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Shower Spectrum from Earth Skimming Tau-Neutrinos

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A Monte-Carlo simulation code for the interactions and propagations of neutrinos and leptons at energy greater than 10^{14} eV inside the Earth is developed. Details of this code are described. This code can be used for underground or above-ground neutrino telescopes. Using this simulation code, we study the shower spectrum initiated by the decays of tau-leptons, which are produced from the Earth-skimming tau neutrinos through charged current interactions. Two neutrino flux predictions (AGN and GZK) are used in this study. Results show that the shower energy are in between For AGN neutrinos, the shower energy are mostly in between 3×10^{14} eV to 10^{16} eV for AGN neutrinos and in between 10^{16} eV to 10^{18} eV for GZK neutrinos. The detector technology still needs many improvements to detect these neutrinos.

1. Introduction

The energy spectrum of observed cosmic rays extends up to 10^{22} eV, while the observed neutrinos spectrum extends up to 10^{13} eV. Not only are very high energy neutrinos less abundant, they are also more difficult to detect due to absorption by the Earth. There are many PeV and EeV neutrino sources, ranging from astrophysics objects such as AGN and GRB, to cosmological sources such as GZK effects [1]. Several neutrino telescopes projects currently under construction or planning have target volume in the order of Km^3 water-equivalent. In terms of detector acceptance, it is approximately slightly less than 2π km^2 sr, since it is sensitive to up-going events and its efficiency dependents on the nadir angle.

To extend to higher energy, a drastic increase in detector volume (in unit of Km^3) or acceptance (in unit of Km^2 sr) is required. Tseng et al. [2] estimated that 1 km^2 sr is required to detect PeV-ν from AGN [3] and 100 km^2 sr is required to detect GZK-ν [4]. Depending on the construction scale, km^3-size detector such as IceCube will be able to detect AGN neutrinos in several years of full-detector operation, if the predicted flux is correct. Detailed knowledge of the spectra shape would shed light on what is really happening in AGN. That would require the detector acceptance to be much larger than km^3. This requirement renders the current technology, the underground PMT-based detector array, too expensive to be applied. Some alternative methods must be used.

One proven technology is the fluorescence detector (FD) pioneered by Fly's Eye/HiRes group. A detector of compact size can reach acceptance in the order of 300 km^2 sr (assumed 10% duty cycle) [5]. Under the Earth-skimming effect, tau-leptons produced inside the Earth can decay in the atmosphere and then shower. Fluorescence detector can detect events with clear signature of near horizontal direction. However, the threshold of FD is approximately 10^{17} eV and difficult to extend to lower energy. To increase photon counts, Cherenkov lights must be included. Traditional Cherenkov telescope aims for small gamma ray point source, and their field-of-view (FOV) is very small, in the order of a few degrees. To be applicable to the detection of PeV-neutrinos, the telescope must have a large FOV, which poses a new technological challenge.

Two projects, NuTel and CRTNT, are underway to overcome such challenge. Aiming for AGN neutrinos, NuTel tries to develop a wide FOV Cherenkov detector on Mauna Loa, Hawaii Big Island, USA [6,7]. Focusing on GZK neutrinos, CRTNT scans Mt. Wheeler in Nevada, USA [8]. Detailed simulation of neutrino interactions with the Earth is required in both projects. Based on analytical calculation, Tseng et al. [2] had many useful insights for the design of neutrino telescope using Earth skimming neutrinos.

We also developed a Monte-Carlo simulation code for detector simulation. Several preliminary versions were used in various stages of NuTel [6,7,9,10] and a semi-Monte-Carlo version [11] was used in NuTel [12] and CRTNT [8]. This semi-Mote-Carlo code use deterministic energy loss for tau leptons. The energy loss algorithm is similar to the formula used in Tseng et al [2], all other procedures are simulated in Monte-Carlo method. Under the same condition, 100 km of standard rock, the simulated results are consistent with that from Tseng et al. [2]. This consistency check prove that our code behave normally [11].

The detection techniques of air shower expand to radio signals and many neutrinos telescopes are buried underground. We had updated our code to accommodate those changes by including new materials such as Iron (in the core of the Earth) and salt (for experiment in underground salt dome [13]) and new particles (ν_e, ν_μ). Here we describe the most recent version and compare the shower spectra for two potential neutrino sources.

2. Mont-Carlo simulation

The major components of this simulation code are discussed briefly below.

1. Neutrino interactions include charged/neutral current of all flavors and W-resonance for $\overline{\nu}_e$. The inelasticity y and differential cross-section $d\sigma/dy$ were calculated in a way similar to that in [14] except that the latest parton distribution function CTEQ6 [15] was used in our code.
2. When μ and τ travel inside material, they lose energy through photonuclear interaction, bremsstrahlung, pair production and ionization. The ranges of τ leptons are plotted in Figure 1. For range in standard rock and water, results from this study and Dutta et al. [16] have small difference, which can be traced back to the different parton distribution functions.
3. The electron and shattered nuclei will shower quickly after their birth and have little chance to escape from the Earth. They are discarded and do not followed in the Monte-Carlo simulation, unless they are within twice of the depth of shower maximum to the surface of Earth, where partial shower could escape.

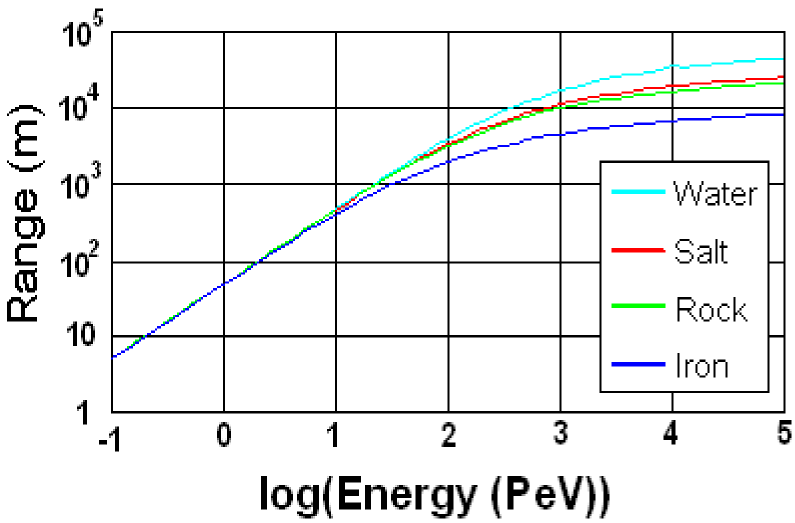

Figure 1. The range of tau leptons in water, salt, standard rock, and iron. Notice that the range in salt are only 18% higher than that in standard rock at 10^{11} GeV. Range in iron is 60% lower than standard rock at 10^{11} GeV.

4. The decay length of τ is R_τ= 49.02 (E_τ/PeV) m. The tau lepton decays are simulated with TAUOLA code with the full polarization. The daughter particles (lepton/mesons/neutrino) were fed back to the simulation. The decay length of μ is R_μ= 6.23381×10^9 (E_μ /PeV) Km, which is too large. Therefore, muon is considered as stable and loss energy while traveling through the Earth.
5. At energy higher than EeV, tau lepton can scatter back to tau neutrino through charged current interaction (also implemented in [2]).
6. The Earth is modeled as a spherical sphere with density varying with geocentric radius [17]. The material of the outer layer can be selected by the user. The mean Earth radius is 6371.2 Km. The earth is defined as a three-layer sphere consisting of iron in the core from 0 - 3480 km, standard rock in the mantle from 3480 to 6367.2 km, and water on the surface.
7. For the surface detector, a digital topological map and the detector position on this map must be supplied by the user.
8. Several types of materials such as standard rock, water, ice, salt rock, and iron can be used.
9. The material and dimension of a region, called detector sensitive region (DSR), can be specified by the user. All the information of particles within this area can be output to files.
10. Initial particles can be selected from three types of neutrinos. Their energy spectrum can be selected from several types such as the fixed value, the power law spectrum, or from a table.
11. Direction of initial particles can be isotropic or fixed. Particles are generated at the DSR and then traced back to their entrance points to the Earth where interactions start.

3. Simulation and Results

Both AGN [3] and GZK [4] neutrinos fluxes are used for simulations. All simulations are terminated when 10^6 tau-leptons are produced. Input neutrino spectra start from 10^{14} eV. A spherical Earth is used for this simulation, without any local information such as proposed site of NuTel or CRTNT. Then the initial fluxes of neutrinos are calculated from the number of neutrinos generated in the simulation. Figure 2 show the spectra of tau leptons from the interactions of GZK and AGN neutrinos inside the Earth.

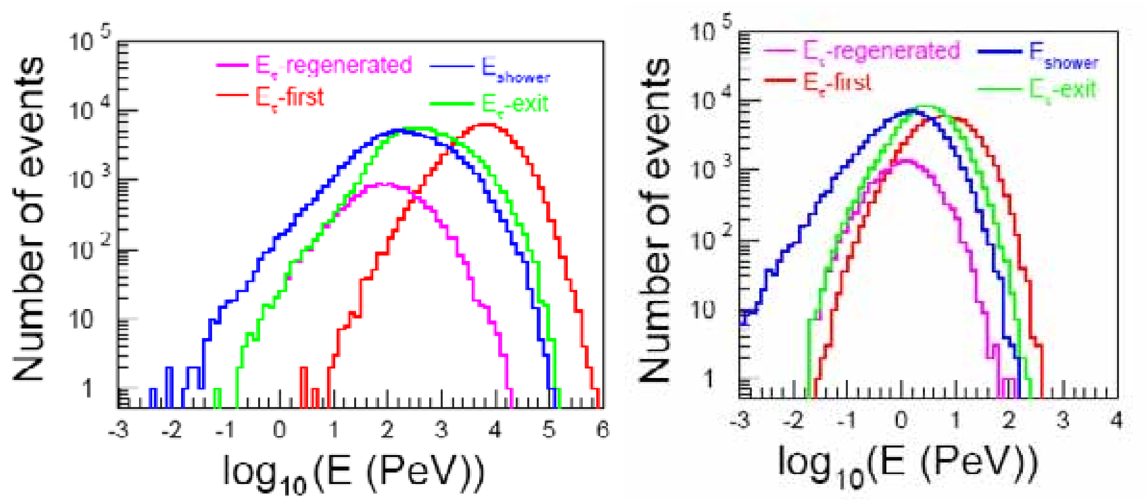

Figure 2. The spectra of tau leptons and shower from GZK (left panel) and AGN (right panel) neutrinos interacting inside the Earth. The red histogram is the energy when tau-leptons are produced first time. The purple histograms are regenerated tau-lepton from $\nu_\tau \rightarrow \tau \rightarrow \nu_\tau$ reaction chain. The green histogram is the energy of tau-lepton when it exits the Earth. The blue histogram is the shower spectra, which is the observable energy for the detector such as NuTel or CRTNT.

For GZK neutrinos, it requires total exposure 3.56×10^6 km^2 sr yr to generate 10^6 tau leptons, or one event per 3.56 km^2 sr yr. A detector like CRTNT could cover acceptance larger than 30 km^2 sr. This study support that detection of GZK neutrino by CRTNT is feasible in principle. However, the shower energy is mostly in between 10^{16} eV to 10^{18} eV. It is quite difficult to detect those events with fluorescence light detector. A combination of fluorescence and Cherenkov photons must be used to lower down the detector threshold to at least 10^{17} eV. CRTNT will use this technique; however, event reconstruction would be more difficult than pure fluorescence detector such as HiRes. Angular resolution would be the most difficult challenge.

For AGN neutrinos, it requires total exposure of 5876 km^2 sr yr to produce 10^6 tau leptons, or 170 events pre km^2 sr yr. The flux may be high enough, but their shower energy are mostly in between 3×10^{14} eV to 10^{16} eV. Only Cherenkov radiation can provide enough photons to trigger. Large field of view would be needed to compensate the small solid angle of Cherenkov radiation. Once event were triggered, angular resolution is easier to achieve. NuTel tries to explore this territory by developing a multi-anode PMT array and wide field of view optical system.

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