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Detecting UHE neutrinos ($E > 10^{18}$eV) with a large radio array.

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Abstract

A relatively cost-effective way to detect ultra high energy (UHE) cosmic neutrinos is with an array of radio antennas buried in Antarctic ice. The GZK process ‘guarantees’ such neutrinos as a result of interactions of high energy cosmic rays with the cosmic microwave background. A suitable geometry for detecting this flux is a large volume (10^4 km^3) instrumented for contained events (100’s of events per yr). For $E_\nu > 10^{18}$ eV, downward moving neutrinos would interact within the detector volume with probability $1.7 \times 10^{-3}(E_\nu/10^{18}\mathrm{eV})^{0.36}$. Upward neutrinos are shadowed by the Earth. High energy muons produced in cosmic ray air showers are negligible. The radio ice Cherenkov technique may permit construction of such a detector at modest cost. By detecting Cherenkov pulses from electromagnetic and hadronic cascades in the ice, an array of radio antennas would be able to detect and possibly identify all flavors of neutrino.

1 Introduction

Active galactic nuclei and gamma ray bursts have been proposed as sources of high energy neutrinos ($E_\nu \gtrsim 1$PeV). (For a review of neutrino astrophysics, see Gaisser, Halzen, and Stanev 1995.) Discovery that these objects do produce neutrinos would tag them as accelerators of hadrons as well as being high energy photon sources. Exciting as this possibility is, these sources are speculative. On the other hand, other sources of high energy neutrinos are virtually guaranteed, being the consequence of the interaction between a known flux of cosmic rays and known target material - the Earth’s atmosphere, galactic gas and dust, and the cosmic microwave background. Pertaining to the latter, the Greissen, Zatsepin, Kuzmin (GZK) cutoff and pileup of high energy cosmic rays has been observed. The $N\gamma$ process causing the cutoff produces pions, muons and eventually ultra high energy (UHE) neutrinos, which may be called GZK neutrinos.

The scientific return from observation of GZK neutrinos would be large. We point out that these neutrinos would be spatially correlated with sources of high energy cosmic rays. The cosmic background from all sources would have spectral features that would be diagnostics for source evolution models. Neutrino flavor identification within the detector would provide information on neutrino mixing with an unprecedented long baseline. It is therefore of great interest to astrophysicists and particle physicists to detect these neutrinos at a reasonable rate.

2 Detector size and geometry

We take neutrino fluxes from Yoshida and Teshima (1993) (YT) who model the cosmological GZK neutrino production allowing for the density of cosmic ray sources to evolve with redshift as $(1+z)^m$ back to a turnon redshift, z_0. They consider several sets of parameters, but we will focus on a relatively conservative model with $m = 2$ and $z_0 = 2$. YT assume a cosmic ray source spectrum $\phi(E) \sim E^{-2}$ which they normalize to the observed cosmic ray flux for $E > 3 \times 10^{19}$eV. This normalization fixes the high energy end of the neutrino spectrum directly from cosmic ray observations. The lower end of their model includes redshifted neutrinos from cosmologically distant sources and is sensitive to the evolution model. The integrated flux of their (2,2) model is roughly 10 km^{-2} yr^{-1} above 1 EeV.

To set the scale of a GZK neutrino detector we need to consider the neutrino nucleon cross-section. Including both charged and neutral currents, $\sigma_{\nu N} \approx 1.4 \times 10^{-32} E_{18}^{0.36}$ cm^2 where E_{18} is the neutrino energy in EeV (Gandhi et al, 1997). Given the flux, an interaction rate of 1 event per yr will require roughly 5×10^{40} nucleons. To do useful science, 100 events per yr is probably a better benchmark, requiring 10^4 km^3 of instrumented volume at water density. It seems evident that a spherical or cubical volume of this dimension is not available, but a slab of ice or water is possible. The Antarctic ice near South Pole is approximately 2 km thick, and so a detector with area 10^4 km^2 is required. Alternatively one may consider such a detector to be a large area detector with neutrino detection efficiency $\epsilon(E) = n\sigma(E)l \sim 1.7 \times 10^{-3} E_{18}^{0.36}$.

At ‘low’ energies, neutrino detection commonly consists of a search for muons produced below the detector and passing through it. Above 10^{14} eV, however, the Earth is opaque to neutrinos. For UHE energies the muon strategy is only viable for a small solid angle near the horizon, $\Omega_\mu = \pi l_{int}/R_\oplus$, where l_{int} is the neutrino interaction length. For a ray within this solid angle, the probability for a muon to be produced and reach the detector is $P_\mu = l_\mu / l_{int}$, l_μ being the muon range. Note that l_{int} drops out. Averaging over the lower hemisphere, above 10^{16}eV the efficiency for detecting upward muon neutrinos, $\epsilon_{up} \approx (\Omega_\mu P_\mu)/(2\pi) \approx 5 \times 10^{-5}/\rho$, is nearly independent of energy. In comparison, the probability for a neutrino to interact while traversing 2 km of ice is $1.7 \times 10^{-3}/\cos\theta E_{18}^{0.36}$. Thus, contained events due to neutrinos from above are some 100 times more likely than throughgoing muons from below.

It therefore makes sense to design an EeV detector as a contained event detector of downward neutrinos. A few comments: a) There is the possibility of detecting neutrinos via horizontal air showers deep in the atmosphere. The amount of target material in an equal area slab of atmosphere is 1% of that in a km thick slab of water/ice, so to obtain comparable event rates would require 10^6 km^2 coverage. This is much larger than AUGER, but is comparable to that proposed by the OWL collaboration. It is likely that a water/ice detector would have higher duty factor and lower cost than a space based experiment. b) Muon and electron neutrinos are absorbed by the Earth, but ν_τ will survive due to the conservation of τ number in weak interactions. However, interactions degrade the tau energy, and so for EeV detection ν_τ are also effectively absorbed by the Earth. c) At EeV energies the background due to muons produced in cosmic ray induced atmospheric cascades is small (see below).

To summarize: to detect neutrinos in excess of 10^{18} eV, the greatest event rate is achieved by optimizing for neutrinos coming from the upward hemisphere and interacting within the detector volume. The detector must contain 10^{43} target nucleons to ‘gaurantee’ 100 events per yr. For ice or water, this corresponds to a detector with dimensions $100 \times 100 \times 2$ km^3.

2.1 Event characteristics.

The physics potential of an EeV neutrino detector is greatly enhanced if the flavor of the interacting neutrino can be determined. This is best done by determining the event topology. In the case of neutral current interactions all neutrinos produce a hadronic cascade, and flavor ID will be difficult. Charged current interactions produce charged leptons, leading to distinctive event topologies for the three neutrino flavors: ν_e produce an electromagnetic cascade. ν_μ produce a penetrating muon which suffers catastrophic dE/dx in the form of bremstrahlung or photonuclear interactions about once per km, as well as quasi-continuous energy loss in the form of pair production. ν_τ produce τs which may decay within the detector yielding a hadronic or electromagnetic cascade depending on the τ decay mode. Tau leptons also experience photonuclear reactions and pair production, but at a lower rate than muons.

We thus must have the ability to detect and identify electromagnetic and hadronic cascades in ice. Eventually hadronic cascades lose their energy to photons through π^0 decays, and resemble their electromagnetic cousins. To distinguish the two types, therefore, we rely on the early part of their evolution. In fact, below 1 PeV the two types of cascades are similar, although hadronic cascades have larger fluctuations.

Above a few PeV, the situation changes. The LPM effect causes the radiation length to increase as $E^{1/2}$ and so electromagnetic cascades get stretched out. Hadronic cascades on the other hand do not. Moreover, at 1.6 PeV the π^0 decay length becomes equal to its interaction length in ice, and so EeV cascades remain purely hadronic early on. Once the cascade evolves to where particle energies are only a few PeV, the energy will leak into radiation and evolve with the profile of a PeV cascade.

2.2 The muon background.

For cascade energies below a PeV, and perhaps upto 10 PeV, an upward looking detector must be able to separate neutrino events from a background of muons produced in cosmic ray air showers, however, by 1 EeV the atmospheric muon flux is totally negligible.

Perhaps the shortest way to see this is to realize that the muons and neutrinos are produced by the same high energy cosmic rays, just with different efficiencies. For neutrinos, cosmic rays all over the universe contribute, and detection efficiency is about 10^{-3}. For EeV muons, only cosmic rays produced within 30 Mpc (about 1% of the column depth) contribute, and production efficiency in the atmosphere is of order 10^{-5} at EeV energies. Thus, on this simple basis one expects the rate for EeV muons to interact in a detector to be of order 10^{-4} that for GZK neutrinos.

3 Detector technology and efficiency

Ultimately, whether or not UHE neutrinos are useful for science depends on the detector efficiency and resolution. Vertex resolution will be important for distinguishing different event topologies, and therefore flavor and background identification. Energy and angular resolution are crucial to the scientific program. In this paper we concentrate on efficiency.

Below a few PeV, the preferred technique for neutrino astronomy is detection of optical Cherenkov radiation arising either from the cascades induced at the interaction vertex or from the energy losses of charged leptons produced in charge current events. This technique has a limitation due to the absorption and scattering properties of the medium. In polar ice, under optimal conditions, this requires optical modules to be placed no further than a couple of hundred meters apart. Indeed, at South Pole this technology is being utilized by the AMANDA collaboration with spacing of order 10's of meters to detect neutrinos up to 100 TeV with an effective volume of roughly 0.03 km^3. The ICECUBE experiment is proposed as a km^3 version to provide sensitivity up to 1 PeV. To detect EeV neutrinos, however, a 10^4 km^2 detector is required, which seems prohibitively expensive.

Above 1 PeV, detection of radio cherenkov radiation from the cascades should allow instrumenting a larger volume with a smaller number of cheaper modules. This possibility has been studied in the context of PeV neutrino detection for a km^3 detector (Frichter, Ralston, and McKay 1996), and indeed this is the basis for RICE, a Radio Ice Cherenkov Experiment colocated with AMANDA. Here we discuss extending the radio technique to EeV energies and estimate the detection efficiency of a simple array geometry as a function of cascade energy and antenna spacing.

3.1 Efficiency of a large radio array. To estimate the efficiency of a large array it is sufficient to model the response to neutrino interactions that take place in the center of a small part of the whole array. Similarly, it is sufficient to take simple rectangular grids for the array geometry and just vary the spacing to study the efficiency. Optimization of the array is not being attempted. It is necessary, however, to have a realistic model for the signal strength, ambient noise, propagation of the signal through the ice, and response of a realistic and simple antenna and receiver electronics, as large errors in any of these inputs could lead to drastically optimistic or pessimistic conclusions.

To this end we perform a monte carlo calculation. The monte carlo itself is a variant of that being used by the RICE experiment. The cherenkov radio signals are taken from Zas, Halzen and Stanev (1992). Although ZHS model electromagnetic cascades below a PeV, their profiles and scaling of signal strengths should be appropriate to hadronic cascades at higher energies. The signal is propagated through the ice including absorptive, refractive and dispersive effects.

The model assumes acquisition hardware moderately advanced from what RICE has deployed to date. Antennas are modeled as biconical dipoles 8.5 cm in diameter, 14.7 cm in length, central frequency of 500 MHz, with good impedence matching to the signal transmission medium, which in this case is taken to be lossless, dispersionless optical fiber. The signal/antenna model includes full geometry information of the beam pattern, orientation of the antenna and electric field vector. The model includes signal loss as a function of ice temperature (depth) using temperature profiles measured at South Pole.

The result of this modeling is simulated pulses within the data acquisition system, which must be detected against noise. Although more sophisticated techniques are available, one simple algorithm is to require that for N channels the signal has a peak amplitude above some threshold, R, typically expressed in units of the RMS thermal noise in each channel. To avoid a large number of false triggers we require the product $RN > 15$ and a noise temperature measured to be about 300K. Specifically, we use $R = N = 4$ here.

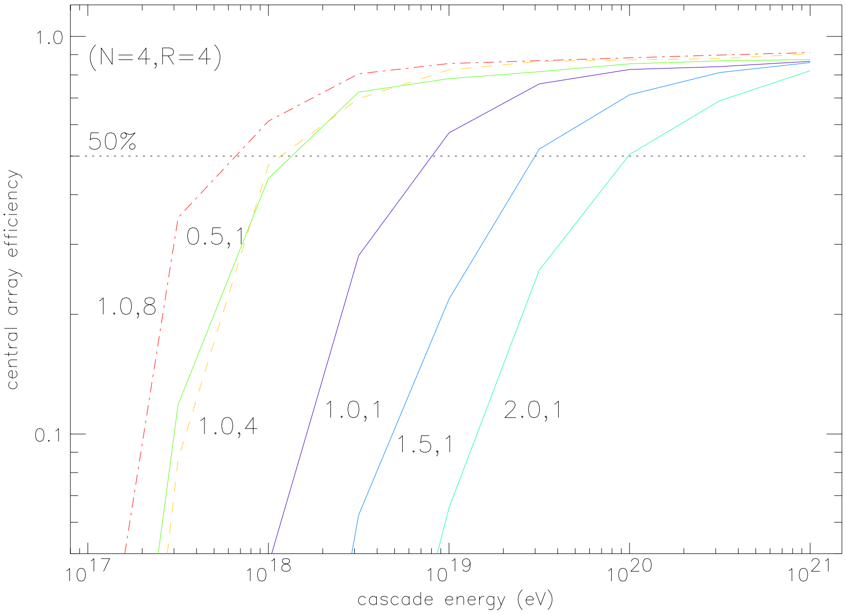

Figure 1: Radio array efficiency as a function of cascade energy. The two numbers labeling each curve are the array spacing (km) and the number of receivers per hole. The trigger condition is N=4 receivers with signal amplitude at least R=4 times the 300 K RMS noise voltage.

With these details in mind, Fig. 1 shows the efficiency as a function of cascade energy for a series of small rectangular planar arrays. The horizontal spacing is varied from 0.5 km to 2 km, but in each case the size of the array is chosen to be the greater of 10 elements or 10 km on a side, ensuring that edge effects are not important. We then expose a 2 km high central unit cell to a monoenergetic flux of neutrinos, isotropic over the upper hemisphere.

We define the threshold E_T as that energy where the efficiency exceeds 50%. Since neutral current hadronic cascades carry about 1/4 of the neutrino energy, the threshold for neutrinos is a factor of 4 higher than that for cascades. For the simplest array geometry, a single antennna per hole, we see that E_T is a strong function of spacing. At 2 km spacing the threshold is 10^{20} eV. However, lowering the spacing to 0.5 km achieves E_T of ~ 1 EeV. Since cost scales as d^{-2} it is natural to try the effects of placing 4 antennas per hole (200 m vertical separation) and using a horizontal spacing of 1 km. This yields similar E_T as for the single plane 0.5 km array. Further increasing the number of antennas to 8 per hole lowers the threshold by another factor of 2.

This result is highly encouraging. Detection seems plausible, although it remains to show that event reconstruction is viable with a modest number of antenna hits. There would clearly be logisitical challenges in constructing an array of this magnitude. Still, this approach seems cheaper than deploying phototubes on the same scale at roughly 100 times the density, or of adopting a space flight mission as proposed for OWL.

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