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100 TeV Gamma-Ray Observation of the Crab Nebula with the Tibet Air Shower Array

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The Tibet air shower (AS) array and underground water-Cherenkov-type muon detector (MD) array have been successfully operated since 2014, at an altitude of 4,300 m in Tibet, China. we observed 24 gamma-ray events with energy greater than 100 TeV against 5.5 background events, which corresponds to 5.6σ statistical significance [1]. The highest energy of the detected gamma rays is estimated to be 450 TeV. This is the first detection of gamma rays beyond 100 TeV from an astrophysical source, and a pioneering work opening a new higher energy window in the astronomy and astrophysics.

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1. Observations of the Crab Nebula from TeV to sub-PeV

The gamma rays beyond 100 TeV has been previously undetected at the earth. The Crab Nebula is one of the most energetic astrophysical sources in the all sky, and its energy spectrum has been widely measured from radio to near 100 TeV gamma rays. It is well known that the multi-wavelength non-thermal energy spectrum is dominated by synchrotron radiation at energies lower than 1 GeV and by the inverse-Compton scattering above 1 GeV [2, 3].

TeV gamma-rays from the Crab Nebula were first clearly detected by the Whipple collaboration using an imaging air Cherenkov telescope (IACT) in 1989 [4]. Since then, IACT has become the standard telescope for TeV gamma-ray observations by virtue of its excellent angular resolution and efficiency. The MAGIC experiment, equipped with the large reflector (17 m in diameter), has measured the lower energy part of the spectrum down to 77 GeV [6]. In the energy above 10 TeV, The HEGRA experiment had obtained the energy spectrum up to 75 TeV with an approximate single power-law [5]. On the other hand, the H.E.S.S. experiment reported the cutoff energy $E_c = (14.3 \pm 2.1_{\rm stat})$ TeV in the energy spectrum of the Crab Nebula, assuming a power-law with an exponential cutoff $E^{-p}\exp(-E/E_c)$, [7]. At the highest energies between 141 TeV and 646 TeV, the CASA-MIA experiment have set flux upper limits to the gamma rays from the Crab Nebula by a large air-shower array with area of 230,000 m^2 and the muon detector (MD) array, which consists of 1024 scintillation counters with an area of 2.5 m^2 [8].

The Tibet ASγ experiment achieved the first successful observation of the Crab Nebula at a multi-TeV region in 1999, using the Tibet-HD (high density) array with an area of 5,175 m^2 [9]. Subsequently, the Tibet-III array with an area of 22,050 m^2 has been operating since 1999. Using the data collected by this array for 1318.9 live days, we measured the energy spectrum of gamma rays from the Crab Nebula from 1.7−40 TeV [10]. In 2007, the proto-type water Cherenkov MD with an area of 100 m^2 was constructed under the Tibet AS array. We searched for gamma rays from the Crab Nebula above 100 TeV using the background rejection technique by means of the counting the number of muons in the air shower. In spite of small MD compared with CASA-MIA experiment, The most stringent flux upper limit above 140 TeV was obtained using the dataset collected for 438 live days[11].

In the begining of 2014, the water-Cherenkov-type MD with the are of 3,400 m^2 in total started operation. Based on the criterion of muon number measured in an air shower by the MD, we successfully suppress 99.9% of the cosmic-ray background events with energies $E > 100$ TeV. As a result, 24 gamma-like events with $E > 100$ TeV were observed from the Crab Nebula against 5.5 cosmic-ray background events, corresponding to 5.6σ statistical significance, with the Tibet AS array and the underground water-Cherenkov-type MD array (Tibet AS+MD array) [1]. This is the first detection of the highest energy gamma rays beyond 100 TeV from an astrophysical source, and a pioneering work opening a new higher energy window in the astronomy and astrophysics. Recently, the HAWC also reported an indication of gamma rays above 100 TeV at the significance 3.3σ [12]. The flux around 100 TeV measured by the Tibet AS+MD is consistent with the flux measured by the HAWC. In the near future, the detection of gamma rays above 100 TeV is a key to solve the very-high-energy cosmic-ray origin which has been a mystery for more than hundred years since their discovery.

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2. Integral Energy Spectrum in sub-PeV

We calculated the integral fluxes for the Crab nebula to be $F(>100\ \text{TeV}) = (3.29 + 1.06 - 0.87) \times 10^{-15}\ \text{cm}^{-2}\ \text{s}^{-1}$ and $F(>250\ \text{TeV}) = (5.72 + 5.72 - 3.48) \times 10^{-15}\ \text{cm}^{-2}\ \text{s}^{-1}$, respectively, to compare with the upper limits measured by past experiments in the sub-PeV energy region [1]. Figure 1 shows the integral energy spectrum observed by the Tibet AS+MD array and the previous upper limits at the 90% C.L. measured by the CASA-MIA experiment (black arrows with diamond marks) and Tibet AS with 100 m^2 prototype MD (magenta arrows with plus marks). The measured integral fluxes by the Tibet AS+MD array are consistent with all the previous upper limits. At the energy above 600 TeV, the CASA-MIA upper limit partly constrains the 1σ error region with the simple extrapolations of observed fluxes. The Tibet AS+MD will continuously observe the gamma rays from the Crab Nebula to extend the spectrum toward higher energy region up to PeV.

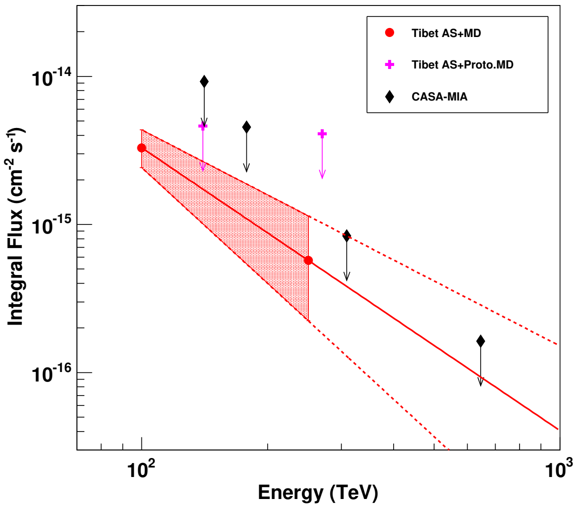

Figure 1: Integral energy spectrum in the sub-PeV region observed by the Tibet AS+MD array and the previous upper limits at the 90% C.L. measured by the CASA-MIA experiment (black arrows with diamond marks) and Tibet AS with 100 m^2 prototype MD (magenta arrows with plus marks). The shaded area is 1σ error region by the Tibet AS+MD array. The solid line shows simple extrapolation of observed fluxes by the Tibet AS+MD array, while the dashed lines show simple extrapolations of 1σ errors.

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