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Search for EeV Neutral Particles from the Point-like Sources with the Telescope Array Surface Detector

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Abstract: We report on the search for steady point-like sources of neutral particles around 10^{18} eV during the period between 2008 May and 2012 October with the surface detector of the Telescope Array experiment. We find overall no significant point-like excess above 0.5 EeV in the northern sky. Hence, we set upper limits at 95% confidence level on the neutron flux which corresponds to an averaged flux 0.067 km^{-2} yr^{-1} above 1 EeV in the northern sky. This is the most stringent flux upper limit in the northern sky survey assuming the point-like sources.

Keywords: Telescope Array, Cosmic rays, Ultra high energy, Ankle region, Anisotropy

1 Introduction

The energy region around 10^{18} eV (EeV) is thought to be a transition from cosmic rays of galactic origin to extra-galactic origin. Many cosmic-ray experiments have searched for point-like sources as the cosmic-ray origin on the isotropic cosmic-ray sky in this energy region. Among them, the Fly's Eye experiment and the Akeno 20-km^2 array reported independently a point-like excess around Cygnus X-3 above 0.5 EeV with statistical significance 3σ level [1, 2]. On the contrary, the Haverah Park array found no significant excess around Cygnus X-3 during the period which overlaps the most of the Fly's Eye observation [3]. After these observations, there is however no systematic search of the northern sky in this energy region so far, although the HiRes-I searched for point-like deviations from isotropy in the northern sky above $10^{18.5}$ eV which is an order of magnitude higher energy threshold than the previous Cygnus X-3 observations [4]. Recently, the Auger Observatory surveyed for point-like sources around 1 EeV with large statistics in the southern sky [5]. They concluded that there was no significant excess. The energy flux limits observed by the Auger are well below what is observed from some Galactic TeV gamma-ray sources. Therefore, they infer that this indicates that TeV gamma-ray emission from those sources might be of electromagnetic origin or else their proton spectra are not up to EeV energies.

In this paper, we will report on the search for point-like sources of EeV neutral particles, such as neutrons or gamma rays, with the surface detector of the Telescope Array (TA) experiment which has the largest effective area in the northern hemisphere.

2 Experiment

The TA is the largest cosmic-ray detector in the northern hemisphere, which consists of the surface detector (SD) array [6] and three fluorescence detector (FD) stations [7, 8]. The TA has been fully operating at Millard Country, Utah, USA (39.30°N, 112.91°W; about 1,400 m above sea level), since 2008. The TA SD consists of 507 plastic scintillation detectors of 3 m^2 placed at grid point 1.2 km apart, and its coverage area is approximately 700 km^2. For more details, see elsewhere [9]. In this analysis, we will use the data taken between 2008 May 11th and 2012 October 15th by the TA SD.

3 Analysis

The air-shower reconstruction and data selection are optimized for the low-energy air showers around 10^{18} eV based on the standard reconstruction code developed in the anisotropy and energy spectrum studies [10, 11]. The number of remaining events after the standard cuts in the standard reconstruction is relatively small $\sim$18,000 events due to hard parameter cuts to mainly improve the energy resolution for the spectrum study. In this analysis, we drastically loose the event cut in the air-shower reconstruction. The number of air showers after the loose cuts is increased by $\sim$10 times, which corresponds to 172,125 events, compared with that of the standard cuts. For the detailed air-shower analysis, see elsewhere [12]. This is a remarkable advantage to search for anisotropy at EeV energy region, even though the angular resolution and the energy resolution are moderately deteriorated. The angular resolution with the loose-cut data is estimated to be 3.0° above 1 EeV, while that of the standard-cut data is estimated to be 2.2°. The energy resolution with the loose-cut data is estimated to be $^{+50}_{-35}$% while that of the standard-cut data is estimated to be $\sim^{+35}_{-25}$%. These are good enough resolutions to find a point-like sources, if its flux gradually changes with the energy. In this analysis, we divided the loose-cut dataset into four energy regions as follows: $0.5 < E(\mathrm{EeV}) \leq 1.0$ (55,010 events); $1.0 < E(\mathrm{EeV}) \leq 2.0$ (63,290 events); $E(\mathrm{EeV}) > 2.0$ (53,825 events); $E(\mathrm{EeV}) > 1.0$ (117,115 events).

Various background estimation methods have been developed to analyze the cosmic-ray anisotropy. As a simple method, the distribution of air-shower directions generated by the MC simulation is directly compared with the data. However, the MC simulation usually does not reproduce the data perfectly due to the simulation model dependence and meteorological effects which are difficult to reflect in the MC simulation. As the other method, the background can be estimated by the data itself independent of the MC simulation. In order to extract an excess of air shower events coming from the direction of a target source, we adopt the Equi-Zenith Angle method developed by the Tibet ASγ experiment [13] to find gamma-ray excesses from huge cosmic-ray background events in the TeV energy region. The signals are searched for by counting the number of events coming from a target source as on-source cell with a finite size. The background is estimated by the number of events averaged over 6 off-source cells with the same angular radius as the on-source, at the same zenith angle, recorded at the same time intervals as the on-source cell events. The search window size of on- and off-source cells should be optimized by the MC simulation to maximize the signal-to-noise S/N (S: the number of detected excess, $N = \sqrt{B}$: the square root of the number of background events) ratio, which depends on the angular resolution. In this MC study, we generated air showers induced by protons, which have the same air-shower development as the neutron. Fig. 1 shows the optimal search window radius R_{sw} as a function of the zenith angle θ and the fitting results by an empirical formula $R_{\mathrm{sw}}(\theta) = R_0 \cos\theta$ degrees, where R_0 is the fitting parameter denoting the window radius at vertical air shower. R_0 values are calculated to be 3.1, 2.9 and 2.1 degrees for three energy regions: $0.5 < E(\mathrm{EeV}) \leq 1.0$; $1.0 < E(\mathrm{EeV}) \leq 2.0$; $E(\mathrm{EeV}) > 2.0$, respectively. It is noted that the R_{sw} values are approximately 0.7 times smaller than the angular resolution. In this analysis, we use these fitting curves in Fig. 1 as the optimal search window radius.

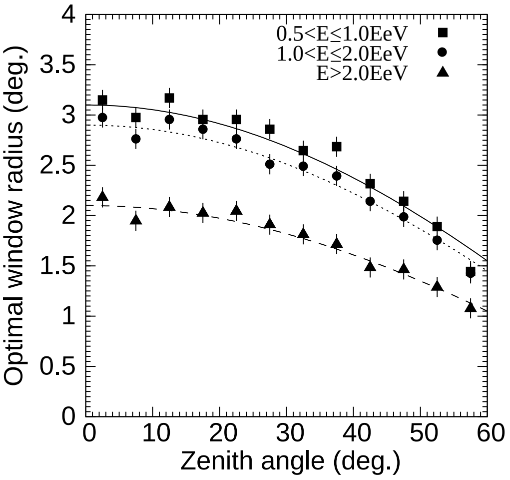

Fig. 1: Optimal search window radius as a function of zenith angle θ by the MC simulation. The curves give best fit by the empirical formula $R_{\mathrm{sw}} = R_0 \cos\theta$. The symbols and line types represent the different energy regions: Circles and solid curve: $0.5 < E(\mathrm{EeV}) \leq 1.0$; Squares and dotted curve: $1.0 < E(\mathrm{EeV}) \leq 2.0$; Triangles and dashed curve: $E(\mathrm{EeV}) > 2.0$, respectively.

4 Results and Discussions

We analyze the air shower dataset collected by the TA SD from 2008 May 11th to 2012 October 15th. Fig. 2 shows the northern sky map of significance drawn by the Equi-Zenith Angle method using cosmic rays observed by the TA SD the four energy regions. In this analysis, to make sure we do not miss any possible unknown sources, the surveyed sky has been oversampled. The centers of tested target sources are set on 0.1° × 0.1° grids, from 0° to 360° in R.A. and from 0° to 70° in the declination. At each grid point, the search window is opened with the optimal radius $R_{\mathrm{sw}}(\theta)$ as shown in Fig. 1. The observed declination band is limited due to the statistics and the analysis method. The number of events in the Dec.$< 0°$ is small. In the Dec. $> 70°$ near the northern pole, the dummy source cells overlap with other cells so that the statistical independence of each cell fails. The closed circles in Fig. 3 show the significance distribution from all directions as in the four energy regions. The shaded area in this figure is 90% containment region of 10^5 MC samples in the isotropic sky. The good agreement between the data points and shaded area indicate that there is overall no significant excess beyond statistical fluctuation in the northern sky.

We calculate the flux upper limits on the neutron intensity (F_{ul}) of the northern sky using the following equation:

$$F_{\mathrm{ul}} = F_{\mathrm{cr}} \frac{N_{\mathrm{ul}}}{N_{\mathrm{bg}}} \frac{\omega_{\mathrm{sw}}}{\varepsilon_{\mathrm{sw}}}, \tag{1}$$

where F_{cr} is the integral cosmic-ray flux, N_{ul} is an upper limit of observed excess according to a statistical prescription assuming unphysical region, such as the minus excess [15], N_{bg} is the number of averaged background events, ω_{sw} is the averaged solid angles of the search window, and $\varepsilon_{\mathrm{sw}}$ is the efficiency deduced from the MC simulation of proton ($\sim$ neutron) signals within ω_{sw} assuming a point source. The F_{cr} values (> 0.5 EeV, > 1 EeV, > 2 EeV) are assumed to be fluxes measured by the HiRes [14], because the TA spectrum below $10^{18.2}$ eV has not been published yet. The HiRes spectrum is consistent with the that of the TA within 10% level at $10^{18.2}$ eV. The value of $\varepsilon_{\mathrm{sw}}$ is estimated to be 0.47 ± 0.02 independent of the zenith angle and the energy. First, we calculate flux upper limits of all northern sky point by point on 0.1° × 0.1° grids using Eq. 1. Then, a mean of flux limits at the same declination is defined as the representative value at each declination. Fig. 4 shows the mean flux upper limits (km^{-2} yr^{-1}) at 95% confidence level (C.L.) in four energy regions, depending on the declination of target sources. An averaged flux upper limit in northern sky is estimated to be 0.067 km^{-2} yr^{-1} above 1 EeV. This is the most stringent flux upper limit in the northern sky survey assuming point-like sources.

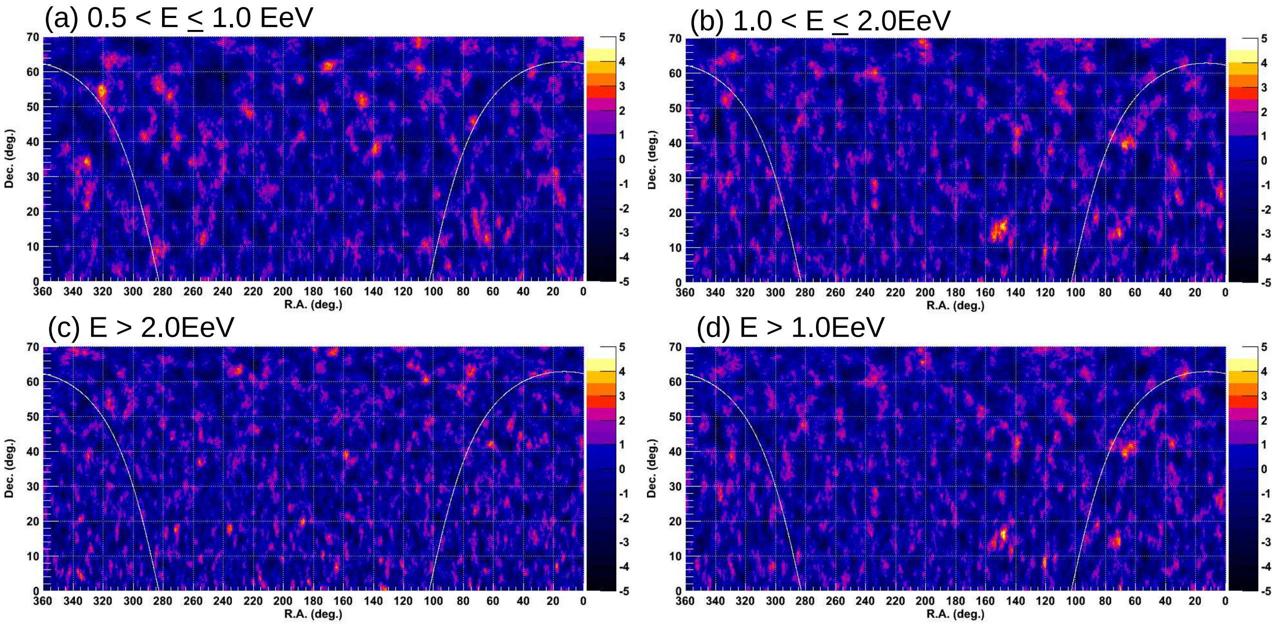

Fig. 2: Significance maps in the surveyed northern sky between Dec.=0° and Dec.=70° by the TA SD in four energy regions: (a) $0.5 < E(\mathrm{EeV}) \leq 1.0$; (b) $1.0 < E(\mathrm{EeV}) \leq 2.0$; (c) $E(\mathrm{EeV}) > 2.0$; (d) $E(\mathrm{EeV}) > 1.0$. The color contours show significance level. The solid curves indicate the Galactic plane.

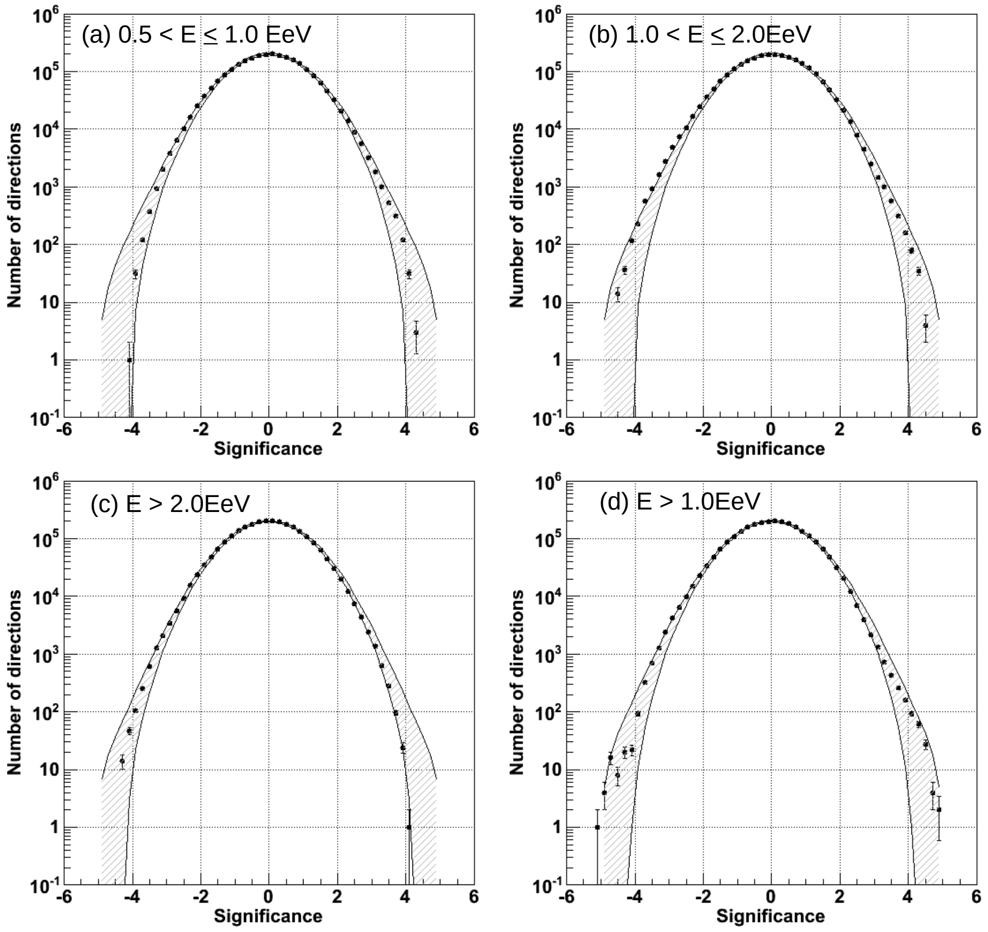

Fig. 3: Histograms show significance distributions of all directions within FoV of the TA SD in four energy regions : (a) $0.5 < E(\mathrm{EeV}) \leq 1.0$; (b) $1.0 < E(\mathrm{EeV}) \leq 2.0$; (c) $E(\mathrm{EeV}) > 2.0$; (d) $E(\mathrm{EeV}) > 1.0$. The shaded area indicates 90% containment region of 10^5 MC samples of isotropic sky.

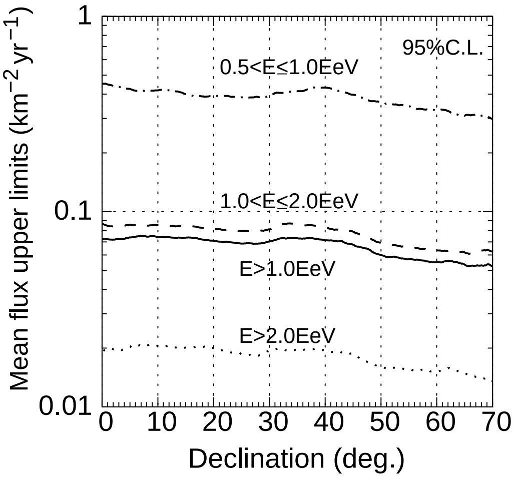

Fig. 4: Mean flux upper limits (km^{-2} yr^{-1}) at 95% C.L., depending on the declination of target sources observed by the TA SD at each energy. Dot-dashed curve: $0.5 < E(\mathrm{EeV}) \leq 1.0$; Dashed curve: $1.0 < E(\mathrm{EeV}) \leq 2.0$; Dotted curve: $E(\mathrm{EeV}) > 2.0$; Solid curve: $E(\mathrm{EeV}) > 1.0$.

5 Summary

We search for steady point-like sources of neutral particles around EeV energy observed by the TA SD which has the largest effective area in the northern sky. The air-shower reconstruction and data selection are optimized for the EeV air showers. The number of air showers above 0.5 EeV is increased by ∼10 times, which corresponds to 172,125 events, after the optimization. In order to search for the point-like sources, the Equi-Zenith Angle method is adopted to these cosmic-ray air showers taken by the TA SD during the period between 2008 May and 2011 October. As a result, we find overall no significant excess above 0.5 EeV in the northern sky. Hence, we set upper limits at 95% C.L. on the neutron flux, which is an averaged flux 0.067 km^{-2} yr^{-1} above 1 EeV in the northern sky. This is the most stringent flux upper limit in the northern sky survey assuming the point-like sources.

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