10^{20} \text{eV cosmic-ray and particle physics with kilometer-scale neutrino telescopes}

J. Alvarez-Muñiz and F. Halzen

Univ. of Wisconsin, Dept. of Physics, 1150 University Avenue, Madison, Wisconsin 53706, USA.

Abstract

We show that a kilometer-scale neutrino observatory, though optimized for TeV to PeV energy, is sensitive to the neutrinos associated with super-EeV sources. These include super-heavy relics, neutrinos associated with the Greisen cutoff, and topological defects which are remnant cosmic structures associated with phase transitions in grand unified gauge theories. It is a misconception that new instruments optimized to EeV energy are required to do this important science, although this is not their primary goal. Because kilometer-scale neutrino telescopes can reject atmospheric backgrounds by establishing the very high energy of the signal events, they have sensitivity over the full solid angle, including the horizon where most of the signal is concentrated. This is important because up-going neutrino-induced muons, routinely considered in previous calculations, are absorbed by the Earth.

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I. INTRODUCTION

It has been realized for some time that topological defects are unlikely to be the origin of the structure in the present Universe \([1]\). Therefore the observation of their decay products, in the form of cosmic rays or high energy neutrinos, becomes the most straightforward way to search for these remnant structures from grand unified phase transitions \([2]\). Such search represents an example of fundamental particle physics that can only be done with cosmic beams. We here point out that a kilometer-scale neutrino observatory \([3]\), such as IceCube, has excellent discovery potential for topological defects. The instrument can identify the characteristic signatures in the energy and zenith angle distribution of the signal events. It is a common misconception that different instruments \([4,5]\), optimized to EeV signals, are required to do this important science, although this is not their primary motivation. Our conclusions for topological defects extend to other physics associated with 10^{20} \text{–} 10^{24} \text{eV energies.}
We will illustrate our claims by demonstrating IceCube sensitivity to:

- generic topological defects with grand-unified mass scale $M_X$ of order $10^{14} - 10^{15}$ GeV and a particle decay spectrum consistent with all present observational constraints [6,8],
- superheavy relics, normalized to the Z-burst scenario [9] where the observed ultra high energy cosmic rays (UHECR) of $\sim 10^{20}$ eV energy and above are locally produced by the interaction of superheavy relic neutrinos with the cosmic neutrino background radiation [11],
- neutrinos produced by superheavy relics which themselves decay into the UHECRs [11,12], and
- the flux of neutrinos produced in the interactions of UHECR cosmic rays with the microwave background [13], the so called Greisen neutrinos. This flux, which originally inspired the concept of a kilometer-scale neutrino detector, is mostly shown for comparison.

The basic reasons for our more optimistic conclusions about the sensitivity of a detector such as IceCube are simple. Unlike first-generation neutrino telescopes, IceCube can measure energy and can therefore separate very high energy signals from the low energy atmospheric neutrino background by energy measurement [14] (see below). The instrument can therefore isolate high energy events over $4\pi$ solid angle, and not just in the hemisphere where the neutrinos are identified by their penetration of the Earth. This is of primary importance here because neutrinos from topological defects have energies high enough so that they are efficiently absorbed by the Earth [15]. The signal from above and near the horizon typically dominates the up-going neutrino fluxes by an order of magnitude. We will show that the zenith angle distribution of neutrinos associated with topological defects form a characteristic signature for their extremely high energy origin.

II. NEUTRINO EVENTS

We calculate the neutrino event rates by convoluting the $\nu_\mu + \bar{\nu}_\mu$ flux from the different sources considered in this paper, with the probability of detecting a muon produced in a muon-neutrino interaction in the Earth or atmosphere:

$$N_{\text{events}} = 2\pi A_{\text{eff}} T \int \int \frac{dN_\nu(E_\nu)}{dE_\nu} P_{\nu \rightarrow \mu}(E_\nu, E_\mu(\text{thresh}), \cos \theta_{\text{zenith}}) dE_\nu \ d\cos \theta_{\text{zenith}}$$

where $T$ is the observation time and $\theta_{\text{zenith}}$ the zenith angle. We assume an effective telescope area of $A_{\text{eff}} = 1 \text{ km}^2$, a conservative assumption for the very high energy neutrinos considered here. It is important to notice that the probability ($P_{\nu \rightarrow \mu}$) of detecting a muon with energy above a certain energy threshold $E_\mu(\text{threshold})$, produced in a muon-neutrino interaction, depends on the angle of incidence of the neutrinos. This is because the distance traveled by a muon cannot exceed the column density of matter available for neutrino interaction, a condition not satisfied by very high energy neutrinos produced in the atmosphere. They are
absorbed by the Earth and only produce neutrinos in the ice above, or in the atmosphere or Earth near the horizon. The event rates in which the muon arrives at the detector with an energy above $E_\mu$(threshold) = 1 PeV, where the atmospheric neutrino background is negligible, are shown in Table I.

Fig. 1 shows the $\nu_\mu + \bar{\nu}_\mu$ fluxes used in the calculations. We first calculate the event rates corresponding to the largest flux from topological defects [6] allowed by constraints imposed by the measured diffuse $\gamma$-ray background in the vicinity of 100 MeV. The corresponding proton flux has been normalized to the observed cosmic ray spectrum at $3 \times 10^{20}$ eV; see Fig. 2 of reference [6]. Models with $p<1$ appear to be ruled out [7] and hence they are not considered in the calculation. As an example of neutrino production by superheavy relic particles, we consider the model of Gelmini and Kusenko [10]. In Figs. 2 and 3 we show the event rates as a function of neutrino energy. We assume a muon energy threshold of 1 PeV. We also show in both plots the event rate due to the Waxman and Bahcall bound [16]. This bound represents the maximal flux from astrophysical, optically thin sources, in which neutrinos are produced in p-p or p-$\gamma$ collisions. The atmospheric neutrino events are not shown since they are negligible above the muon energy threshold we are using. The area under the curves in both Figs. is equal to the number of events for each source. In Fig. 4 we plot the event rates in which the produced muon arrives at the detector with an energy greater than $E_\mu$(threshold). In Fig. 5 we finally present the angular distribution of the neutrino events for the different very high energy neutrino sources. The characteristic shape of the distribution reflects the opacity of the Earth to high energy neutrinos, typically above $\sim 100$ TeV. The limited column density of matter in the atmosphere essentially reduces the rate of downgoing neutrinos to interactions in the 1.5 km of ice above the detector. The events are therefore concentrated near the horizontal direction corresponding to zenith angles close to 90$^\circ$. The neutrinos predicted by the model of Gelmini and Kusenko are so energetic that they are even absorbed in the horizontal direction as can be seen in Fig. 5.

| Model                                      | $N_{\nu_\mu+\bar{\nu}_\mu}$ (downgoing) | $N_{\nu_\mu+\bar{\nu}_\mu}$ (upgoing) |
|--------------------------------------------|----------------------------------------|----------------------------------------|
| TD, $M_X = 10^{14}$ GeV, $Q_0 = 6.31 \times 10^{-35}$, $p=1$ | 11                                     | 1                                      |
| TD, $M_X = 10^{14}$ GeV, $Q_0 = 6.31 \times 10^{-35}$, $p=2$ | 3                                      | 0.3                                    |
| TD, $M_X = 10^{14}$ GeV, $Q_0 = 1.58 \times 10^{-34}$, $p=1$ | 9                                      | 1                                      |
| TD, $M_X = 10^{15}$ GeV, $Q_0 = 1.12 \times 10^{-34}$, $p=2$ | 2                                      | 0.2                                    |
| Superheavy Relics Gelmini et al. [10]      | 30                                     | $1.5 \times 10^{-7}$                   |
| Superheavy Relics Berezinsky et al. [11]   | 2                                      | 0.2                                    |
| Superheavy Relics Birkel et al. [12]       | 1.5                                    | 0.3                                    |
| $p$-$\gamma_{\text{CMB}}$ ($z_{\text{max}} = 2.2$) [13] | 1.5                                    | $1.2 \times 10^{-2}$                   |
| W-B limit $2 \times 10^{-8} \frac{E^{-2}}{(\text{cm}^2 \text{s sr GeV})^{-1}}$ | 8.5                                    | 2                                      |
| Atmospheric background                     | $2.4 \times 10^{-2}$                  | $1.3 \times 10^{-2}$                  |

Table I: Neutrino event rates (per year per km$^2$ in 2$\pi$ sr) in which the produced muon arrives at the detector with an energy above $E_\mu$(threshold) = 1 PeV. Different neutrino sources have been considered. The topological defect models (TD) correspond to highest injection rates $Q_0$ (ergs cm$^{-3}$ s$^{-1}$) allowed in Fig. 2 of [6]. Also shown is the number of events from $p$-$\gamma_{\text{CMB}}$ interactions in which protons are propagated up to a maximum redshift $z_{\text{max}} = 2.2$ [13] and the number of neutrinos from the Waxman and Bahcall limit on the diffuse flux from optically thin sources [16]. The number of atmospheric background events above 1 PeV.
is also shown. The second column corresponds to downward going neutrinos (in $2\pi$ sr). The third column gives the number of upward going events (in $2\pi$ sr). We have taken into account absorption in the Earth according to reference [13]. IceCube will detect the sum of the event rates given in the last two columns.

Energy measurement is critical for achieving the sensitivity of the detector claimed. For muons, the energy resolution of IceCube is anticipated to be 25% in the logarithm of the energy, possibly better. The detector is able to determine energy to better than an order of magnitude, sufficient for the separation of EeV signals from atmospheric neutrinos with energies below 100 TeV. Notice that one should also be able to identify electromagnetic showers initiated by electron and tau-neutrinos. Their energy measurement is linear and expected to be better than 20%. Such EeV events will be gold-plated, unfortunately their fluxes are expected to be even lower. For instance for the first TD model in Table I (p=1, $M_X = 10^{14}$ GeV and $Q_0 = 6.31 \times 10^{-35}$ ergs cm$^{-3}$ s$^{-1}$), we expect $\sim 1$ contained shower per year per km$^2$ above 1 PeV initiated in charged current interactions of $\nu_e + \bar{\nu}_e$. The corresponding number for the Gelmini and Kusenko flux is $\sim 4$ yr$^{-1}$ km$^{-2}$.

One should also worry about the fact that a very high energy muon may enter the detector with reduced energy because of energy losses. It could become indistinguishable from atmospheric background [17]. We have accounted for the ionization as well as catastrophic muon energy losses which are incorporated in the calculation of the range of the muon. In the PeV regime region this energy reduction is roughly one order of magnitude, it should be less for the higher energies considered here.

In conclusion, if the fluxes predicted by our sample of models for neutrino production in the super-EeV region are representative, they should be revealed by the IceCube observatory operated over several years.

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FIG. 1. Maximal predictions of $\nu_\mu + \bar{\nu}_\mu$ fluxes from topological defect models by Protheroe and Stanev (p=1,2). Also shown is the $\nu_\mu + \bar{\nu}_\mu$ from superheavy relic particles by Gelmini and Kusenko and the flux by Berezinsky et al.
FIG. 2. Differential $\nu_\mu + \bar{\nu}_\mu$ event rates in IceCube from the topological defect fluxes in Fig.1. The muon threshold is $E_\mu$(threshold)=1 PeV. We have separated the contribution from upgoing and downgoing events to stress the different behavior with energy. The event rate expected from the Waxman and Bahcall bound (see text) is also shown for illustrative purposes. The rate due to atmospheric neutrinos is negligible (see Table I) and hence it is not plotted.
FIG. 3. Differential $\nu_\mu + \bar{\nu}_\mu$ event rates in IceCube from super-heavy relic particles. We have separated the contribution from upgoing and downgoing events to stress the different behavior with energy. The muon threshold is $E_{\mu}(\text{threshold})=1$ PeV. The event rate due to atmospheric neutrinos as well as the one expected from the Waxman and Bahcall bound (see text) is shown for illustrative purposes. The rate due to atmospheric neutrinos is negligible (see Table I) and hence it is not plotted.
FIG. 4. $\nu_\mu + \bar{\nu}_\mu$ event rates in IceCube from the fluxes in Fig.1. The plot shows the number of events in which the produced muon arrives at the detector with an energy above $E_\mu$(thresh). Atmospheric neutrino events and the event rate expected from the Waxman and Bahcall upper bound (see text) are also plotted. The topological defect (TD) models shown (p=1 and p=2) correspond to $M_X = 10^{14}$ GeV. Upgoing and downgoing events are shown separately.
FIG. 5. Zenith angle distribution of the $\nu_\mu + \bar{\nu}_\mu$ events in IceCube in which the produced muon arrives at the detector with energy above 1 PeV. Left: Topological defect models. Right: Superheavy relics. $\cos(\theta_{\text{zenith}}) = -1$ corresponds to vertical upgoing neutrinos, $\cos(\theta_{\text{zenith}}) = 0$ to horizontal neutrinos and $\cos(\theta_{\text{zenith}}) = 1$ to vertical downgoing neutrinos. The detector is located at a depth of 1.8 km in the ice.