the nature of the primary particle, but it will be most likely a hadronic cosmic ray. The right panel shows the relative intensity of the air shower events with respect to the direction of the moon at the center. The blue shaded area represents the deficit of cosmic-ray intensity blocked by the moon (moon shadow). The amplitude and size of the deficit are consistent with the angular resolution of ALPAQUITA. A small shift of the deficit of the center from the origin, though not statistically significant, is also consistent with the deflection of charged cosmic rays by the geomagnetic field between the moon and the earth. Details of the ALPAQUITA status and the initial data analyses are found in [9, 10].

2.3. *Plan of ALPACA*

Configurations and the time line of different stages of ALPACA are summarized in Table 2. As discussed in Section 2.2, the construction of ALPAQUITA will be completed in 2024 by the construction of the first MD. Science observations with good gamma-ray sensitivity will start by the end of the year. In parallel to the ALPAQUITA operation, the construction of the full ALPACA, meaning 3 more MDs and 230 more scintillating detectors, will be planned in 2025. After completion, ALPACA will run for at least 10 years to deepen the exposure to the southern sky, enabling the detection of weak gamma-ray sources, transient events, and any anomalies expected from the BSM physics.

For further extension, a 1 km^2 (1 Mega m^2) array, Mega ALPACA, is proposed [11]. Mega ALPACA enables even deeper survey, sufficient reach to measure >PeV photon flux, and the possible detection of nearby extragalactic objects [12, 13], although there is a strong $\gamma\gamma$ attenuation as discussed in Section 3.

3. BSM PHYSICS BY SUB-PEV GAMMA-RAY OBSERVATIONS

To search for the signals from physics beyond the standard model, photons from the standard model physics, such as $p + p \to \pi^0 + X$ and inverse Compton scattering of high energy electrons, can be a prove of BSM physics but can also be background. Let us consider some examples of these cases. We note that they are studied not only in the context of sub-PeV to PeV but mainly in

FIGURE 2: Photograph of the ALPAQUITA array.

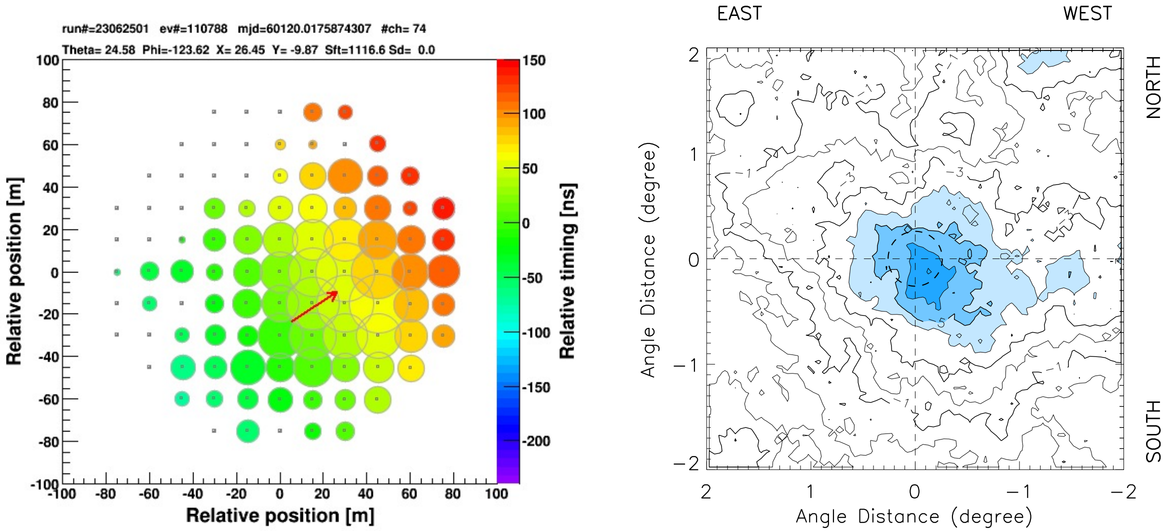

FIGURE 3: *Left*: an example of the air shower events observed by ALPAQUITA. *Right*: shadow of the moon. Deficit of the cosmic-ray intensity around the moon.

Stage	Construction Year	Surface coverage (Number of SDs)	Number of MDs (1 = 16 cells)	References
ALPAQUITA w/o MD	−2024	18,450 m^2 (97)	0	[9, 10]
ALPAQUITA	2024	18,450 m^2 (97)	1	[8]
ALPACA	2025	82,800 m^2 (401)	4+	
Mega ALPACA	2028+	1,000,000 m^2 (1500)	50	[11]

TABLE 2: Construction stages of ALPACA. Mega ALPACA is a proposal for a future 1 km^2 array.

the GeV to TeV range. The uniqueness of ALPACA, the first sub-PeV observations in the southern hemisphere, wide field of view, and high duty cycle, have advantages to provide new information in many of these studies.

3.1. *BSM Physics in the Photon Propagation*

When photons propagate over astrophysical distance to reach the earth, we can test new physics coupled with photons. Because we are searching for anomaly in the energy spectra of gamma-ray sources, we need to have a robust understanding of the energy spectrum within the standard model. The first point is about particle acceleration at the source. According to the shock acceleration theory supported by many observations, the energy distribution of accelerated particles follows a power law. Additionally, due to the limitation of the maximum energy, the spectrum becomes steeper at higher energy. Such a steepening spectrum is a common feature of gamma-ray spectra at the sources. Then, depending on the energy and distance, the attenuation through a process, $\gamma_{HE} + \gamma_{LE} \to e^+ + e^-$, becomes important. Here γ_{HE} denotes the high-energy photons and γ_{LE} means the starlight or the Cosmic

Microwave Background. With $\gamma_{HE} > 10\,\mathrm{TeV}$, the cross section rapidly increases, and the attenuation length reaches the minimum value of 10 kpc when $\gamma_{HE} = 1\,\mathrm{PeV}$. This means in the sub-PeV observations, the space outside our galaxy is opaque, and even inside our galaxy, the attenuation cannot be ignored when the distance to a source is far [14]. This $\gamma\gamma$ attenuation even steepens the energy spectra at the earth.

(i) *Axion-like particle (ALP)*: Because ALPs are thought to couple with the electromagnetic field, such as $a\gamma\gamma$, a high-energy photon (γ) can be converted to an ALP (a) in the magnetic field (γ) near the source. The ALP can propagate over a long distance without any attenuation and will reach our galaxy. Another conversion of the ALP to a high-energy photon in the galactic magnetic field allows an escape from the $\gamma\gamma$ attenuation even when the source is at far away. In this case, an unexpectedly flat energy spectrum will be evidence of new physics [15]. Because the probability of the second conversion in our galaxy is higher through the inner galactic plane, the ALPACA observations at the southern hemisphere have an advantage in this study.

(ii) *Lorentz invariance violation (LIV)*: Some LIV scenarios predict the decay of photons at high energy. Because this effect becomes strong above a certain threshold energy, the energy spectrum shows an abrupt cutoff [16], which is the opposite effect to the case of ALP. Because we need high-energy sources at various distances, the ALPACA observations in the source-rich southern hemisphere have an advantage.

3.2. Photon Emission through BSM Physics

When the BSM physics itself generates high-energy photons, any astrophysical photons become background. In this case, we must define properties of BSM signals distinguishable from the astrophysical signals. Energy spectrum, spatial distribution, and variability (evolution in time) are usually discussed.

(i) *Annihilation of dark matter*: If the dark matters can pair-annihilate by themselves, they will pair-create standard model particles. (See [17] for a review of dark matter session in ICRC2023, where indirect search through high-energy photon observations is one of the major topics.) If the process $DM + DM \to \gamma + \gamma$ occurs, a line emission at the mass of the dark matter becomes very strong evidence of dark matter. Other decay channels also produce high-energy photons at the final states, but they result in broad band spectra limited below the mass of the dark matter. There are many efforts to model the energy spectra in such processes. Another distinguishable property is the spatial distributions. A robust target is the center of our galaxy. Dark matters are thought to spherically surround the galactic center, while the astrophysical objects distribute along the galactic plane. Another important target is the dwarf galaxies surrounding our galaxy. Because the dwarf galaxies are known to host less energetic astrophysical objects and have high dark matter abundances, clear signals from the dark matter are expected. Importantly, as the energy spectra from the dark matter annihilation must be identical, spectra from multiple dwarf galaxies are crucial observations. ALPACA has advantages to observe the galactic center first time above 100 TeV and to survey many dwarf galaxies in the southern hemisphere due to its wide field of view and high duty cycle.

(ii) *Dark matter decay*: If dark matter has a lifetime and decays into standard model particles, it also produces high-energy photons at the final states. The spatial distribution of the decay follows the distribution of the dark matter density (ρ), while the annihilation follows the square of the density (ρ^2). This results in a wider distribution of decay photons than the annihilation photons [18]. ALPACA has a very unique possibility to search these dark matter decay photons because the decay flux is strongest in the direction of the galactic center, and the wide field of view is necessary to catch the wide distribution. A known background is the galactic diffuse photons produced by the high-energy cosmic rays and interstellar matters [5, 19]. A spherically symmetric distribution from higher galactic latitudes can be evidence of the dark matter decay signals.

(iii) *Evaporation of primordial black hole (PBH)*: Primordial black holes with an initial mass of $\sim 5 \times 10^{11}$ kg at the beginning of the universe are known to evaporate at the current epoch. When a PBH evaporates, the temperature of the PBH rapidly increases and the thermal emission reaches 10 TeV at the last moment. The process is well understood, and the time-evolving spectra in the last moment are modeled [20]. Observations by air shower arrays with a wide field of view and high duty cycle are advantageous in the detection of PBH evaporation [21].

4. SUMMARY

ALPACA is a new air shower array under construction (and partly in operation) in the Bolivian Andes. Leveraging established techniques from the Tibet experiment in the northern hemisphere, ALPACA can explore the sub-PeV to PeV sky for the first time in the southern hemisphere, where many high-energy astrophysical objects are known to exist up to TeV. The energy reach of the astrophysics up to PeV provides opportunities for research in physics beyond the standard model, which is not available through laboratory experiments. The unique properties of ALPACA, (1) southern hemisphere where the inner galaxy and galactic center are in the field of view, (2) sub-PeV to PeV, (3) wide field of view, and (4) high duty cycle, enable unique reesarh in the BSM physics in the coming decade.

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References

[1] The LHCf Collaboration, Phys. Lett. B780 (2018) 233–239.
[2] The Tibet ASγ Collaboration, Phys. Rev. Lett., 123, 051101 (2019).
[3] The HAWC Collaboration, Astrophys. J., 881:134 (2019).
[4] The LHAASO Collboration, Chinese Phys. C, 45, 025002 (2021).
[5] The Tibet ASγ Collaboration, Phys. Rev. Lett., 126, 141101 (2021).
[6] The LHAASO Collaboration, arXiv:2305.1703.
[7] The H.E.S.S. Collaboration, A&A 612, A1 (2018).
[8] The ALPACA Collaboration, Exp. Astron. (2021) 52:85–107.
[9] The ALPACA Collaboration, PoS(ICRC2023) 767.
[10] The ALPACA Collaboration, PoS(ICRC2023) 257.
[11] The ALPACA Collaboration, PoS(ICRC2023) 632.
[12] H.E.S.S. and Fermi LAT Collaborations, A&A 619, A71 (2018).
[13] The H.E.S.S. Collaboration, Nature, 582, 356–359 (2020).
[14] R. J. Protheroe and H. Meyer, Phys. Lett. B, 493, 1–9 (2000).
[15] C. Eckner and F. Calore, Phys. Rev. D, 106, 083020 (2022).
[16] The HAWC Collaboration, Phys. Rev. Lett., 124, 131101 (2020).
[17] M. J. Zurowski, PoS (ICRC2023) 035.
[18] K. Murase, R. Laha, S. Ando, and M. Ahlers, Phys. Rev. Lett., 115, 071301 (2015).
[19] P. Lipari and S. Vernetto, PRD 98, 043003 (2018).
[20] T. N. Ukwatta, et al., Astropart. Phys., 80, 90–114 (2016).
[21] The HAWC Collaboration, JCAP04 (2020) 026.