Ultra High Energy ν_τ Detection Using Air Shower Fluorescence/Cerenkov Light Detector

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Abstract

The possibility of using air shower fluorescence/Cerenkov light detectors for ν_τ detection has been explored. A detector of this type is proposed to be set in the shadow of Mt. Wheeler Peak in Nevada, USA. The ν_τ to shower conversion probability density is calculated over an energy range from 1 PeV to 10 EeV. The number of showers converted from ν_τ's are estimated according to several models of neutrino sources.

1. Introduction

The source of cosmic rays with particle energies above 10^{15} eV remains unknown. The observation of neutral cosmic ray particles allows the possibility to directly locate the sources. The universe is opaque between 10^{14} eV and at least 10^{18} eV to photons due to the strong γ-ray absorption due to the interaction with 2.7K cosmological radiation. The neutrino may be used to explore cosmic ray sources in this energy region. Newly discovered evidence on neutrino oscillation[1] makes a plausible argument that the astrophysical neutrino flux tends to have an even flavor ratio of $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$[2] due to the $\nu_\mu \leftrightarrow \nu_\tau$ oscillation. This opens a window between 1 PeV to 1 EeV for the ultra high energy τ-neutrino astronomy. Comparing with ν_e and ν_μ, the ν_τ has a much larger probability to be converted into a detectable air shower via an interaction with rock. The probability of converting a ν_τ into a τ that can escape the rock to subseqently decay is slowly varying along the trajectory in the rock. The large branching ratio for τ decaying into hadrons or electron guarantees that most decayed τ's initiate air showers once the τ escapes from the rock. This makes the ultra-high energy τ-neutrino unique in that it is potentially detectable through the atmospheric cascade process.

2. ν_τ to air shower conversion

A convenient coordinate system to describe the air shower conversion process is one where the origin is set at a point on the mountain surface where the

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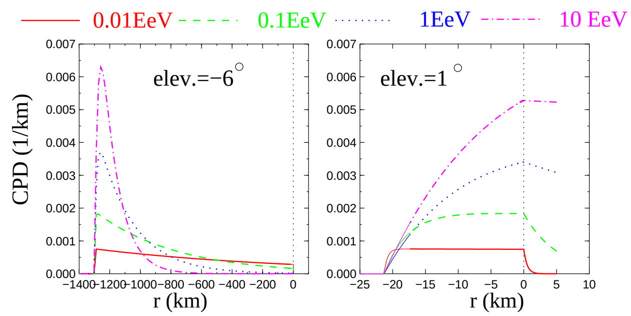

Fig. 1. ν_τ to shower CPD as a function of distance along trajectory.

shower or τ escapes from the mountain. r-axis is the trajectory of ν_τ. The density of the medium, $\rho(r)$, and the total path length T vary depending on the trajectory. The trajectory is described by elevation angle, ϵ, azimuth angle, ϕ, and the location of the escape point. In this local coordinate system, the ν_τ-shower converting probability at r is

$$p_c(r;\mathcal{T})dr = \begin{cases} \frac{dr}{R_d - \Lambda_I/\rho(r+T)}\left[\mathrm{e}^{-\frac{r+T}{R_d}} - \mathrm{e}^{-\frac{r+T}{\Lambda_I/\rho(r+T)}}\right] & (\mathrm{r}<0) \\ \frac{dr}{R_d - \Lambda_I/\rho(T)}\left[\mathrm{e}^{-\frac{T}{R_d}} - \mathrm{e}^{-\frac{T}{\Lambda_I/\rho(T)}}\right]\mathrm{e}^{-\frac{r}{R_d}} & (\mathrm{r}\geq 0) \end{cases} \tag{1}$$

where $p_c(r;\mathcal{T})$ is the conversion probability density (CPD) for a given trajectory $\mathcal{T} = \mathcal{T}(\epsilon, \phi, x_e, y_e)$, Λ_I is the ν_τ interaction length in g/cm^2 and R_d is average range of τ in km. Without energy loss, $R_d = \gamma c\tau$. However, the energy loss through ionization and radiation becomes severe above 10^{17} eV[3]. R_d then shrinks by a factor of 5 at 1 EeV in rock. This feature enhances the conversion of high energy ν_τ's but largely reduces the energy of τ when the τ escapes from the mountain. Fig. 1. shows two cases of the CPD functions corresponding to down-going and "earth-skimming" up-going trajectories respectively.

3. Detection of air shower converted from ν_τ

The conversion efficiency is maximized, depending upon energy, for certain thicknesses of rock. Recent calculations[4][5] show that the conversion efficiency is optimized around E_ν = 10-100 PeV by a rock thickness of 10 to 20 km. The Air fluorescence detection technique has been used by the HiRes/MIA collaboration [6] for showers of energies above 0.3EeV. The Dice Experiment[7] successfully measured energy spectrum and composition of cosmic rays between 0.1 PeV and 10 PeV by using a HiRes type detector but triggered by shower Cerenkov light. Ground detector arrays have almost zero triggering efficiency for near horizontal direction air showers and would not be suitable. A combination of the fluorescence and Cerenkov light detector appears to be the only option for the ν_τ induced air shower detection.

All estimates of the flux from all types of neutrino sources, e.g. AGN[8], GRB[9], cosmological sources including the top-down [10] and Z-burst[11] scenarios, show that the neutrino flux could be a factor between 3 and 100 lower than cosmic ray flux. Therefore, the fluorescence light or a small angle scattering Cerenkov light detector must have a wider field of view. The difficulty in using a traditional fluorescence detector is that it is typically operated at high thresholds to avoid background light from the sky. It also views larger emission angles to the shower axis to avoid Cerenkov light contamination. This contamination results in poor shower energy resolution. For searching for ν_τ induced showers, the detector would be operated in the shadow of a mountain. In principle the background from cosmic rays of the same or slightly lower energy is reduced to zero in the shadow of the mountain. The sky noise light is also reduced to low levels. The detector can then be operated at sufficiently low thresholds to observe ν_τ induced air showers. There are other background sources that still need to be measured. It is important to note that the shower energy resolution is not crucial for ultra-high energy ν_τ searches, therefore the Cerenkov light can be tolerated and be used to help trigger the detector.

A site in a shadow of a mountain is an ideal location for such a detector. A cliff-like mountain is crucial because the steeper mountain side provides the larger elevation coverage for the detector. The shadow of the mountain not only provides an effective volume for air shower development, but also screens the cosmic ray background out therefore enhances the sensitivity of the detector. A dry and clear atmospheric environment is a vital consideration for the fluorescence/Cerenkov light technique. The west side of Mt. Wheeler Peak, near Nevada/Utah border fits many of these conditions. The thickness of approximately 10$\sim$15 km nearly maximizes the ν to air shower conversion probability.

4. Converted shower event rate

The observational energy window rapidly closes at both lower and higher energy because of the shrinking of the τ range in conversion material. At low energy, the τ range, is the decay length $\gamma\tau c$, is not sufficiently long to allow the τ to escape the converter. Beyond 10 EeV, the τ-neutrino has a high probability to interact via the weak interaction with the rock before decaying. The study [3] shows that the energy loss of τ leads to a significant shortening in its range for energies greater than 10^{17} eV. This feature cuts off the shower energy spectrum slightly above 10^{17} eV. Fig. 2. shows the number of converted showers as functions of neutrino energy E_ν in the left panel and of shower energy E_0 in the right.

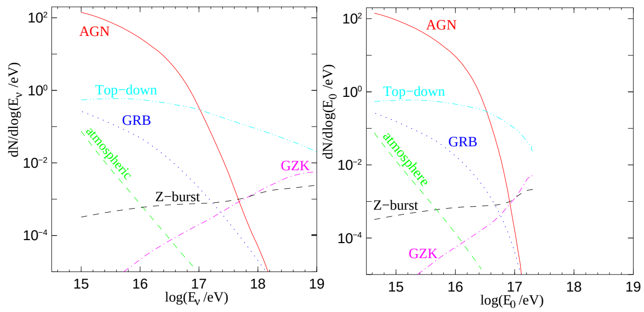

Fig. 2. Number of converted showers versus shower energy. All candidate neutrino sources are included. The predicted fluxes are from [8],[9],[10],[11],[12].

5. Conclusion

The technique of using a mountain to convert ν_τ with energies between 10^{17} eV and 10^{19} eV into air showers can be optimized with a $\sim$20 km thick mountain. Mt. Wheeler Peak near Nevada/Utah border maximizes the conversion in this energy range. The energy reduction that occurs in the conversion process is so severe for high energy τ's that a cut-off around 10^{17} eV occurs for the shower energy spectrum. Cerenkov light may be useful to aid in the triggering of air shower detectors for the observation of ultra-high energy tau neutrinos.

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