UDC 501

MONTE CARLO SIMULATIONS OF ULTRA HIGH ENERGY SECONDARY NEUTRINO DETECTION IN THE DUNE EXPERIMENT

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Abstract

In this research we do an evaluation on expected secondary neutrino flux in the DUNE detector from ultra high energy cosmic rays. Using Monte Carlo simulation software *SimProp v.2.r.4.* spectra of ultra high energy secondary neutrinos were obtained, and their flux on the Earth was evaluated. Two different primary sources (free protons and ^{56}Fe cores) that correspond to different cosmic rays origins were used. For the calculations the source was considered to have cosmic ray injection power as $L \simeq 10^{45}$ erg/year. Simulations were conducted at three distances (in terms of redshift z): $z = 0.1$, $z = 1.0$ and $z = 3.0$. Numbers of secondary neutrino events in DUNE over 1 year is expected to be: 39.7, 0.17 and 0.006 for protons and 0.006, 0.0002 and $1.6 \cdot 10^{-5}$ for ^{56}Fe cores accordingly.

Keywords: simulations, high energy neutrinos, DUNE detectors

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1. Introduction

For the last decade astrophysics made a huge step toward better understanding of the Universe. At present data from cosmic sources is collected not only with electromagnetic radiation, but also with particles from cosmic rays and gravitational waves.

Neutrinos as a carrier of information about physics processes have many essential characteristics. Their neutral charge, small mass and only weak interactions make them capable for long distance travelling without affect of magnetic fields and almost without matter interactions.

Here we focus on ultra high-energy neutrinos with the typical energies starting from 1 TeV (10^{12} eV) and up to 100 EeV (10^{20} eV).The main value of information carried by ultra high-energy cosmic neutrinos is that in most cases other information from cosmic processes connected with massive star deaths or active galactic nuclei flares is available only thought UHE gamma rays and neutrinos. However, it is important to notice that at the long distances (high redshifts) very intensive high-energy gamma rays absorption is observed [1]. Thus, information about astrophysical objects is partially lost. In such situation neutrinos can be the only one carrier of information.

The Deep Underground Neutrino Experiment (DUNE) that is located at Fermailab and SURF in the USA will be a world-class neutrino observatory and nucleon decay detector designed to answer fundamental questions about the nature of elementary particles and their role in the universe [2].

The goal of this research is to make a simple estimate for the DUNE detectors' capability to detect UHE neutrinos.

2. UHE neutrino sources and spectra

Nowadays the origin of ultra high-energy neutrinos is considered to be active galactic nuclei (AGN) [3], massive core-collapse supernovae (so called hypernovae) [4], supernova remnants and neutron stars [5] and gamma ray bursts [6]. Important impact of powerful magnetic field from magnetars was shown in [7]. There are several mechanisms that explain UHE neutrinos' creation. While efficient electron acceleration is limited by high radiative losses, protons and heavy nuclei can reach UHE through the same acceleration mechanisms. The dominant process is $p\gamma$ interaction through the Δ-resonance (especially in AGN, GRB and supernova remnants) , i.e.

$$p + \gamma \to \Delta^+ \to \begin{cases} p\pi^0, & \text{frac. } 2/3 \\ n\pi^+ \to n\, e^+\nu_e\nu_\mu\bar{\nu_\mu}, & \text{frac. } 1/3 \end{cases} \tag{1}$$

but electron-nucleon interactions and nucleon-nucleon interactions also play a great role (mostly in supernovae and hypernovae)

$$e^\pm + N \to e^\pm + N + \nu + \bar{\nu} \tag{2}$$

$$N + N \to N + N + \nu + \bar{\nu} \tag{3}$$

In general, these energetic charged particles (electrons and protons) have a power-law spectrum given as $dN/dE \propto E^{-\alpha}$ with the power index $\alpha \geqslant 2$ that is energy dependent.

$$\gamma \simeq \begin{cases} 2.7 \text{ if } E \leq 10^{15} \text{ eV} \\ 3.0 \text{ if } 10^{15} \leq E \leq 5 \cdot 10^{17} \text{ eV} \\ 3.3 \text{ if } 5 \cdot 10^{17} \leq E \leq 5 \cdot 10^{18} \text{ eV} \\ 2.7 \text{ if } E \geq 5 \cdot 10^{18} \text{ eV} \end{cases} \tag{4}$$

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3. Monte Carlo simulations

For obtaining of a UHE spectrum simulation software *SimProp* v.2.r.4 was used. [8]

3.1. Software description

SimProp is a Monte Carlo code for simulating the propagation of ultra-high energy cosmic rays in intergalactic space. *SimProp* takes into account that a type and trajectory of propagating particles can change in their intergalactic journey through different processes [8]. These include:

(i) the adiabatic energy loss that all particles travelling cosmological distances undergo due to the expansion of the Universe (the redshift loss);
(ii) photonuclear interactions with cosmic microwave background (CMB) and infrared/visible/ultraviolet extragalactic background light (EBL) photons;
(iii) deflections by intergalactic and galactic magnetic fields.

For neutrinos only (i) and (ii) take place with domination of the photonuclear interactions with CMB. Photonuclear interactions include electron positron pair production, disintegration of nuclei (whereby one or more nucleons or other light fragments are ejected from a nucleus), and photohadronic interactions producing one or more mesons (mainly pions). These processes influence energy spectrum, mass composition and distribution of arrival directions of UHE neutrinos expected at the Earth.

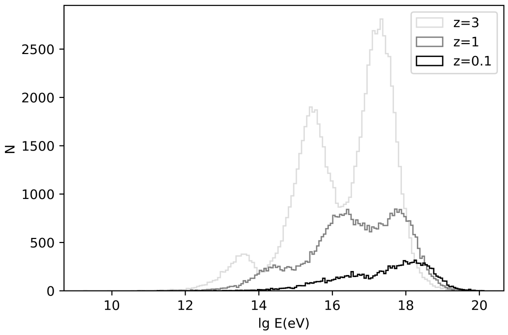
3.2. Simulation input

We have simulated two kinds of sources (free protons and ^{56}Fe cores) that corresponds to different cosmic rays origins: free protons can be named as simplified model of cosmic rays from AGN or magnetars, while ^{56}Fe cores represent cosmic rays from hypernovae explosions and GRBs. Three different distances were used in units of redshift – $z = 0.1$, $z = 1.0$ and $z = 3.0$. Spectrum was simulated accordingly to (4). Number of simulated events for every case was 10^5.

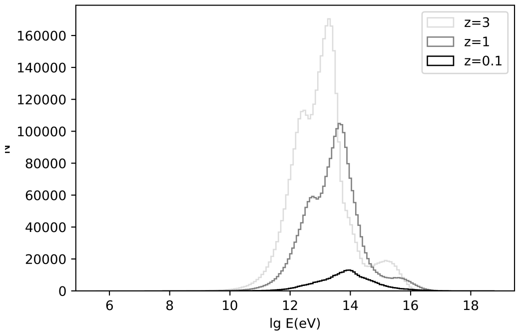
3.3. Simulation output and analysis

Spectra obtained in result of our simulations are shown in Fig.1a and Fig.1b for free protons and ^{56}Fe cores respectively as primary sources at $z = 0.1$, $z = 1.0$ and $z = 3.0$.

Energy spectra for different neutrino flavours are shown in Fig.2a, 2b.

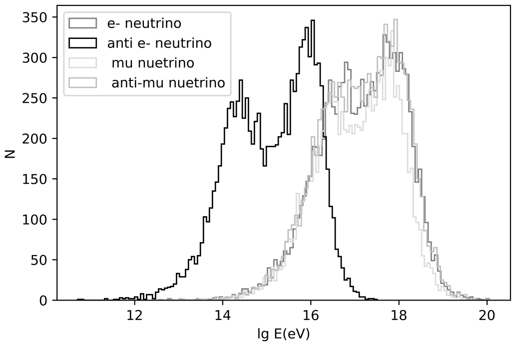


(a) Spectrum with free protons as a primary source.

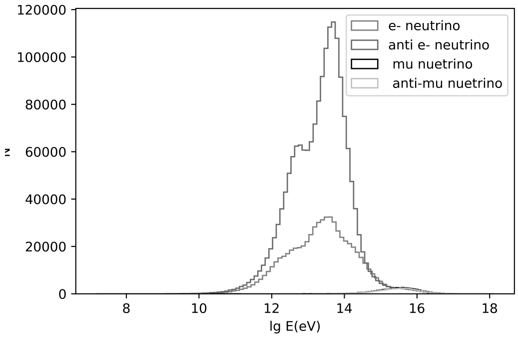


(b) Spectrum with ^{56}Fe cores as a primary source.

Fig. 1. Secondary neutrinos from UHE cosmic rays spectrum.



(a) Spectrum flavor composition with free protons as a primary source at $z = 1.0$ and $\gamma = 2.7$.



(b) Spectrum flavor composition with ^{56}Fe cores as a primary source at $z = 1.0$ and $\gamma = 2.7$.

Fig. 2. Secondary neutrinos from UHE cosmic rays spectrum.

3.4. Neutrino fluxes

Choosing space cosmic rays injection power as $L \sim 10^{45}$erg/year we have obtained neutrino fluxes shown in Fig.3.

In such extremely high energies the difference between $\nu_e N$, $\nu_\mu N$ and $\nu_\tau N$ interactions almost disappears, so for our calculations the number of neutrinos of particular flavor is not important. For this reason neutrino oscillations which change neutrino flavour are not taken into account.

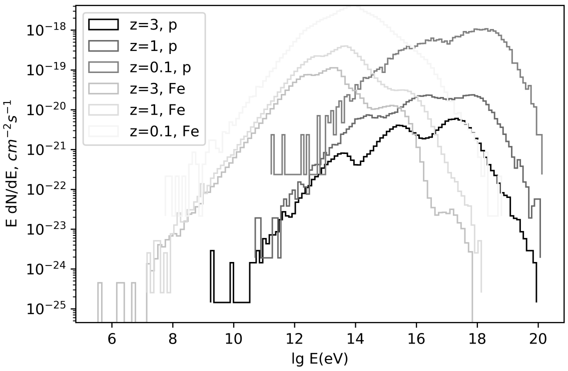
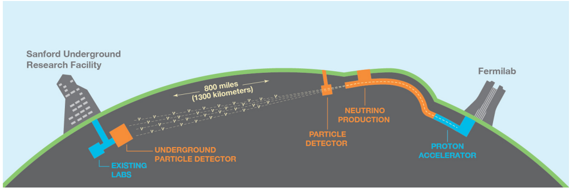


Fig. 3. Secondary neutrino flux from UHE cosmic rays.

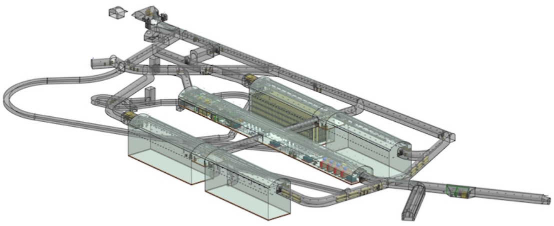
4. The DUNE detector's response on UHE secondary neutrinos

4.1. The DUNE detector

The DUNE will consist of 4 liquid argon time projection chambers (LArTPC) [9] of 10 kt of fiducial volume each (see Fig.4a, 4b). Two of them will be located at Fermilab in Illinois (near detector), another two are expected to be located about 1.5 km underground at the Sanford Underground Research Facility (far detector) in South Dakota, USA. At least one of two far detector LArTPCs will be dual-phase chamber. [10]



(a) DUNE facilities.



(b) DUNE detector.

Fig. 4. The DUNE experiment.

4.2. Event rate calculations

4.2.1. Observing neutrino interactions

The expected number of neutrino interactions inside detector's sensitive volume can be calculated as:

$$N_{obs} = N_{targ}\, T \int \Phi(E_\nu)\, \sigma(E_\nu) dE_\nu \qquad (5)$$

where N_{targ} is number of targets, T – exposure time, $\Phi(E_\nu)$ – neutrino flux as function of energy (in cm^{-2}s^{-1}), $\sigma(E_\nu)$ – cross section for particular type of neutrino interactions.

4.2.2. Neutrino cross sections for UHEs

Till now cross sections for UHE part of neutrino spectrum have never been measured experimentally. However, a lot of theoretical calculations in conjunction with computer simulations were done. Here we are going to use cross sections plotted in Fig.5 from [11].

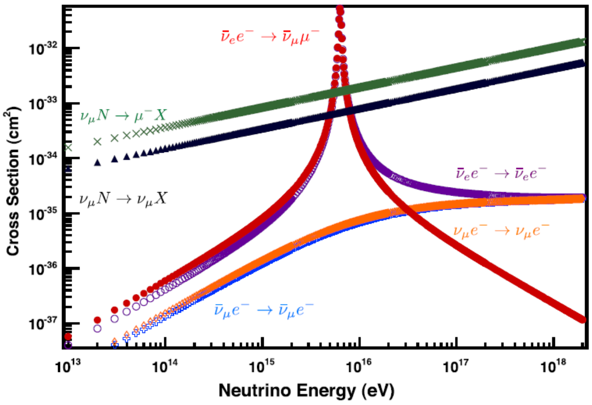


Fig. 5. Neutrino electron and nucleon scattering in the ultra-high-energy regime ($E > 10^4$ GeV). Shown are the electron interactions $\bar{\nu_\mu}\, e^- \to \bar{\nu_\mu}\, e^-$ (crosses), $\nu_\mu\, e^- \to \nu_\mu\, e^-$ (diamonds), $\bar{\nu_e}\, e^- \to \bar{\nu_e}\, e^-$ (hollow circles), $\nu_e\, e^- \to \nu_e\, e^-$ (filled circles), and the nucleon charged current (cross markers) and neutral-current (filled triangles) interactions.[11]

Quantitative studies of particular type of cross sections, for example νN [12], confirm these results. Peak at $\sim 10^{16}$ is caused by resonance with W$^-$ boson production [13] [14].

4.2.3. Event rate

Following formula (5) we can estimate every value in it. Since DUNE detectors' fiducial volume is 40kt, number of targets (which is total number of nucleons) can be calculated as $N = 2.4 \cdot 10^{31}$. All results are shown in Table 1.

Table 1. Expected number of events per year in the DUNE detector.

Primary source	z=0.1	z=1	z=3
Protons	39.7	0.17	0.006
^{56}Fe	0.006	0.0002	$1.6 \cdot 10^{-5}$

5. Discussion

For our calculations model with $L \sim 10^{45}$ erg/year was used. This cosmic rays injection power was estimated as typical scale for our Universe [15] [16], however more energetic space sources are also possible. In such situation increase of L by one order leads to increase of all values in Table 1 by one order.

In general, our flux simulations agree with similar work that was done with other simulation software for secondary neutrino event rate evaluation in IceCube and ANTARES [17] [18].

6. Conclutions

In this research we made an evaluation of expected secondary neutrino flux in the DUNE detector for ultra high energy cosmic rays. Spectra of ultra high energy secondary neutrinos were obtained with *SimProp* software, they agreed with similar simulations conducted within the frame of another software for IceCube and ANTARES. Simulations were conducted at three distances (in terms of redshift z): $z = 0.1$, $z = 1.0$ and $z = 3.0$. Numbers of secondary neutrino events in DUNE over 1 year is expected to be: 39.7, 0.17 and 0.006 for protons and 0.006, 0.0002 and $1.6 \cdot 10^{-5}$ for ^{56}Fe cores accordingly.

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