Tibet AS+MD Project

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***Abstract*. We are proposing a future project to observe 10-1000 TeV gamma rays from the cosmic-ray accelerators in our Galaxy with very low background noise and wide field of view. In order to achieve this purpose, we are planning to build a 10,000 m^2 water-Cherenkov-type muon detector (MD) array under the Tibet air shower (AS) array. The gamma-ray induced air shower has significantly less muons compared with a cosmic- ray induced one. Therefore, we can significantly discriminate between the primary gamma rays and cosmic-ray background events by means of counting the number of muons in an air shower. Our current MC simulation predicts that the cosmic-ray background events can be suppressed by approximately 99.99% at 100 TeV using a full-scale MD array.**

***Keywords*: Gamma rays, Muons, Cerenkov detectors.**

I. Introduction

Recent imaging atmospheric Cherenkov telescopes (IACTs), such as CANGAROO, H.E.S.S., MAGIC and VERITAS, and wide field-of-view extensive air shower arrays, such as Milagro and the Tibet air shower (Tibet AS) array, detect a lot of very-high-energy (VHE) gamma-ray sources in the 100 GeV to 10 TeV energy region. Remarkably, H.E.S.S. reported dozens of new unidentified TeV gamma-ray sources which have a harder energy spectrum (indices: -1.8 to -2.8) at TeV energies than the standard candle Crab (index: -2.6) [1]. These are called " dark cosmic-ray accelerator".

Cosmic rays are supposed to be accelerated up to the knee energy region ($\sim$4 PeV) [2] at VHE astrophysical objects in our galaxy. Therefore, we naturally expect gamma rays in the 100 TeV region which originate in π^0 decays produced by the accelerated charged cosmic rays interacting with matter surrounding VHE gamma-ray source. However, the origin of VHE gamma rays might also be attributed to the leptonic processes, such as the inverse-Compton (IC) scattering or bremsstrahlung by accelerated electrons. One solution of this dilemma is to find a peak of π^0 decays around 70 MeV in the gamma-ray energy spectrum. The FERMI gamma-ray space telescope, succeeding the EGRET telescope, was launched on June 2008 to cover an energy range from 20 MeV to 300 GeV [3], with a sensitivity approximately hundred times better than EGRET. An alternative approach is to search for a continuous gamma-ray spectrum up to 100 TeV or more, because gamma rays of the leptonic origin rapidly diminished at higher energies due to the strong synchrotron cooling process and the Klein-Nishina effect. Although the air shower experiments have [4][5][6] searched for gamma-ray sources in the 100 TeV region, there is no compelling evidence for gamma-ray sources so far. Thus, it is interesting to observe the gamma-ray sources above 10 TeV to investigate the mechanism of gamma-ray emissions, the cosmic-ray acceleration and its origins.

In this paper, we will introduce our future plan which is called the Tibet AS+MD project. The Tibet AS+MD array will have the sensitivity to gamma rays in the 100 TeV region by an order of magnitude better than previous existing detectors.

II. Tibet AS Array

The Tibet AS experiment has been successfully operated at Yangbajing (90.522° E, 30.102° N, 4,300 m above sea level) in Tibet, China since 1990 [7]. The array was constructed first in 1990 and gradually upgraded by increasing the number of detectors, then the Tibet AS array consists of 533 plastic scintillation detectors of 0.5 m^2 placed on a 7.5 m square grid to detect high-energy ($>$ a few TeV) cosmic-ray showers. In the late fall of 2003, the area of the Tibet AS array was further enlarged up to 36,900 m^2 by adding 256 detectors. This final array configuration has been successfully in operation, triggering air shower events at a rate of 1,700 Hz. Using these arrays, we already successfully detected VHE gamma rays from Crab, Mrk 501 and Mrk 421 [8][9][10]. Also, we set stringent upper limits to gamma rays from Galactic plane at 3 TeV and 10 TeV [11][12].

Recently, we updated the VHE gamma-ray energy spectrum of the Crab Nebula [13]. We found no evidence for time variability of flux intensity from the Crab Nebula at multi-TeV energies. Also the VHE gamma-ray energy spectrum of the Crab Nebula is consistent with our previous results and other observations by the IACTs. We also have successfully observed VHE gamma-ray sources and precise large-scale cosmic-ray anisotropy in the northern sky [14][15]. In these results, we first pointed out new small anisotropies in Cygnus region at multi-TeV energies [15]. One of them is coincident with MGRO J2019+37 which the Milagro experiment recently established as a VHE gamma-ray source [16].

The absolute gamma-ray energies in multi-TeV region observed by the Tibet AS array are verified by the Moon's shadow observation [13]. As primary cosmic rays are shielded by the Moon, we observed a deficit in cosmic rays called the Moon's shadow, and the center of the Moon's shadow shifts westward depending on primary cosmic-ray energies due to the geomagnetic field. Using this effect, the systematic error of absolute energy scale is estimated to be less than $\pm$12%.

III. Tibet MD Array

A problem in VHE gamma-ray astronomy with the ground-based experiment is the presence of dominant cosmic-ray background events against gamma-ray signals. In order to significantly discriminate between gamma rays and background cosmic rays, we are planning to build a water-Cherenkov-type muon detector array (Tibet MD array) around the Tibet AS array [17][18][19][20], because gamma-ray induced air shower have much less muons than cosmic-ray induced one. Each muon detector is a waterproof concrete pool, 7.2 m wide $\times$ 7.2 m long $\times$ 1.5 m deep in size, equipped with two 20 inch-in-diameter PMT (HAMAMATSU R3600) as shown in Fig. 1. The Tibet MD array consists of 192 muon detectors set up 2.5 m underground as shown by the shaded areas in Fig. 2. Its total effective area amounts to be 10,000 m^2 approximately for muon detection with an energy threshold of 1 GeV. The surface AS array will be a simple extension of the Tibet AS array, consisting of 1081 scintillation detectors covering an effective area of 83,000 m^2.

The Monte Carlo simulation including the air shower generation and responses of the Tibet AS+MD array was done to estimate the discrimination power between gamma rays and cosmic-ray background events based on counting the number of muons accompanying an air shower [19]. As a result, cosmic-ray induced air showers are suppressed by 99.99% around 100 TeV, while gamma-ray-induced air showers remain by more

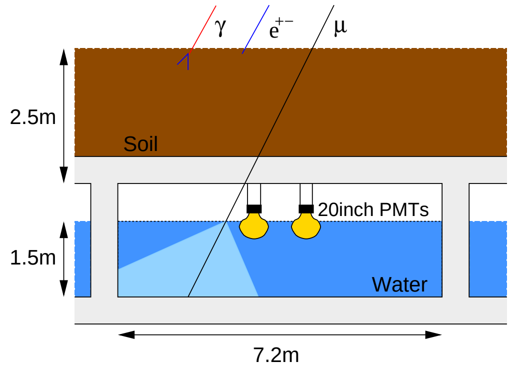

Fig. 1. Schematic side view of the Tibet MD array. Each muon detector is set up 2.5 m underground and has a waterproof concrete pool, 7.2 m wide × 7.2 m long × 1.5 m deep in size, equipped with two 20 inch-in-diameter PMT (HAMAMATSU R3600).

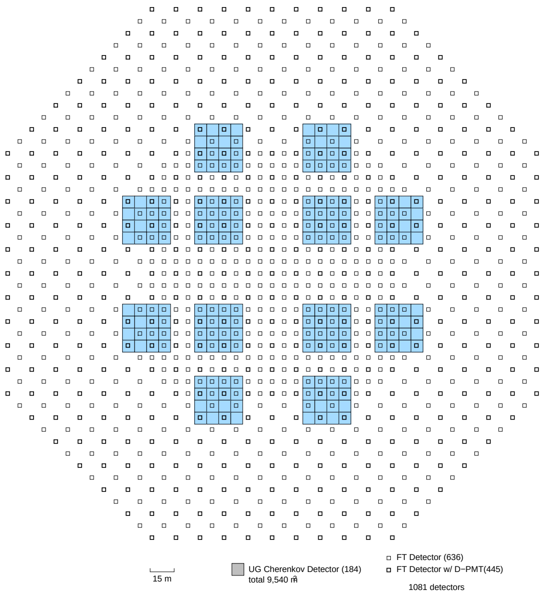

Fig. 2. Schematic view of the Tibet AS+MD array for the MC simulation. The open squares show 0.5 m^2 plastic scintillation detectors which composed Tibet AS array. This array is extended to 8,3000 m^2 from the present array (3,7000m2). The filled squares show the proposed 52 m^2 water Cherenkov detector cells of the Tibet MD array buried 2.5 m underground.

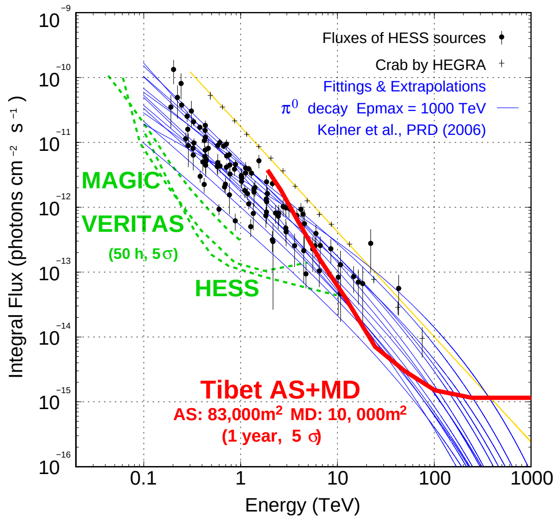

Fig. 3. Integral flux sensitivities to point-like gamma-ray sources. Dashed curves show sensitivities of IACTs at 5 σ for 50 hours (MAGIC, VERITAS and HESS from the upper curve) [21]. The thick solid curve demonstrates the sensitivity of the Tibet AS+MD array at 5 σ for 1 calendar year [20]. Closed circles show the integral fluxes converted from observed differential fluxes of “HESS J” sources point by point assuming their spectral indices [1]. Thin lines show fittings and extrapolations to HESS data points assuming gamma-ray production model at proton-proton interaction by Kelner et al. [22]. The maximum energy of protons is set to 1000 TeV.

than 95%. Finally, we calculate the integral flux sensitivity of the Tibet AS+MD array to point-like gamma rays as shown by the thick solid curve in Fig. 3. Note that our sensitivity above 200 TeV is defined as a flux corresponding to 10 gamma-ray events, since the background events are fully suppressed to be less than one event.

The Tibet AS+MD array will have the sensitivity to gamma rays in the 100 TeV region by an order of magnitude better than any other previous existing detectors in the world. The sensitivity of the full-scale Tibet AS+MD array is shown in Fig. 3, together with gamma-ray fluxes of unidentified “HESS J” sources [1]. If the “HESS J”-like sources also exist in the northern hemisphere, we will discover gamma-ray signals and cutoff energy from 10 TeV to 1000 TeV at high significance level. In the whole of northern sky, we can expect to detect a dozen known/unknown point-like/extended sources and diffuse gamma rays from Galactic plane with extremely low background level ($\sim$1 event / degree^2). In the near future, the MAGIC and VERITAS experiments, together with the Tibet AS+MD array will contribute to a deeper understanding of the origin and acceleration mechanism of cosmic rays.

In the late fall of 2007, a prototype muon detector of approximately 100 m^2 in total was constructed at $\sim$90 m away from the center of the existing Tibet AS array. The prototype detector’s goals are to check construction feasibility, development of calibration method, confirmation of our Monte Carlo (MC) simulation and searching for sub-PeV gamma rays in the northern sky. The preliminary data analysis is in good agreement with our MC simulation results [23][24][25].

IV. SUMMARY

Aiming at observations of cosmic gamma rays in the 10-1000 TeV energy region, we propose a 10,000 m^2 water-Cherenkov-type muon detector (MD) array under the Tibet AS array. The Tibet MD array will enable us to improve gamma-ray sensitivity in 100 TeV energy region by an order of magnitude better than any other previous existing experiments in the world. In late fall of 2007, a prototype water Cherenkov muon detector of approximately 100 m^2 was successfully constructed under the Tibet AS array. The preliminary data analysis is in good agreement with our MC simulation. This

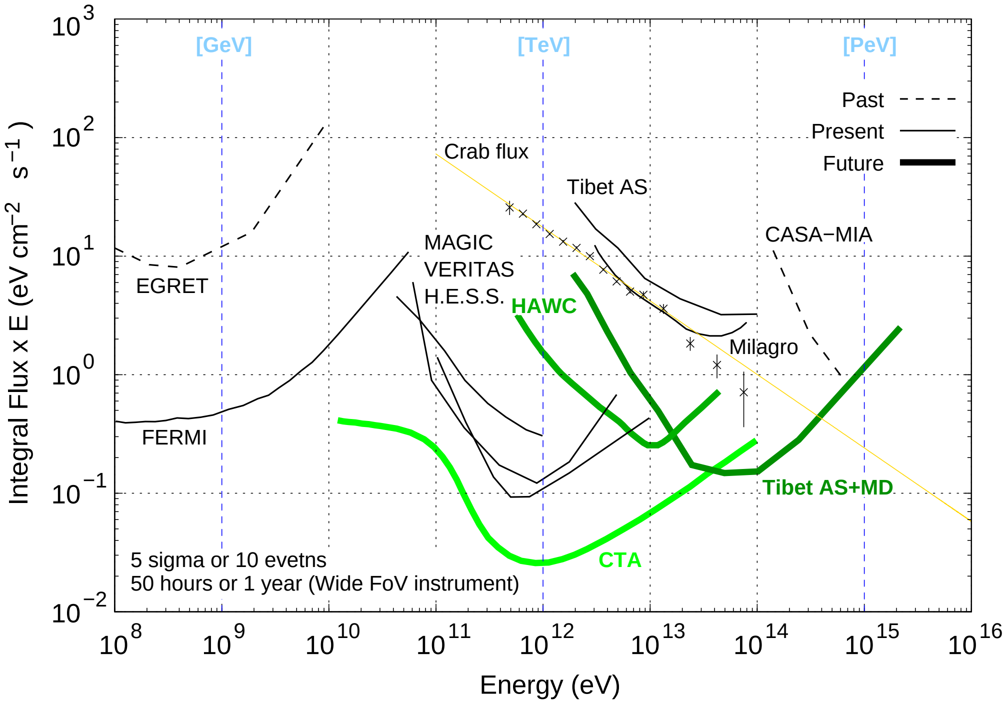

Fig. 4. Past, present and future sensitivity to gamma-ray point-like sources in the GeV-PeV range. The vertical axis indicates the integral flux (m^{-2} s^{-1}) multiplied by the energy (eV). All sensitivity curves indicate 5σ or 10 events detection. The dashed, thin solid and thick solid curves represent past, present instruments and future plans, respectively. EGRET and FERMI [3] are the satellite-borne wide field-of-view telescopes with 1 year observation. MAGIC, VERITAS, H.E.S.S. [21] and CTA [26] are the IACTs with 50 hours observation. Tibet AS, Milagro [28], CASA-MIA [27], HAWC [28] and Tibet AS+MD [20] are wide field-of-view extensive air shower arrays with 1 year observation. The sensitivity curve of the CASA-MIA is calculated by its gamma-ray flux upper limits of the Crab Nebula [27]. The cross points show the gamma-ray flux of the Crab Nebula observed by HEGRA [29].

prototype detector will be the first step to pioneer the 100 TeV gamma-ray astronomy.

In the near future, the FERMI gamma-ray space telescope, present/future IACTs, HAWC and the Tibet AS+MD array will contribute to a deeper understanding of the origin and acceleration mechanism of cosmic rays with complementary energy and approach as shown in Fig. 4.

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References

[1] F. Aharonian, et al. 2006, ApJ, 636, 777.
[2] M. Amenomori, et al. 2008, ApJ, 678, 1165.
[3] W. B. Atwood, et al. 2009, submitted to ApJ (arXiv:0902.1089).
[4] T. A. McKay, et al. 1993, ApJ, 417, 742.
[5] T. Antoni, et al. 2004, ApJ, 608 865.
[6] M. Amenomori, et al. 2005, ApJ, 635, L53.
[7] M. Amenomori, et al. 1992, Phys. Rev. Lett., 69, 2468.
[8] M. Amenomori, et al. 1999, ApJ, 525, L93.
[9] M. Amenomori, et al. 2000, ApJ, 532, 302.
[10] M. Amenomori, et al. 2003, ApJ, 598, 242.
[11] M. Amenomori, et al. 2002, ApJ, 580, 887.
[12] M. Amenomori, et al. 2006, Advances in Space Research, 37, 1932.
[13] M. Amenomori, et al. 2009, ApJ, 692, 61.
[14] M. Amenomori, et al. 2005, ApJ, 626, L29.
[15] M. Amenomori, et al. 2006, Science, 314, 439.
[16] A. A. Abdo, et al. 2007, ApJ, 664, L91.
[17] M. Amenomori, et al. 2007, Astrophysics and Space Science, 309, 435.
[18] M. Amenomori, et al. 2008, Proc. 30th Int. Cosmic Ray Conf. (Mérida), 2, 353 (arXiv:0710.2757).
[19] M. Amenomori, et al. 2008, Proc. 30th Int. Cosmic Ray Conf. (Mérida), 2, 357 (arXiv:0710.2752).
[20] M. Amenomori, et al. 2008, Journal of Physics: Conference Series, 120, 062024.
[21] P. Majumdar, et al. 2005, Proc. 29th Int. Cosmic Ray Conf. (Pune), 5, 203.
[22] S. R. Kelner, F. A. Aharonian and V. V. Bugayov, 2006, Physical Review D, 74, 034018.
[23] M. Amenomori, et al. 2008, AIP Conf. Proc., 1085, 723.
[24] M. Amenomori, et al. 2008, Proc. 31st Int. Cosmic Ray Conf. (Łódź) *Demonstration of hadronic cosmic-ray rejection power by a water Cherenkov underground muon detector with the Tibet air shower array*.
[25] M. Amenomori, et al. 2008, Proc. 31st Int. Cosmic Ray Conf. (Łódź) *A northern sky survey for PeV gamma rays using the Tibet air shower array with water-Cherenkov-type underground muon detectors*.
[26] http://www.cta-observatory.org/
[27] A. Borione, et al. 1997, ApJ, 481, 313.
[28] http://hawc.umd.edu/
[29] F. Aharonian, et al. 2004, ApJ, 614, 897.