Ultrahigh energy cosmic neutrinos and the physics beyond the Standard Model

Ina Sarcevic
Department of Physics, University of Arizona, Tucson, AZ 85721
E-mail: `ina@physics.arizona.edu`

Abstract. We study ultrahigh energy astrophysical neutrinos and their interactions. We find that for GZK neutrinos three flavor mixing is important and the neutrino flavor ratio at Earth deviates from 1:1:1. We show the effect of tau neutrino regeneration and tau energy loss as they propagate through the Earth. We also consider production of mini black holes, neutrino interactions via TeV string resonances and the supersymmetric charged sleptons (stau) production in neutrino interactions. We discuss signals for these processes in detectors such as Anita, EUSO and OWL.

1. Introduction

Astrophysical neutrinos provide unique probes of particle physics at energies currently not accessible to collider experiments. In addition, since neutrinos are stable neutral particles, and they interact weakly, astrophysical neutrinos point back to their sources and they travel very large distances without interactions, providing valuable information about extreme enviroments.

Neutrinos from astrophysical sources are usually produced via pion decays, which determine the flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ to be $1 : 2 : 0$. After propagation over very long distances, neutrino oscillations change this ratio to $1 : 1 : 1$ because of the maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing. For the GZK flux, ν_e and ν_μ incident fluxes are different because of the additional contributions from $\bar{\nu}_e$ from neutron decay and ν_e from μ^+ decays [1]. Because of this, the flavor ratio at Earth is affected by the full three flavor mixing and is different from $1 : 1 : 1$. Given fluxes at the source $F^0_{\nu_e}$, $F^0_{\nu_\mu}$ and $F^0_{\nu_\tau}$, the fluxes at Earth become:

$$\begin{aligned} F_{\nu_e} &= F^0_{\nu_e} - \frac{1}{4}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \\ F_{\nu_\mu} &= F_{\nu_\tau} = \frac{1}{2}(F^0_{\nu_\mu} + F^0_{\nu_\tau}) + \frac{1}{8}\sin^2 2\theta_{12}(2F^0_{\nu_e} - F^0_{\nu_\mu} - F^0_{\nu_\tau}) \end{aligned}$$

where θ_{12} is the mixing angle relevant for solar neutrino oscillations. We have assumed that θ_{23}, the mixing angle relevant for atmospheric neutrino oscillations, is maximal and θ_{13} is very small, as shown by reactor experiments, as well as atmospheric and solar data.

In Fig. 1 we show enhancement of the tau neutrino flux relative to the initial flux, after the propagation through the Earth for different nadir angles [2]. This enhancement is due to ν_τ regeneration via $\nu_\tau \to \tau \to \nu_\tau$ processes. At higher energies, above 10^8 GeV, the energy loss of taus, via its photonuclear interactions, is a dominant process over the decay, thus there is suppression of the ν_τ flux similar to the ν_μ case.

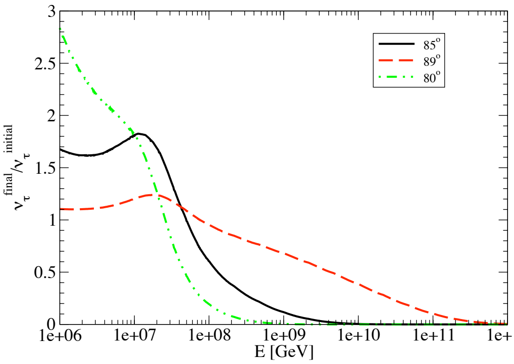

Figure 1. Ratio of the tau neutrino flux after the propagation through the Earth for different nadir angles, and the initial tau flux.

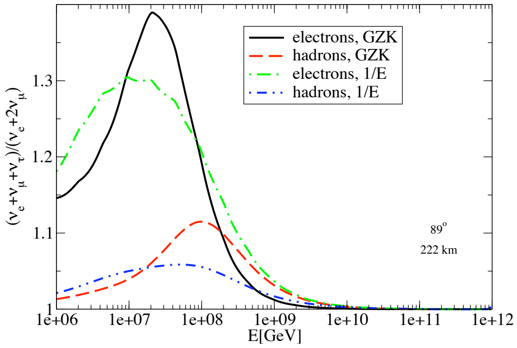

Figure 2. Ratio of electromagnetic and hadronic shower rates in the presence and absence of $\nu_\mu \to \nu_\tau$ oscillations for GZK and $1/E$ fluxes of neutrinos for detection over 222 km of ice.

Signals of neutrino interactions in the rock below the ice or in ice depend on the energy and flavor of the neutrino. Muon neutrino charged current (CC) conversions to muons are noted by the Cherenkov signal of upward going muons in a detector such as IceCube [3]. High energy electromagnetic showers from $\nu_e \to e$ CC interactions produce Cherenkov radiation which is coherent for radio wavelengths. The Antarctic Impulsive Transient Antenna (Anita) [4] monitors the ice sheet for refracted radio frequency signals with an effective telescope area of 1M km^2. All flavors of neutrinos produce hadronic showers. In addition, tau decays contribute to both electromagnetic and hadronic showers that could be detected by IceCube or Anita.

In Fig. 2 we show our results for the electromagnetic and hadronic shower fluxes at 89°, of relevance to Anita in the presence and absence of oscillations for the GZK and for a generic $1/E$ neutrino flux [2]. In absence of oscillations, the only contribution to electromagnetic showers comes from ν_e interactions. In the presence of $\nu_\mu \to \nu_\tau$ oscillations, electromagnetic decays of taus from tau neutrinos add significant contributions to these rates at energies below 10^8 GeV. In the same time, for the GZK flux, $\nu_e \to \nu_{\mu,\tau}$ oscillations reduce the number of ν_e's at low energy, such that below a few $\times 10^6$ GeV there are fewer electromagnetic showers than in the absence of oscillations.

2. Probing the Physics Beyond the Standard Model with UHE Neutrinos

Cosmic neutrinos with energies E_ν above 10^{17} eV probe neutrino-nucleon scattering at center-of-mass (c.m.) energies above

$$\sqrt{s_{\nu N}} \equiv \sqrt{2 m_N E_\nu} \simeq 14 \left(\frac{E_\nu}{10^{17}\ \mathrm{eV}}\right)^{1/2} \ \mathrm{TeV}$$

These energies are beyond the proton-proton c.m. energy $\sqrt{s_{pp}} = 14$ TeV of the LHC, and Bjorken-x values below

$$x \simeq 2 \times 10^{-4} \left(\frac{Q^2}{m_W^2}\right)\left(\frac{0.2}{y}\right)\left(\frac{10^{17}\ \mathrm{eV}}{E_\nu}\right)$$

The parton structure functions, necessary for evaluating neutrino cross sections, at these low values of x and large Q^2 are not experimentally measured, thus introducing some uncertainty (about a factor of two at $E_\nu \sim 10^{12}$ GeV) in theoretical extrapolations necessary to obtain charged-current and neutral-current neutrino cross sections [5].

At these energies neutrinos may also provide unique probes of physics beyond the Standard Model such as production of the microscopic black holes as predicted in TeV scale gravity models [6, 7, 8, 9, 10, 11], neutrino interactions via TeV string resonances [12], or the production of supersymmetric charged sleptons in neutrino interactions [13, 14, 15].

In Fig. 3 we show neutrino-nucleon cross sections in the Standard Model and beyond. The charged-current and neutral-current cross sections have much weaker energy dependence than the cross section due to the mini black hole production (dashed curves) for $M_D = 1, 2$TeV and $M_{BH}^{min} = 1, 3, 6$TeV (from top to bottom), TeV string resonance processes (dotted lines) for $M_S = 1$ TeV (top curve) and $M_S = 2$ TeV (bottom curve) or the electroweak instanton-induced processes (dot-dashed lines), as proposed by Ringwald [16] and Bezrukov et al. [17]. We note that the onset of new physics depends on the fundamental Planck scale M_D (in case of the mini black hole production), string scale M_S (for TeV string resonance processes) or the approximation taken in obtaining the onset of electroweak instanton-induced processes.

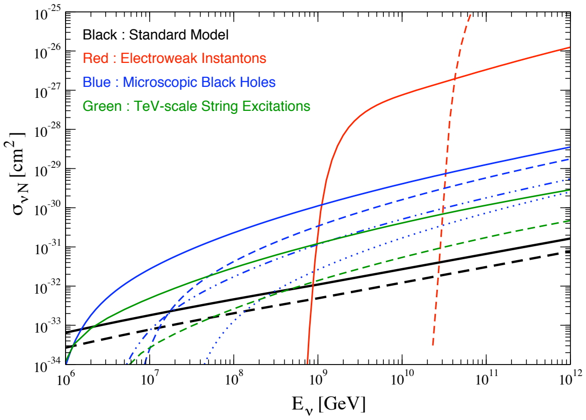

Figure 3. Neutrino-nucleon cross sections in the Standard Model and beyond [18].

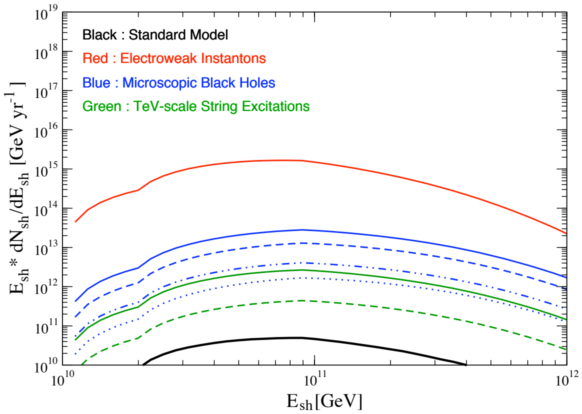

Figure 4. The electromagnetic and hadronic shower flux for processes presented in Fig. 3, for EUSO obtained for GZK neutrino flux.

In Fig. 4 we show our results for the hadronic and electromagenic showers that the Extreme Universe Space Observatory (EUSO) [19] would observe for each of the processes shown in Fig. 3. We find that enhancement in the showers rates is large. The enhancement is even more pronounced for the Orbiting Wide-angle Light-collectors Experiment (OWL) [20], which has effective aperture much larger than EUSO.

$\sigma_{\nu N}$		EUSO	OWL
SM (CC)		0.1	0.5
BH	$M_D = 1$TeV, $M_{BH}^{min} = 1$TeV	31	134
	$M_D = 2$TeV, $M_{BH}^{min} = 6$TeV	1.8	7.7
SR	$M_S = 1$TeV	3.0	12.7
	$M_S = 2$TeV	0.5	2.1

Table I. Event rates for neutrino space telescopes, EUSO and OWL for the Standard Model processes (SM), mini black hole production (BH) and for neutrino interactions via TeV string resonances (SR).

The EUSO and OWL event rates as shown in Table I. Both neutrino space telescopes have capability of probing the cosmogenic flux farther than ground-based air shower experiments. The non-observation of an excess of shower events at the AGASA air shower array lead to limits on the black hole production parameters and require $M_D \geq 1.3 - 1.8$ TeV [21]. The rates for OWL are ten to hundreds of events per year for $M_D = 1$ TeV for $M_{BH}^{\rm min} = 1 - 10$TeV, even in the case of the conservative evolution of the cosmogenic flux [11]. Similar results are found for the Waxman-Bahcall flux [11], which represents the upper bound for optically thin sources. EUSO and OWL have much larger reach in parameter space that the terrestrial experiments.

Ultrahigh energy neutrinos could also probe low scale supersymmetry [13]. In the low scale supersymmetric models, lightest supersymmetric particle (LSP) is the gravitino and the next to lightest particle (NSLP) is typically a long lived charged slepton, stau. Collisions of high energy neutrinos with nucleons in the Earth can result in the production of staus. The cross section for stau production is about three orders of magnituge smaller than the charged-current cross section. However, for supersymmetry breaking scale $\sqrt{F} > 10^7$ GeV, stau's very high boost means they travel very long distances before decaying [13]. As staus traverse the Earth they lose their energy via bremsstrahlung, pair production, photonuclear interactions and weak interactions. We find that the dominant energy loss at high energies is the photonuclear process, which increases with energy [14]. Weak interactions of staus, in particular the charged-current processes, reduce the effective range of staus for energies above 10^8 GeV, or relevance to Anita [15]. The size of the reduction depends strongly on the stau mixing angle. The energy dependence of the energy loss of stau translates into energy spectrum of the staus that reach the detector. We find that weak interactions could reduce stau flux at the detector up to 30% at $E_\nu = 10^8$ GeV and up to 90% at 10^{12} GeV, for the maximal stau mixing angle [15]. Detection of staus with Anita depends on their decay or their weak interactions in the ice, which would result in detectable hadronic showers [23].

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