Underground Water Cherenkov Muon Detector Array
with the Tibet Air Shower Array
for Gamma-Ray Astronomy in the 100 TeV Region

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Abstract We propose to build a large water-Cherenkov-type muon-detector array (Tibet MD array) around the 37,000 m² Tibet air shower array (Tibet AS array) already constructed at 4,300 m above sea level in Tibet, China. Each muon detector is a waterproof concrete pool, 6 m wide × 6 m long × 1.5 m deep in size, equipped with a 20 inch-in-diameter PMT. The Tibet MD array consists of 240 muon detectors set up 2.5 m underground. Its total effective area will be 8,640 m² for muon detection. The Tibet MD array will significantly improve gamma-ray sensitivity of the Tibet AS array in the 100 TeV region (10-1000 TeV) by means of gamma/hadron separation based on counting the number of muons accompanying an air shower. 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.

Keywords Gamma ray · Cosmic ray · Muon · SNR

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1 Introduction

Based on observation by 4 large imaging air Cherenkov telescopes in Namibia, the HESS group recently reported the discovery of 14 new gamma-ray sources in the TeV region, among which 8 sources are UNIdentified (UNID) or SuperNova Remnant (SNR)-like [1]. Many of the 14 sources have a harder energy spectrum (indices: −1.8 to −2.8) at TeV energies than the standard candle Crab (index: −2.6). These energy spectra were measured from 200 GeV and turned out to extend up to 10 TeV approximately. Cosmic rays are supposed to be accelerated up to the knee energy region at SNRs in our galaxy. Therefore, we naturally expect gamma rays in the 100 TeV region (10-1000 TeV) which originate in $\pi^0$ decays produced by the accelerated charged cosmic rays interacting with matter surrounding the SNRs.

Here, we will demonstrate our excellent sensitivity of the Tibet air shower array plus muon detector array (Tibet AS+MD array) to gamma rays in the 100 TeV region calculated by the Monte Carlo (MC) simulation and give some speculation on 100 TeV gamma-ray source candidates.

2 The Tibet AS+MD array

The Tibet air shower experiment has been successfully operated at Yangbajing (90.522° E, 30.102° N, 4,300 m above sea level) in Tibet, China since 1990. At present, the Tibet AS array consists of 789 plastic scintillation counters of 0.5 m² each viewed by the 2 inch-in-diameter photo-multiplier tube (PMT), placed on a 7.5 m square grid with an enclosed area of 37,000 m² to detect high-energy (> a few TeV) cosmic-ray air showers as shown by open squares and circles in Figure 1.

We are planning to build a water-Cherenkov-type muon detector array (Tibet MD array) around the Tibet AS array. Each muon detector is a waterproof concrete pool, 6 m wide × 6 m long × 1.5 m deep in size, equipped with a 20 inch-in-diameter (20″φ) PMT (HAMAMATSU R3600). The inside of the concrete pool is painted with white epoxy resin to waterproof and to efficiently gather catoptric water Cherenkov lights by a downward facing PMT. The Tibet MD array consists of 240 muon detectors set up 2.5 m underground (2.0 m soil + 0.5 m concrete ceiling: ∼19 radiation length) as shown by gray areas in Figure 1. Its total effective area amounts to be 8,640 m² for muon detection with an energy threshold of 1 GeV. This configuration of the Tibet MD array is simply one example for easy installation under the existing Tibet AS array. Advantages of the under-
ground water Cherenkov detector are high cost performance and high sensitivity to muons rather than the electromagnetic component caused by the environmental background radioactivity and the air shower cascade, because it is easy to design its pool depth (= path length of a muon) deeper, compared with a scintillation detector.

The dark pulse rate of 20°φ PMT measured in laboratory is typically 100 Hz above 10 photoelectrons (PEs) at 10° gain at 1500 V supplied voltage. In this case, relativistic muons made by primary cosmic rays near the top of atmosphere dominate the accidental background at approximately 10 kHz per 36 m² muon detector. Our DAQ system will enable us to set the time window for muons to 200 ns by the offline analysis, therefore, the accidental event rate will be 0.5 (10¹⁰⁰ Hz) events per air shower trigger. The water for the Tibet MD array (~13 kton) will be supplied from abundant underground water pumped up at a village adjacent to our site. According to an examination of this water, the light attenuation length is longer than several tens of meters. The water in the pools will be continuously circulated through 0.1 μm mesh filter and UV sterilizer to keep the light attenuation length. The water never freezes and bacteria do not proliferate easily, since the temperature at 2.5 m underground remains stable and cold between 3°C and 12°C through the year.

3 MC simulation

The air shower events induced by cosmic rays and gamma rays are generated by the CORSIKA Ver.6.204 code [3] with QGSJET01c for the hadronic interaction model. Primary cosmic rays are thrown along Crab’s orbit around the Earth, and the relative chemical composition model [4] of primary cosmic rays is adopted based on direct observational data in the energy range from 0.3 TeV to 10000 TeV. Primary gamma rays are also thrown along Crab’s orbit around the Earth assuming a differential power-law spectrum of $E^{-2.6}$ in the energy range from 0.3 TeV to 10000 TeV. Air shower events are uniformly thrown within a circle radius 300 m centered at the array center. This radius is sufficient to collect all air shower events which are actually triggered in our array.

The simulation of the Tibet AS array including the scintillation detector response was already established based on the Epics u8.00 code [6]. Finally, we get the estimated/true air shower direction, core position, the sum of particle density for all detectors ($\Sigma \rho$) related to true energy, and so on for each air shower event. Distributions of the MC events, such as parameters mentioned above, etc., are consistent with experimental data. The trigger condition is imposed by the Tibet AS array, i.e., each shower event should fire four or more of the scintillation detectors recording 1.25 particles or more. The energies at 100% trigger efficiency are estimated to be approximately 10 TeV for gamma rays and 30 TeV for cosmic rays, respectively. After the air shower reconstruction and some event selections, the angular resolution and energy resolution are also estimated to be approximately 0.2° and 40% at 100 TeV, respectively.

The response of the water Cherenkov muon detector and the soil as an absorber are simulated based on GEANT4 8.0 code [3], considering the detailed structure of the Tibet MD array. First, we trace the secondary particles of air showers triggered by the Tibet AS array in the underground soil ($2.0 \text{g/cm}^2$, 70% SiO$_2$, 20% Al$_2$O$_3$, 10% CaO). All surviving particles under the soil with energies exceeding the Cherenkov threshold are subsequently fed into the simulation of the Tibet MD array including 0.5 m thick concrete ($2.3 \text{g/cm}^2$: 100% SiO$_2$) ceilings and walls. The reflectance at the surface of walls is assumed to be 70% with isotropic reflection. After we simulate Cherenkov radiation, propagation of Cherenkov photons in water, and the response of 20°φ PMT, the number of photoelectrons ($N_{\text{PE}}$) is counted up for each muon detector. The quantum efficiency of 20°φ PMT for wavelengths of 340–400 nm is approximately 20%. The peak of $N_{\text{PE}}$ is estimated to be 26 PEs with width $\sigma_{N_{\text{PE}}}$ +130%–30% approximately for one muon detector when a vertical muon passes through a muon detector.

4 Results and discussions

Figure 2 shows the distribution of $\Sigma N_{\text{PE}}$ for the Tibet MD array as a function of $\Sigma \rho$ for the Tibet AS array. Blue and green points indicate gamma-induced and hadron-induced air showers, respectively. Closed circles and error bars show median, 80% and 20% values, respectively. The cut to suppress hadron-induced air showers is shown as a solid line. Air showers with no recorded PE by the Tibet MD array are plotted as $\Sigma N_{\text{PE}} = 1.2$. Upper right: $\Sigma N_{\text{PE}}$ distribution in typical energy band 10 TeV (100 ≤ $\Sigma \rho$ < 215). Lower right: 100 TeV (1000 ≤ $\Sigma \rho$ < 2154).

Fig. 2 Distribution of $\Sigma N_{\text{PE}}$ for the Tibet MD array as a function of $\Sigma \rho$ for the Tibet AS array. Blue and green points indicate gamma-induced and hadron-induced air showers, respectively. Closed circles and error bars show median, 80% and 20% values, respectively. The cut to suppress hadron-induced air showers is shown as a solid line. Air showers with no recorded PE by the Tibet MD array are plotted as $\Sigma N_{\text{PE}} = 1.2$. Upper right: $\Sigma N_{\text{PE}}$ distribution in typical energy band 10 TeV (100 ≤ $\Sigma \rho$ < 215). Lower right: 100 TeV (1000 ≤ $\Sigma \rho$ < 2154).
condition on To select muon-poor air showers, we optimize the cut showers are suppressed by 99% around the cuts by the MC simulation. Hadron-induced air We calculate the integral flux sensitivity of the Tibet AS+MD array to gamma rays as shown by the thick solid curve in Figure 1. Note that our sensitivity above 200 TeV is defined as a flux corresponding to 15 gamma-ray events, since the background events are fully suppressed to less than one event.

Then, how many known/unknown sources do we expect to detect by the Tibet AS+MD array, assuming the energy spectra of the gamma-ray sources extended up to the 100 TeV region? The diffuse gamma rays from the Cygnus region reported by the Milagro group [7], TeV J2032+4130 [8], HESS J1837-069 [1], Crab, Mrk421 are clearly detectable. Cas A [9], HESS J1834-087 [11], and M87 [11] are marginal. In addition to these existing/established sources, we can expect unknown sources in the northern sky. Most of the HESS 14 sources would be detected by the Tibet AS+MD array, as is shown in Figure 1 if it were located at the HESS site. There exist approximately 80 SNRs within the scanned area by the HESS telescopes, while the Tibet AS+MD array also observes 80 SNRs within its field-of-view. This in turn means that we can expect to discover a dozen new sources, half of which will be UNID or SNR-like, in the northern sky where no extensive search has been done by an apparatus with sensitivity comparable to HESS. The MAGIC and VERITAS experiments in the northern hemisphere, together with the Tibet AS+MD array will contribute to a deeper understanding of the origin and acceleration mechanism of cosmic rays.

Fig. 3 Survival efficiency after the cut. Blue and green circles show gamma-induced and hadron-induced air showers, respectively.

Fig. 4 Integral flux sensitivities to point-like gamma-ray sources. Dashed curves show sensitivities of Cherenkov telescopes at 5σ for 50 hours (MAGIC, VERITAS and HESS from the upper curve). The thick solid curve demonstrates the sensitivity of the Tibet AS+MD array at 5σ for 3 calendar years. Closed circles show the integral fluxes converted from observed differential fluxes of “HESS J” sources point by point assuming their spectral indices. Thin lines show fittings and extrapolations to HESS data points.

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References
1. Aharonian, F., et al.: The H.E.S.S. survey of the Inner Galaxy in very high-energy gamma-rays. ApJ 636, 777-797 (2006)
2. Amenomori, M., et al.: A northern sky survey for steady Tera-electron Volt gamma-ray point sources using the Tibet air shower array. ApJ 633, 1005-1012 (2005)
3. Heck, D., Knapp, J., Capdevielle, J.N., Schatz, G., Thouw, T.: CORSIKA: A Monte Carlo code to simulate extensive air showers. Forschungszentrum Karlsruhe Report FZAK 6019 (1998)
4. Amenomori, M., et al.: Flux upper limits of diffuse TeV gamma rays from the Galactic plane using the effective area of the Tibet-II and -III arrays. Advances in Space Research 37, 1932-1937 (2006)
5. Kasahara, K.: http://cosmos.n.kanagawa-u.ac.jp/EPICSHome/
6. Agostinelli, S., et al.: GEANT4 — a simulation toolkit. NIM A 506, 250-303 (2003)
7. Atkins, R., et al.: Evidence for TeV gamma-ray emission from a region of the Galactic plane. PRL 95, 251103 (2005)
8. Aharonian, F., et al.: The unidentified TeV source (TeV J2032+4130 and surrounding field: Final HEGRA IACT-System results. A&A 431, 197-202 (2005)
9. Aharonian, F., et al.: Evidence for TeV gamma ray emission from Cassiopeia A. A&A 370, 112-120 (2001)
10. Belicev, M., Götting, N., Thünykent, M.: Observation of the giant radio galaxy M87 with the HEGRA Cherenkov telescopes. New Astronomy Reviews 48, 407-410. (2004)