Demonstration of hadronic cosmic-ray rejection power by a water Cherenkov underground muon detector with the Tibet air shower array

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***Abstract*. We demonstrate excellent hadronic cosmic-ray rejection power by a 100 m^2 water Cherenkov underground muon detector constructed in late fall of 2007, under the Tibet air shower array located at 4300 m above sea level, in Tibet, China. Our Monte Carlo simulation reproduces cosmic-ray data quite well. The water Cherenkov technique together with the Tibet air shower array will provide us with a very low-background and low-cost cosmic gamma-ray observation above 10 TeV, assuming a**

reasonable muon detector area.

***Keywords*: Gamma rays, Muons, Tibet**

I. Introduction

The HESS group with 4 large IACTs in Namibia, reported on discovery of new 14 gamma-ray sources by galactic plane survey [1] in 2005. Surprisingly, most of them are UNIDentified (UNID) sources and faint in X-rays or other wavelengths. As the HESS survey was limited within the galactic plane in the southern hemisphere due to its narrow field of view, the importance of a wide field-of-view unbiased survey is emphasized. Furthemore, many of the 14 sources have a harder energy specturm (indices;-1.8 to -2.8) at TeV energies than the standard candle Crab (index;-2.6). The energy spectra turned out to extend up to approximately 10 TeV. Cosmic rays are supposed to be accelerated up to the knee energy region at supernova remnants (SNRs) in our galaxy. Therefore, we naturally expect gamma rays in the 100 TeV region (10-1000TeV) which originate in π^0 decays produced by the accelerated cosmic rays interacting with matter surrounding the SNRs. The gamma ray emission of electron origin might be highly suppressed in the 100 TeV region due to rapid decrease of inverse-Compton cross section by the Klein-Nishina effect as well as synchrotron radiation energy loss in the magnetic field around the SNRs. Multi-wavelength (radio, X-ray, gamma-ray) observations are essential to discriminate between the two processes.

II. Tibet Air Shower Experiment

The Tibet air shower array has been in operation at Yangbajing (90°31′ E, 30°06′ N; 4300 m above sea level) in Tibet, China since 1990. It has continuously made a wide field-of-view (approximately 2 steradian) observation of cosmic rays and gamma rays in the northen sky.

The Tibet I array was constructed in 1990 [2], and it was gradually upgraded to the Tibet II by 1994 which consisted of 185 fast-timing (FT) scintillation counters placed on a 15 m square grid covering 36,900 m^2, and 36 density (D) counters around the FT-counter array. Each counter has a plastic scintillator plate of 0.5 m^2 in area and 3 cm in thickness. All the FT counters are equipped with a fast-timing 2-inch-diameter photomultiplier tube (FT-PMT), and 52 out of 185 FT counters are also equipped with a wide dynamic range 1.5-inch-diameter PMT (D-PMT) by which we measure up to 500 particles which saturates FT-PMT output, and all the D-counters have a D-PMT. A 0.5 cm thick lead plate is put on the top of each counter in order to increase the counter sensitivity by converting gamma rays into electron-positron pairs in an electromagnetic shower. The mode energy of the triggered events in Tibet II is ∼10 TeV/∼7TeV for cosmic rays/gamma rays [3], [4].

In 1996, we added 77 FT counters with a 7.5 m lattice interval to a 5,200 m^2 area inside the northern part of the Tibet II array. We called this high-density array Tibet HD [5]. The mode energy of the triggered events in Tibet HD is ∼3 TeV/∼2 TeV for cosmic rays/gamma rays. In the late fall of 1999, the array was further upgraded by adding 235 FT-counters to increase the high-density area from 5,200 m^2 to 22,050 m^2. We call this array and further upgraded one Tibet III [6]. In 2002, all of the 36,900 m^2 area was covered by the high-density array by adding 200 FT-counters. Finally we set up 56 FT-counters around the 36,900 m^2 high density array and equipped 8 D-counters with FT-PMT in 2003. At present, the Tibet air shower array consists of 761 FT-counters (249 of which have a D-PMT) and 28 D-counters [7].

The performance of the Tibet air shower array has been well examined by observing the Moon's shadow (approximately 0.5 degree arc in diameter) in cosmic rays [6], [8]. The deficit map of cosmic rays around the Moon demonstrates the angular resolution to be around 0.9° at a few TeV for the Tibet III array. The pointing error is estimated to be less than ∼0.01° by displacement of the shadow's center from the apparent center in the north-south direction, as the east-west component of the geomagnetic field is very small at the experimental site. On the other hand, the shadow center displacement in the east-west direction due to the geomagnetic field enables us to spectroscopically estimate the energy scale uncertainty less than ±12 % [8].

The first celestial TeV gamma-ray signal from the Crab (the standard candle in gamma-ray astronomy) was detected by an imaging air Cherenkov telescope (IACT) developed by the Whipple group in 1989 [9]. The pioneering work opened a new energy window in astronomy.

Ten years later in 1999, we succeeded in observing multi-TeV gamma-ray signal from the Crab Nebula at 5.5 σ confidence level, using the Tibet HD array [5]. This was the first detection of multi-TeV gamma-ray signal by a conventional air shower array. Subsequently, in 2000, we reported on detection of multi-TeV gamma rays successfully at 3.7σ level from Mrk501 which was in a highly flaring state during March 1997 and August 1997 [3]. We also succeeded in observing multi-TeV gamma-ray flares at 5.1σ level from Markarian 421 which was in a very active phase during the year 2000 and 2001 [6]. Multi-TeV gamma-ray signal was successfully detected from the Crab by the Tibet-III array as well [8].

We searched for TeV steady point sources in the northern sky. No statistically significant point source is found except for well established Crab and Mrk421 [10].

Search for steady PeV gamma-ray emission from the Monogem ring region is done with the Tibet data taken from 1997 to 2004 [11]. No evidence for statistically significant gamma-ray signal is found in the Monogem ring where the MAKET-ANI experiment recently claimed a positive (approximately 6σ) detection of PeV high-energy cosmic radiation [12], although our flux sensitivity is approximately 10 times better than MAKET-ANI's.

The 2-dimensional anisotropy ($\sim\pm0.2$ %) in the equatorial coordinates are obtained for the first time in the multi-TeV energy range [13]. The "Tail-in" (hump) and "Loss-cone" (dip) structures are impressive. Furthermore, we discovered a new diffuse cosmic-ray anisotropy (approximately 0.2 % level excess) in the Cygnus region [14], although we cannot judge currently whether it is caused by gamma rays and/or a local cosmic-ray anisotropy. Overlapping the large-scale anisotropy in the Cygnus region, a few spacially separated enhancements of smaller scale were observed. These small-scale excesses ($\sim2°$) hint at the extended gamma-ray emission[14]. The two of the small-scale excesses were shortly established[15], [16] as extended gamma-ray sources by the Milagro experiment capable of hadron/gamma-ray discrimination.

We also searched for multi-TeV diffuse gamma rays from the galactic plane [4], [17]. As there was no significant signal, flux upper limits were obtained. Meanwhile, the Milagro group recently claimed detection of TeV diffuse gamma-ray signal in the Cygnus region along the galactic plane [18]. Currently, we can not draw any clear conclusion on the Milagro result, as the Tibet air shower array is unable to distinguish between cosmic gamma rays and hadrons in the multi-TeV energy region at present.

To positively observe gamma rays in the 100 TeV region with much better sensitivity than Tibet III, we plan to add a muon detector array to the air shower array. Gamma-ray induced electromagnetic air showers are muon-poor, while cosmic-ray induced hadronic ones are accompanied by many muons. This enables us to separate gamma rays from cosmic rays. Our current plan [19], [20] relevant to gamma-ray astronomy above 10 TeV is Tibet AS (Air Shower array with 83,000m^2 in area) + MD (Muon Detector array with $\sim$10,000 m^2 in area under Tibet AS). 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 photomultiplier tubes (PMTs), i.e., HAMAMATSU R3600. The Tibet MD array are made up of 192 muon detectors set up 2.5 m underground. Its total effective area amounts approximately to 10,000m^2 for muons with energies more than $\sim$1 GeV. Our current MC simulation predicts that the cosmic-ray background events will be rejected by approximately 99.99% at 100 TeV using full-scale (10,000 m^2) MD array. the full-scale MD array will improve the sensitivity to gamma-ray sources by more than an order of magnitude.

To confirm the hadron rejection power with this full-scale MD array, we constructed a prototype muon detector in 2007.

III. Prototype Muon Detector

In the late fall of 2007, we constructed a prototype water Cherenkov muon detector (approximately 100 m^2) at $\sim$90 m away from the center of the existing Tibet airshower array, as is shown in Figure 1. The purposes of the prototype detector are to demonstrate construction feasibility, development of calibration method, confirmation of our Monte Carlo (MC) simulation and searching for sub-PeV gamma rays in the northern sky.

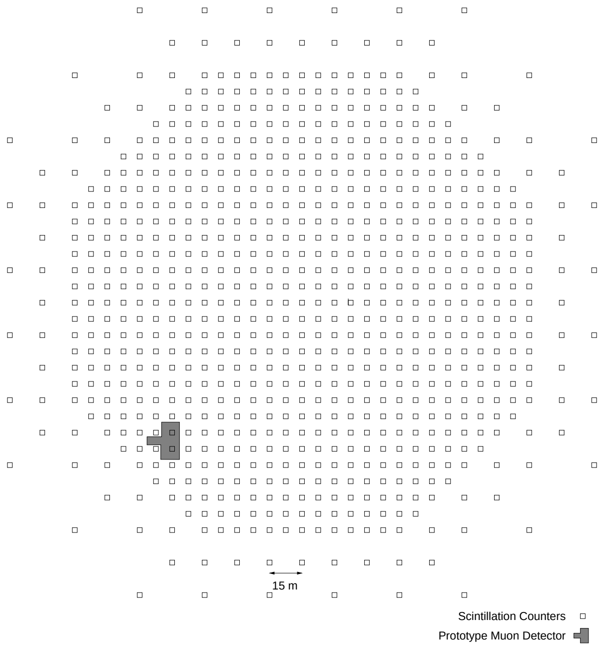

Fig. 1. The Tibet airshowr array with scintillation counters (Open squares) and the 100 m^2 prototype water Cherenkov muon detector (Gray area).

The muon detector is made from reinforced concrete and composed of two water pool cells located at 2.5 m under the ground. Each cell is filled up with water of 1.5 m in depth, 7.2 m $\times$ 7.2 m in area, equipped with three $20''\phi$ downward facing PMTs (HAMAMATSU R3600). Among of the 3 PMTs, one is covered by a black sheet with $\sim$1% light transmission to effectively reduce the PMT gain (wider dynamic range), although we do not use it in this paper. The timing and charge information for each PMT is recorded by a trigger generated from surface scintillation counter array. We started the data taking in December, 2007. For a test, we did not install any water purifier or circulation system. However, the water never freezes and bacteria do not proliferate easily, since the water temperature remains stable and cold around 5°C.

IV. Results and Discussions

Figure 2 shows the charge distribution by the sum of two PMTs in a cell (52 m^2) extracted from air shower data. In this figure, a clear peak around 28 pC indicates the average charge when one particle pass through the muon detector cell. We calculate the muon number assuming this peak is defined as one muon.

Figure 3 and Figure 4 show the muon number distribution recorded by the prototype muon detector in an air shower at 10 TeV region ($100<\Sigma\rho<300$) and 100 TeV region ($1000<\Sigma\rho<3000$), respectively, where $\Sigma\rho$ means the sum of the number of particles per m^2 for each

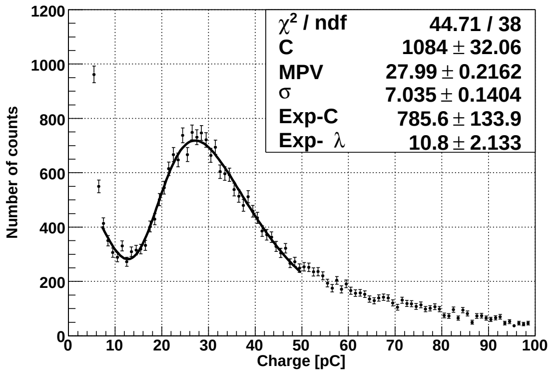

Fig. 2. From [20]. Charge distribution recorded by the sum of two PMTs in a cell of the prototype muon detector. A peak of charge distribution is defined as one muon.

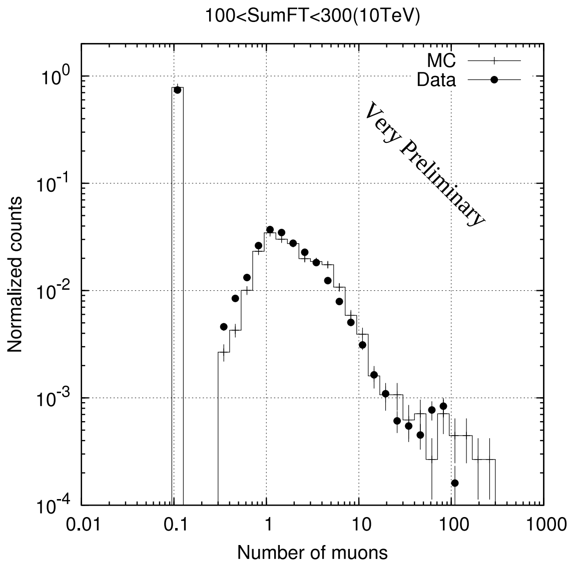

Fig. 3. Number of muons recorded by the prototype muon detector in an air shower at 10 TeV region ($100<\Sigma\rho<300$). The filled diamonds indicate experimental data, while the solid histograms are the MC simulation. Air showers with null muons detected by the muon detector are plotted at number of muons of 0.1.

scintillation detector (10 TeV corresponds to $\Sigma\rho\sim100$ roughly). As for the air shower MC simulation, air shower events are generated using CORSIKA code with QGSJET01c model for hadronic interactions assuming the cosmic-ray composition estimated mainly from direct observational data. Our MC simulation reproduces well the experimental data obtained by the prototype muon detector.

V. SUMMARY

In 2007, we constructed a prototype water Cherenkov muon detector (approximately 100 m^2) under the existing Tibet air shower array. We have been successfully taking data since December in 2007. The preliminary analysis shows that the data is in good agreement with our MC simulation . We are ready for the full-scale (10,000 m^2) underground water Cherenkov muon detector arrays.

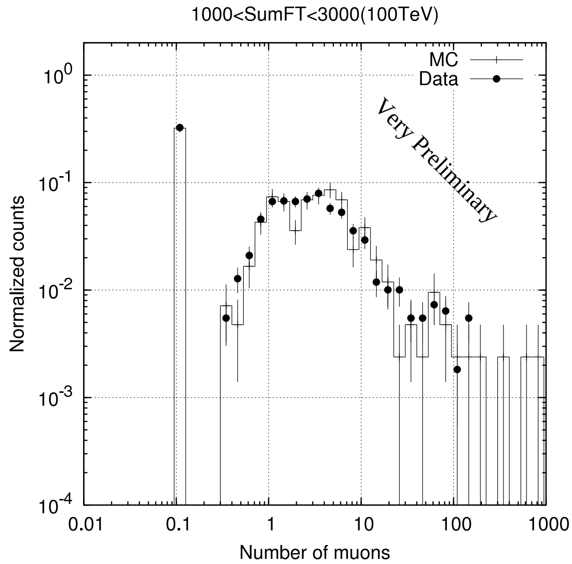

Fig. 4. Number of muons recorded by the prototype muon detector in an air shower at 100 TeV region ($1000<\Sigma\rho<3000$). The filled diamonds indicate experimental data, while the solid histograms are the MC simulation. Air showers with null muons detected by the muon detector are plotted at number of muons of 0.1.

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