Performance of CRTNT Fluorescence Light Detector for Sub-EeV Cosmic Ray Observation*

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Abstract Cosmic Ray Tau Neutrino Telescopes (CRTNT) for sub-EeV cosmic ray measurement is discussed. Performances of a stereoscope configuration with a tower of telescopes plus two side-triggers are studied. This is done by using a detailed detector simulation driven by Corsika. Detector aperture as a function of shower energy above 10^{17}eV is calculated. Event rate of about 20k per year for the second knee measurement is estimated. Event rate for cross calibration with detectors working on higher energy range is also estimated. Different configurations of the detectors are tried for optimization.

Key words fluorescence light telescope, detector aperture, ultrahigh energy cosmic rays, Monte Carlo simulation

1 Introduction

Cosmic rays observed in the energy range of 10^{16}eV to 10^{20}eV behave that their sources may switch from inside our galaxy to the larger space range[1]. The detailed modeling of the acceleration of the cosmic rays and their transportation through the space between the sources and the earth strongly depends on an accurate observation of spectrum and composition of the cosmic rays. The existing measurements have rather large discrepancies between each others[2] mainly due to a lack of a common calibration for all experiments and limited dynamic range of a single experiment. A way to overcome the difficulty is to put several independent experiments together and dedicate each of them to cover a suitable energy range and maintain good overlaps between the experiments. Using the cosmic ray events falling in the overlaps, one can cross-calibrate the detectors and achieve a complete and self-consistent measurement of the cosmic ray energy spectrum and their composition above 10^{16}eV. The CRTNT experiment is designed to cover the energy range from 10^{17}eV to 5×10^{18}eV and co-site with the TALE (10^{18}eV—5×10^{19}eV)[3] and the TA (above 10^{19}eV)[4].

2 Detector

The proposed CRTNT project uses fluorescence light telescopes analogous to the detectors of the HiRes experiment[5]. The telescopes are distributed in three groups located at three vertices of an isosceles triangle which has an eight km base line and three km height, named as FD1, FD2 and FD3, as shown in Fig. 1. At the central site FD1, twelve telescopes are used to form a "tower of power" detector that observes an area covered by 64° in azimuth and 42° in elevation starting from 3°. FD2 and FD3 are located at the bottom vertices and both have two telescopes watching into each other and cover an area about 32° in azimuth and 14° in elevation starting from 44°. The total field of view covers about 58° in elevation.

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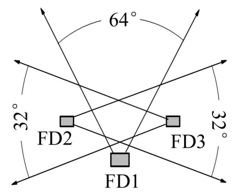

Fig. 1. Two CRTNT detector configuration with different 3D location.
Configuration 344: FD1(0,0,0) FD2(−4,3,0) FD3(4,3,0); configuration 455: FD1(0,0,0) FD2(−5,4,0) FD3(5,4,0).

By comparing two different configurations, the distances between groups are determined by simulation results discussed at the end of this paper.

A 5.0m^2 light collecting mirror with a reflectivity of 82% is used for each telescope. A focal plane camera is made of 16×16 pixels. Each pixel is a 40mm hexagonal photomultiplier tube that has about a $1^\circ \times 1^\circ$ field of view. Each tube is read out by a 50MHz flash ADC electronics system to measure the waveform of the shower signals. A pulse finding algorithm is developed for providing an individual channel trigger using a field programmable gate array (FPGA). The first level trigger is set by requiring the signal–noise ratio to be greater than 3.5σ, where σ is the standard deviation of the total photo-electron noise within a running window of 320ns. The second level trigger requires at least five channels triggered within a 5×5 running box over a single telescope camera of 16×16 pixels. The trigger condition for an event is that at least one telescope is triggered. All triggers are formed by FPGA chips. Event data from all channels are scanned from the FPGA buffers into a local Linux box.

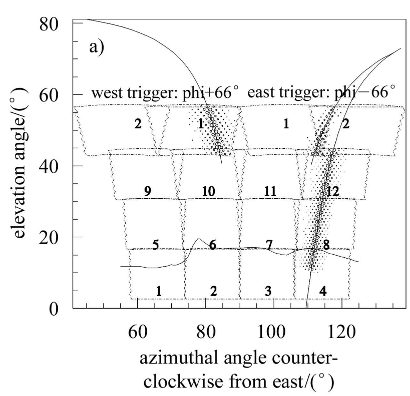

Fig. 2. An example event triggered by all three CRTNT detectors.

A Monte Carlo simulation program for the CRTNT detector is developed as described in the next section. A triggered event shown in the Fig. 2 is an example that has an angular track length about 50° and covers both rising and decaying stages of the shower development.

3 Monte Carlo simulation

In the simulation, the incident cosmic rays are coming from all directions above the ground. The flux of cosmic rays is assumed to be isotropic and uniform in the field of view of the detector. The impact parameter, $R_{\rm p}$, to the central position between the two side-trigger detectors is limited to be less than 10km. A pure proton primary composition is assumed in the simulation. The lowest energy is set to be 2×10^{16}eV and a $1/E$ spectrum is assumed for the detector aperture estimation and a $1/E^3$ spectrum is assumed for the resolution study.

3.1 Air shower simulation

Corsika 6.0[6] is used to generate air showers in the atmosphere. A four-seasonal atmospheric model is used to describe the air density as a function of height. A big set of the simulated showers above 10^{16}eV are parameterized by using three parameters, the shower maximum location $X_{\max}$, the maximum number of shower charged particles $N_{\max}$ and the dimensionless width of the shower longitudinal development function $\sigma_{\rm s}$, including their energy dependence and the correlations between them. The longitudinal development of each shower is then described by a function[7]

$$N_{\rm ch}(x)=N_{\max}\exp\left\{-\frac{2(x-x_{\max})^2}{\sigma_{\rm s}^2(2x_{\max}+x)^2}\right\},$$

where $N_{\rm ch}(x)$ is the number of charged shower particles at the slant atmospheric depth x.

3.2 Photon production and light propagation

Charged shower particles excite the nitrogen molecules as they pass through the atmosphere. The de-excitation of the molecules generates ultra-violet fluorescence light. The number of fluorescence photons is proportional to the shower size, and these photons are emitted isotropically. The shower simulation carried out in this paper assumes a fluorescence light spectrum according to a recent summary of world-wide measurements[8], including the dependence of the yield on the atmospheric pressure and temperature. Since energies of charged shower particles are higher than critical energy, shower particles generate Cerenkov photons at every stage of the shower development. The accumulated Cerenkov light is concentrated in a small forward cone, therefore intensity of the light is much stronger than the fluorescence light along the shower direction. A significant part of the Cerenkov light can be scattered out via Rayleigh and Mie scattering during the whole shower development history. The fraction of this light scattered in the direction of the detector can also make a noticeable contribution to detector triggering. Cerenkov light generation and scattering is fully simulated. A detailed description of the calculation can be found in Ref. [1] and references therein.

Shower charged particles and therefore fluorescence light photons, spread out laterally following the NKG distribution function. The Molier unit of the NKG function is about 95m at about 1500m a.s.l. Photons originating from Cerenkov radiation have an exponential lateral distribution from the axis of the shower. Therefore, photons coming from a shower are spread over a range of directions around the shower location in the sky due to its longitudinal motion and lateral extension. A ray tracing procedure is carried out to follow each photon to the PMT's from the photon source location. All detector responses are considered in the ray tracing procedure, including mirror reflectivity, UV filter transmission, quantum efficiency of photo-cathode, location-sensitive response function of the photo-cathode and optical effects associated with the off-axial and defocusing effects. Sky noise photons, $40\text{ph}\cdot\mu\text{s}^{-1}\cdot\text{m}^{-2}$, are randomly added in this ray tracing procedure both in time and arrival directions. The uncertainty associated with the varying weather conditions is negligible for the Rayleigh scattering. Scattering due to aerosols is more dependent on weather conditions. However, for a detector that has an aperture within 6km, the aerosol scattering contribution to light extinction is close to be its minimum. The uncertainty in the triggering efficiency due to weather conditions is thus small. In the simulation, an average model[9] of aerosol scattering for western US deserts is employed.

4 Detector aperture and event rate

The detector aperture is estimated using more than 10^4 simulated events. The triggering condition is the signal to noise ratio being greater than 3.5 for the tower detector and 2.5 for the side-trigger detectors. The trigger aperture is shown in the Fig. 3 as the dash line. It is noticed in Fig. 2 that the tower detector has two vertical edges that could cause very biased measurement of the triggered showers. A cut on those events that fall in the detector edges is applied for good shower reconstruction quality. We also made cuts on the Cerenkov light dominant events by removing tubes that have viewing angles less than $20°$ and requiring the track lengths being still greater than $6°$. The other cut is that the amplitude weighted average vector of the fired tubes in the side-trigger detectors must be in the neighborhood ($< 0.5°$) of a true shower-detector-plane. The last cut guarantees the shower geometric reconstruction resolution to be better than $0.7°$. After all the cuts for the quality of shower measurement, the aperture is calculated shown in Fig. 3 as the dot line. For energy above 10^{18}eV, the aperture is greater than 100 $\text{km}^2\cdot\text{sr}$. This allows that there are about 700 common events per year to be observed by both CRTNT and TALE for cross calibration between the two detectors. Based on this, we have 30k events per year measured above 10^{17}eV.

In order to measure the structure of the cosmic ray energy spectrum around $10^{17.5}$eV, an aperture independent to the energy is ideal. A geometric constraint, i.e. R_p <6km, makes a significant suppression in the high energy range and remains the low energy aperture unchanged, as the solid lines shown in Fig. 3, where the straight line is a fit to the histogram for eye guiding only. With such a flat aperture, about 20k reconstructible events per year are expected above 10^{17}eV.

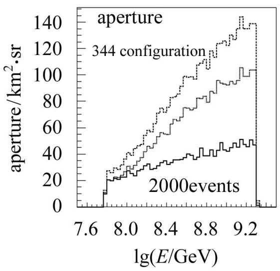

Fig. 3. CRTNT detector apertures, see text for details.

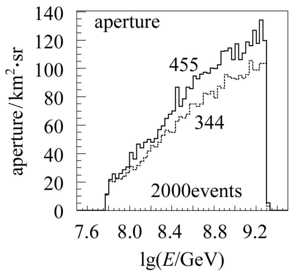

Fig. 4. Apertures of two configurations after quality cuts.

5 Comparison between different configurations

Comparing with other experiment, the CRTNT detector has an advantage of mobility. This allow us to easily change the detector configuration for different physics. Two configurations of the CRTNT detector are compared for optimizing the aperture of the detector. In the simulation described above, the detector is set symmetrically at three sites as shown in Fig. 1. As described in the beginning of this paper, the distances from the detector sites to the bisection of the connection between FD2 and FD3 are 3km, 4km and 4km, respectively. This configuration is denoted as 344 in Fig. 4. The other configuration investigated is to put all three detectors by 1km further apart, i.e. the distances become 4km, 5km and 5km, and denoted as 455. The simulation is repeated for the configuration 455. Results suggest that the aperture for configuration 455 is larger than configuration 344 at higher energy while the aperture remains no change at low energies around 10^{17}eV. This feature provides more events above 10^{18}eV (about 15%) for cross-calibration with other detectors, such as TALE.

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用大气荧光观测超高能宇宙线的τ中微子望远镜(CRTNT)性能研究*

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摘要　讨论了测量超高能宇宙线的τ中微子望远镜(CRTNT)的性能. 利用Monte Carlo方法对探测器作了详细的模拟, 并研究了探测器以一个塔形主探测器和两个高视角辅探测器协同触发的布局, 以及对大气簇射作立体观测时的物理性能. 计算了当能量高于10^{17}eV时, 探测器的有效面积. 用于第2个膝区物理研究时事例率估计可达20k个/年. 还估算了与其他探测器交叉定标的事例率. 比较和优化了探测器的不同几何布局.

关键词　大气荧光望远镜　探测器有效面积　超高能宇宙线　Monte Carlo模拟

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