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The Cosmic Ray Tau Neutrino Telescope (CRTNT) project -tau neutrino detection using fluorescence/Cerenkov light detectors

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We have investigated the possibility of ν_τ detection using the Cosmic Ray Tau Neutrino Telescopes (CRTNT) based on air shower fluorescence/Cerenkov light detector techniques. This approach requires an interaction of a ν_τ with material such as a mountain. The τ lepton produced in the interaction must escape from the earth then decay and initiate a shower in the air. Trigger efficiency has been estimated for the CRTNT detector. A rate of 8 triggered events per year is expected for the AGN neutrino source model.

1. Introduction

Searches for the cosmic ray point sources are best performed using observations of neutral particles,like photons and neutrinos, because they can be directly traced back to the source. The universe is opaque to photons between 10^{14} eV and at least 10^{18} eV (1 EeV) due to the interaction with the 2.7° K cosmological microwave background. Neutrinos play an important role to explore cosmic ray sources in the energy region above 10^{15} eV. Newly discovered evidence on neutrino oscillation [1] makes a plausible argument that the astrophysical neutrino flux tends to have a flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$ [2]. However, one obvious effect of neutrino mixing is the appearance of tau leptons, which is yet to be seen. Projects have recently been proposed for detecting tau neutrinos. One[3] of them is describe here in some details.

Through the charged current interaction, neutrinos convert to electrons, muons and taus. The interaction probability is much higher in the Earth than in the atmosphere, due to the higher density. However, electrons will shower quickly inside the target material. Muons travel very long distances before they decay and can only be detected by small energy losses along the trajectory. τ leptons are able to escape from a target volume due to their long lifetime, decay in the atmosphere into mainly hadrons or electron and develop showers in front of the detector.

Fluorescence light detectors such as HiRes or Cerenkov light detectors such as Dice have proved to be successful techniques, having small physical sizes but huge detection volumes. They are good detector candidates for τ neutrino searches.

2. Detection of earth skimming ν_τ with the CRTNT

τ lepton fluxes from the earth-skimming neutrino flux could be a few orders of magnitude lower than the cosmic ray flux. A successful detection would need a detector of large acceptance. Detection through optical signals produced by charged shower particles seems to be more efficient. However, since most of the earth-skimming neutrinos are concentrated near the horizon, the detector must cover a wide field of view (FOV), especially, a large azimuth angle coverage.

Fluorescence light detectors, such as the HiRes prototype experiment [4], have a large FOV and acceptance. Using the same detector but triggered by Cerenkov light, the Dice Experiment [5] successfully measured energy spectrum and composition of cosmic rays between 0.1 PeV and 10 PeV. Therefore, to achieve a satisfactory statistics for the measurement of the neutrino flux requires a combination of the fluorescence and Cerenkov light detector.

In this paper, we consider to place the detec-

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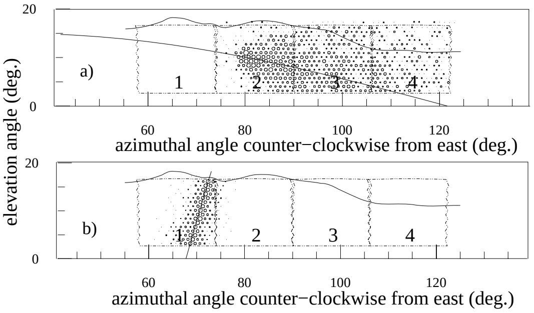

Figure 1. Simulated air showers seen by the CRTNT. a) a τ neutrino event, b) a normal cosmic ray air shower event. The curve shows the profile of Mt. Wheeler Peak., the dashed lines the boundary of the telescopes and the circles the triggered tubes

tor described below in proximity to Mt. Wheeler Peak(3984 m a.s.l.) near the Nevada-Utah border, USA. The mountain is a range in the north-south direction about 40 km long. The west side of the range is very steep. Further west, there is a flat valley about 30 km wide. For the detector located about 9 km away from the peak horizontally, the shadow of the mountain is about 15.5° in elevation. It almost blocks the views of the telescopes of the detectors, thus cutting off most of the cosmic ray background.

The proposed Cosmic Ray Tau Neutrino Telescope (CRTNT) project uses fluorescence/Cerenkov light telescopes that are distributed in three groups. They are located at three sites separated by eight km in front of Mt. Wheeler Peak. At each site, four telescopes watch an area on the mountain side within 64° in azimuth and 14° in elevation. This area is about 9 km long in north-south direction. The total field of view covers about 60° × 14° (60 km^2) with a small overlap between the telescopes of the three sites.

A 5.0 m^2 light collecting mirror with a reflectivity of 82% is used for each telescope. The focal plane camera is made of 16×16 pixels. Each pixel is a 44 mm hexagonal photomultiplier tube that has about a 1° × 1° field of view.

A pulse area finding algorithm was developed for providing individual channel triggers. The trigger condition is set for a signal-to-noise ratio to be greater than 4σ, where the σ is the standard deviation of the total noise photoelectrons for the duration of the signal pulse. The second trigger level requires at lease five channels to trigger within a 5×5 running box over the whole camera of 16×16 pixels.

3. Monte Carlo simulation

A Monte Carlo simulation program for the CRTNT detector has been developed. Thousands of showers initiated by the products of τ-decays and normal cosmic rays are generated. Two simulated event examples and the detector configuration are shown in FIG.1. In FIG.1 a), a τ neutrino induced air shower starts in the shadow of the mountain where a normal cosmic ray event is not expected. In contrast, a normal cosmic ray event is shown in FIG.1 b).

In the simulation, an incident ν_τ is coming from an interval of elevation angles between $-11°$ and $17°$, where the negative direction means an up-going neutrino. The azimuthal range is from 90° to 270°, all directions from the back of the mountain. The flux of neutrinos is assumed to be isotropic and uniform in the field of view of the CRTNT. Every incident ν_τ is tested to see if it interacts inside the rock. The energy and momentum of a produced τ is traced to its decay in the case that the neutrino interacted. Energy losses and range of the τ leptons are calculated according to the result of Ref. [6]. If the τ decays outside the rock, there is about an 80% probability that electrons or multiple hadrons are produced in the decay. Those particles will initiate electromagnetic or hadronic showers from the decay point. If the τ decays inside the rock, there is a chance of regeneration of the τ lepton that repeats the previous process.

The ν_τ to shower conversion efficiency is defined as the ratio between the total number of successfully converted events and the number of incident ν_τ's. The simulation yields the conversion efficiency of 1.99×10^{-4} and 2.21×10^{-2} for the AGN[7] and GZK[8] neutrino source models, respectively. The distributions of the trigger efficiency as a function of energy are shown in FIG. 3 and FIG. 2.

CORSIKA 6.0 [9] is used to generate air showers in the space between the shower initiating point outside the mountain and the CRTNT telescopes. Since all showers are initiated in almost horizontal directions, a uniform air density is assumed for the air shower development.

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 particles also generate Cerenkov photons at every stage of the shower development. The procedure of Cerenkov light generation and scattering is fully accounted for in the simulation. A detailed description of the calculation can be found in Ref. [4] and references therein.

A ray tracing procedure is carried out to follow each photon all the way to the photocathode of the PMT's once the photon source is located in the sky. 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 are randomly added in this ray tracing procedure both in time and arrival directions. An average model [10] of aerosol scattering for the standard desert in the western US is used.

4. Predicted event rate

For the CRTNT detector, we calculate the event rate. The AGN neutrino source model [7] and the GZK neutrino source model [8] are used. We generate 10^9 and 10^7 trials for AGN and GZK models, respectively.

Due to the stronger energy loss of the higher energy τ leptons, the observed GZK neutrino spectrum is severely distorted, namely the high energy neutrinos are piled up at the low energies once they are converted into lower energy showers. On the other hand, the shower triggering simulation shows that the trigger efficiency is slightly higher for higher energy showers. The competition between those two effects yields a relatively flat event rate distribution between 10 PeV and 2 EeV. The distribution is shown in FIG.2. The overall detection efficiency is 2.4×10^{-3}. According to the flux suggested by the authors of [8] and a typical 10% duty cycle of the fluorescence/Cerenkov light detector, the event rate is about 0.23 ± 0.01 per year.

The AGN source spectrum breaks down from $\sim E^{-1}$ to $\sim E^{-3}$ near 10 PeV. The neutrino flux is cut off around 0.6 EeV. The energy loss of τ leptons inside the mountain is no longer a significant effect. The converted shower spectrum has a similar shape to the incident neutrino spectrum at high energies. The conversion efficiency drops fast with energy in the low energy region. This softens the event rate as a function of energy below 10 PeV.

The average trigger efficiency of showers induced by the products of τ-decays is 11.0%. The overall detection efficiency of AGN neutrinos is 2.19×10^{-5}. The spectra of ν_τ are shown in FIG. 3. According to the flux predicted by the authors of [7], the event rate is 5.04 ± 0.05 per year, where 10% duty cycle is assumed for the detector.

5. Conclusion

The technique of using a mountain to convert $10^{16} \sim 10^{19}$ eV neutrinos to air showers and detecting the showers can be optimized with a $\sim$20 km thick mountain body. The energy reduction in the conversion process is so severe for high energy τ's that showers pile up below 10^{17} eV in the shower energy spectrum. ν_τ regeneration is found to have an insignificant effect on the conversion of ν_τ to air showers. The contribution is less than two percent even for the GZK neutrino source model which predicts many high energy ν_τ's. Cerenkov light may dominate over fluorescence light and become the main light source to trigger the CRTNT detectors. An air shower

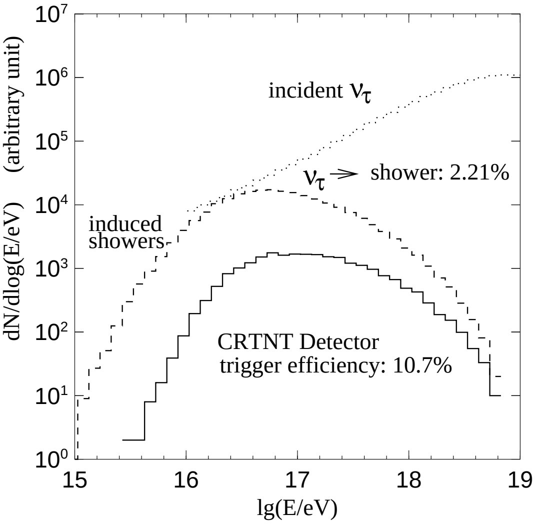

Figure 2. GZK ν_τ to air-shower conversion and triggering rate.The incident ν_τ energy spectrum (dotted line) and converted shower energy distribution (dashed line) are plotted. The triggered air-shower event distribution (solid) is calculated based on the detector described in Sec. 2.

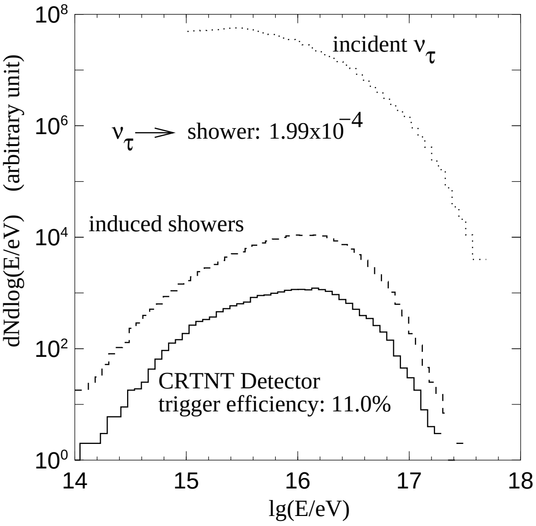

Figure 3. AGN ν_τ to air-shower conversion and triggering rate.The incident ν_τ energy spectrum (dotted line) and converted shower energy distribution (dashed line) are plotted. The triggered air-shower event distribution (solid) is calculated based on the detector described in Sec. 2.

development algorithm has been developed using CORSIKA in a uniform atmosphere for the trigger efficiency estimation. The CRTNT detector simulation indicates a rate of 7.56 ± 0.08 events per year. An optimized 15% duty cycle is assumed because partial operation under moon light may be possible since the whole detector covers only 14° in elevation toward the east. Most of the night, the moon will be at the back of the detector.

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