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Search for gamma rays above 100 TeV from the Crab Nebula using the Tibet air shower array and the 100 m^2 muon detector

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We search for continuous gamma-ray emission from the Crab Nebula above 100 TeV, using the data collected from March 2008 to July 2009 by the Tibet air shower array and the 100 m^2 muon detector. We find that our MC simulation is in good agreement with the experimental data. No significant excess is found. An upper limit, comparable to the world's best limit until now, is obtained above 140 TeV.

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1. Introduction

It is supposed that cosmic rays are accelerated up to the knee ($\sim$4 PeV) energy region by very high-energy (VHE) astrophysical objects in our Galaxy, such as supernova remnants. Naturally, the subsequent π^0 decay due to the interactions of accelerated charged cosmic rays with matter surrounding the VHE sources is expected to produce gamma rays in the $10-1000$ TeV region. Meanwhile, VHE gamma rays may also come from leptonic processes, such as the inverse-Compton scattering and the bremsstrahlung of accelerated electrons. Considering that gamma rays of leptonic origin decrease sharply in flux above 100 TeV due to the synchrotron cooling and the rapid suppression of the inverse-Compton cross section (Klein-Nishina effect), searching for gamma-ray sources with energy spectra extending up to 100 TeV and higher would be an effective approach to identify the sources accelerating cosmic rays up to the knee. Observationally, however, there has been no convincing evidence for those π^0-decay gamma rays so far. An unprecedentedly high-sensitivity observatory aimed at the measurement of gamma-ray spectra in the $10-1000$ TeV energy region is interesting at the moment.

Since the Whipple collaboration first detected TeV gamma rays from the Crab Nebula in 1989 [1], the VHE gamma-ray spectrum of the Crab Nebula has been measured by a number of imaging air Cherenkov telescopes and air shower arrays. Among air shower arrays, the Tibet ASγ collaboration was the first that successfully observed the Crab Nebula at multi-TeV energies [2]. Ground-based gamma-ray detectors now commonly use the Crab Nebula as a standard calibration candle. Its energy spectrum can be well reproduced by a mechanism based on the synchrotron self-Compton (SSC) emission of high energy electrons. None of the experiments has detected gamma rays above 100 TeV from the Crab Nebula, and the currently best upper limits have been given by the CASA-MIA experiment [3]. The measurement of the gamma-ray energy spectrum of the Crab Nebula around 100 TeV with higher sensitivity is important in order to confirm the leptonic origin of the Crab's TeV gamma-ray emission. We therefore search for gamma rays above $\sim$100 TeV from the Crab Nebula, using the Tibet air shower (AS) array combined with a 100 m^2 muon detector (MD) described below.

2. Tibet Air Shower Experiment

The Tibet ASγ experiment started in 1990 at Yangbajing in Tibet (90.522°E, 30.102°N) at the atmospheric depth of 606 g/cm^2 [4], which corresponds to 4,300 m above sea level. The Tibet AS array currently has the effective area of 36,900 m^2 covered by 761 fast-timing (FT) scintillation counters and 28 density (D) counters. All the 761 FT counters are equipped with a fast-timing 2-inch-in-diameter photomultiplier tube (PMT), while 249 FT counters and all the D counters are equipped with a wide-dynamic-range 1.5-inch-in-diameter PMT. The sum of the number of detected secondary particles/m^2 for each FT counter, which is called $\sum \rho_{\rm FT}$, is used for the energy estimation of primary cosmic rays and gamma rays. The performance of the Tibet AS array has been studied by the observation of the Moon's shadow [5, 6]. At 100 TeV, the energy resolution and the angular resolution for primary gamma rays is 40% and 0.2°, respectively. The displacement of the shadow's center from the Moon's apparent position in the north-south direction shows that the pointing error of the Tibet AS array is smaller than $\sim$0.01°. The displacement of the shadow's center in the east-west direction due to the geomagnetic field demonstrates that the uncertainty in the absolute energy scale is $< \pm 12\%$. The Tibet ASγ experiment has produced a lot of results on gamma-ray astronomy as well as on cosmic-ray physics: the observation of the steady TeV gamma-ray emission from the Crab Nebula [2, 6], the detection of the multi-TeV gamma-rays from Mrk 421 [5] and Mrk 501 [7], etc. To improve the sensitivity of the AS array to $10-1000$ TeV gamma rays, we are planning to add a water-Cherenkov MD array to the AS array. The number of muons in air showers can be a good parameter to distinguish gamma rays from cosmic rays, because gamma-ray-induced air showers are muon-poor and cosmic-ray-induced ones are muon-rich. The current design of the full-scale MD array consists of 12 pools, set up under a 2.6 m-thick layer of soil that is expected to absorb the electromagnetic components of air showers. Each pool is made up of 16 MDs. Each MD is a waterproof concrete cell, 7.15 m wide $\times$ 7.15 m long $\times$ 1.5 m deep in size, equipped with two downward-facing 20-inch-in-diameter PMTs (HAMAMATSU R3600) to detect Cherenkov photons produced by the penetrating component of air showers. The total effective area of the MD array is approximately 10,000 m^2 for muons with energies greater than $\sim$1 GeV. Our detailed MC simulation demonstrates that using the full-scale MD array will enable us to reject background cosmic-ray events by $\sim$99.99% at 100 TeV, and that the sensitivity of the AS array to $10-1000$ TeV gamma-ray sources will be improved by more than an order of magnitude [8]. We constructed a 100 m^2 MD to confirm the construction feasibility of the MD and the hadron rejection power expected by our MC simulation.

3. 100 m^2 Muon Detector

The 100 m^2 MD was constructed in the late fall of 2007, 90 m southwest of the center of the existing Tibet AS array. The detector consists of two waterproof concrete cells, set up under the 2.25 m-thick soil and the 0.35 m-thick concrete ceiling. The measured density of the soil and the concrete cells is 2.1 g/cm^3 and 2.41 g/cm^3, respectively. Each cell, 7.15 m wide $\times$ 7.15 m long $\times$ 1.5 m deep in size, equipped with three downward-facing PMTs (HAMAMATSU R3600) on the ceiling, is filled with water. One of the three PMTs, which is not used for the analysis of this work, is covered by a piece of black sheet with $\sim$1% light transmission to reduce the number of collected photons. It is important to note that it is the surface AS array, not the MD, that issues a trigger signal to record the timing and charge information of each PMT. Neither water purifier nor water circulation system is installed, because bacteria scarcely proliferate and water never freezes at the depth of 2.6 m underground where the water temperature is cold and stable at 5°C$-$10°C. The data collected by the 100 m^2 MD and the surface Tibet AS array are used in this work.

4. Results and Discussion

We carried out full MC simulation about the air-shower generation and the detector response. Details about our MC simulation can be found elsewhere [8]. We find that the photo-electron distribution obtained by our MC simulation reasonably reproduces the ADC charge distribution recorded by one of the two PMTs in a cell extracted from the air shower data. The "one muon" charge is defined as the peak of the charge distribution fitted with the Landau distribution. The average of the numbers of muons from the two PMTs is taken for each cell, and then the number of muons N_μ for an air shower event is calculated as the sum of the averages from the two cells. Gamma-like (muon-poor) events are selected on the basis of N_μ, so as to maximize the detection significance of the gamma-ray source. According to our MC, over 90% of gamma rays survive the N_μ-based event selection above 100 TeV.

We studied the fraction of the number of background cosmic rays that survive the N_μ-based event selection, as a function of $\sum \rho_{\rm FT}$ approximately proportional to the primary cosmic-ray energy. The experimental data that the fraction sharply decreases as the energy of primary cosmic rays increases, and that the fraction reaches 5×10^{-4} around 4000 TeV. Considering the difference of the covering area between the full-scale (10,000 m^2) MD array and the 100 m^2 MD, the number of muons obtained by the 100 m^2 MD would be rougly 100 times fewer than that by the full-scale MD array, since the lateral distribution of air shower muons is relatively flat. In terms of the number of muons, the 100 m^2 MD observes the energy scale $\sim$100 times higher in comparison with the full-scale MD array, because the number of muons in air showers is roughly proportional to the primary particle's energy. The fraction expected by the full-scale MD array comes at $\sim$200 times lower along the horizontal axis than the experimental data obtained by the 100 m^2 MD. This fact would allow us to safely say that our MC simulation for the full-scale MD array is valid, at least up to $\sim$20 TeV.

Using the data collected by the 100 m^2 MD and the surface Tibet AS array from March 2008 to July 2009 (302 live days), we next search for steady gamma-ray emission from the Crab Nebula above $\sim$100 TeV. To estimate the numbers of background events ($N_{\rm OFF}$) and signal events ($N_{\rm ON}$), we adopt what we call the equi-zenith angle method [6] with the search window radius fixed at 0.4°. Table 1 summarizes the statistics of the data remaining after the N_μ-based event selection by the 100 m^2 MD, within the 0.4° radius window centered at the Crab Nebula. No significant excess is found, and the upper limits at the 90% confidence level on the Crab's differential and integral flux are calculated according to a statistical prescription [9], as shown in Figure 1 (a) and (b), respectively. Figure 1 (b) compares our upper limits with the 90% confidence-level upper limits obtained by the CASA-MIA experiment [3]. It can be seen that above 140 TeV this work is comparable to the limit by CASA-MIA, which has been the world's best limit until now.

During the period that we used for the analysis of this work, there was a gamma-ray flare from the Crab Nebula reported above 100 MeV [15], which lasted $\sim$16 days in February 2009 with a flux of four Crabs. Unfortunately, the Tibet AS array was briefly not in operation at the time of this flare.

5. Conclusions

The 100 m^2 water Cherenkov MD was successfully constructed in 2007 under the ground of the existing Tibet air-shower array. We find that our detailed MC simulation is in good agreement with the experimental data. Using the data collected by the 100 m^2 MD from March 2008 to July 2009 (302 live days), we search for continuous gamma-ray emission from the Crab Nebula above 100 TeV. No significant excess is found, and the upper limit obtained above 140 TeV is comparable to the world's best limit until now.

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Table 1: Statistics of the data remaining after the N_μ-based event selection by means of the equi-zenith angle method [6] with the search window radius fixed at 0.4°. The representative energy for a differential upper limit is defined as the logarithmic mean of the primary gamma-ray energies in the $\sum\rho_{\rm FT}$ bin, while the representative energy for an integral upper limit is the mode of the primary gamma-ray energies in the $\sum\rho_{\rm FT}$ bin. The upper limits assuming zero excess counts are also written.

Differential					
$\sum\rho_{\rm FT}$ bin	Energy (TeV)	$N_{\rm ON}$	$N_{\rm OFF}$	Excess	Flux upper limit (90% C.L.) $\times 10^{-17}$ [cm^{-2}s^{-1}TeV^{-1}]
$1700 \leq \sum\rho_{\rm FT} < 3000$	170	53	61.2	−8.2	6.84
				if 0	10.0
$3000 \leq \sum\rho_{\rm FT} < 4500$	300	9	10.5	−1.5	3.02
				if 0	3.58

Integral					
$\sum\rho_{\rm FT}$ bin	Energy (TeV)	$N_{\rm ON}$	$N_{\rm OFF}$	Excess	Flux upper limit (90% C.L.) $\times 10^{-15}$ [cm^{-2}s^{-1}]
≥1700	≥140	66	75.2	−9.2	6.97
				if 0	10.3
≥3000	≥270	13	14.1	−1.1	4.59
				if 0	5.11

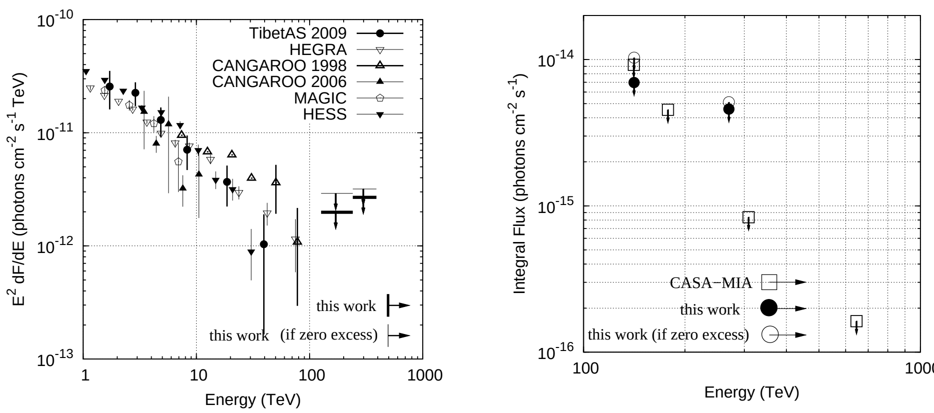

Figure 1: (a) 90% C.L. upper limits on the Crab Nebula's differential flux obtained by this work (thick solid lines with downward arrows). Thin solid lines with downward arrows represent the upper limits obtained by this work assuming zero excess counts. The flux points measured by our previous work (closed circles) [6] as well as by HEGRA (open inverse triangles) [10], CANGAROO (filled and open triangles) [11, 12], MAGIC (open pentagons) [13], and H.E.S.S. (filled inverse triangles) [14] are also plotted. (b) 90% C.L. upper limits on the Crab Nebula's integral flux obtained by this work (filled circles with downward arrows), along with the 90% C.L. upper limits by CASA-MIA (open squares with downward arrows) [3]. Open circles with downward arrows represent the upper limits obtained by this work assuming zero excess counts.