# In-ice radio detection of GZK neutrinos

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**Abstract.** Models for the source and propagation of cosmic rays are stressed by observations of cosmic rays with energies $E > 10^{20}$ eV. A key discriminant between different models may be complementary observations of neutrinos with energies $E > 10^{18}$ eV. Independent of the source of the cosmic rays, neutrinos are produced during propagation via the GZK mechanism. Event rates for GZK neutrinos are expected to be in the range of $0.01 - 0.1$ per km$^3$ yr, suggesting a detector mass in excess of 1 Eg. Detection of radio cherenkov emission from showers produced in Antarctic ice may be an economical way to instrument such a large mass. It is suggested that a 100 km$^2$ array of antennas centered on Icecube may allow confirmation of the radio technique and also increase the science achievable with Icecube by providing vertex information for events with throughgoing muons.

## INTRODUCTION

Observations of cosmic rays with energies greater than $10^{20}$ eV present a problem. Assuming the particles are baryons, energy losses due to pair production and photoproduction demand that the sources of such particles be located within about 10 Mpc. Since the Universe is fairly lumpy on those length scales, it is somewhat surprising that the events appear to be distributed smoothly on the sky. Further, there are no obvious candidate sources when you look back along the arrival directions. Other particle choices present no better alternatives. Faced with this conundrum, source models generally fall into two classes. a) Astrophysical sources which satisfy the locality and isotropy constraints via a set of just so conditions. b) Models motivated by particle physics, which invoke the injection of high energy particles through the decay of massive particles or topological defects. These models may be distinguished through their associated neutrino fluxes.

Most astrophysical cosmic ray acceleration models involve proton acceleration in a modestly dense environment. Within that source region, interactions may take place of the form $p + X \rightarrow n + \pi^+ + X'$, where $X$ and $X'$ may be anything. Two things happen at this juncture. 1) The neutron may escape from the acceleration region. 2) The $\pi^+$ decays, ultimately producing an $e^+$, $\nu_e$, $\nu_\mu$ and an $\bar{\nu}_\mu$. Such models produce neutrinos at energy $E$ in comparable abundance to nucleons at energy $10E$. It is also possible to have acceleration in low density environments, with no associated neutrino production. By contrast, the particle physics models result in the production of quark jets, which fragment into mesons, and eventually produce neutrinos, other leptons or photons. Baryon production in the fragmentation process accounts for a few percent of all particles, so the neutrinos outnumber the baryons. Finally, once energetic protons are released into the cosmological medium, they produce more neutrinos through the GZK process (Greisen, Zatsepin, Kuzmin) involving photoproduction of pions from collisions with microwave background photons. Since protons with energies above the GZK theshold have been observed, one cannot avoid the conclusion that neutrinos are produced during cosmic ray propagation.

With these comments, one can distinguish source models by their neutrino fluxes. An absolute minimum flux is the GZK flux inferred from the cosmic ray observations themselves. If this is all, then one is inclined to astrophysical acceleration models where the acceleration takes place is low density environments, such as at the interface of galactic winds, the termination shocks of jets from active AGN, etc. If the neutrino fluxes are modestly in excess of the predicted GZK fluxes, then acceleration in a dense astrophysical environment is favored, such as within AGN jets, around magnetars, or in gamma ray bursts, etc. Finally, if neutrino fluxes are greatly in excess of GZK models, then exotic particle physics models are indicated.

To understand the observations of high energy cosmic rays, it is imperative to make complementary observations of ultra high energy cosmic neutrinos. To ensure that one has reached a correct interpretation, one should be prepared to search for fluxes as low as the GZK fluxes. The rest of this contribution is devoted to estimating the size detector required and comparing the potential of proposed detection techniques. In doing this analysis, a rate of 100 events per yr is suggested to go beyond simple discovery level science, an argument which should be familiar to supporters of the AUGER project. Since total fluxes are at a minimum in astrophysical models, I focus on this possibility.

## EVENT RATES

Event rates are estimated by convolving cross-section and neutrino flux. Calculations of the GZK neutrino flux are illustrated by Figure 1, based primarily on results from Yoshida and Teshima [1] (YT). They start with a simple cosmic ray injection model, a homogeneous distribution of sources with proton spectrum $dN/dE = P(t)E^{-2}$. The power law is motivated by shock acceleration models. Their source evolution is described by $P(t) = P_0(1+z)^m$ for $z < z_{max}$ and zero otherwise, with $P_0$, $m$ and $z_{max}$ taken as parameters, and $(1+z)(t)$ described by the cosmological expansion. YT normalize their models by integrating the predicted cosmic ray flux with energies $E > 10^{19.5}$ eV and comparing to the AGASA data. Since photoproduction is efficient at high energies, the normalization only

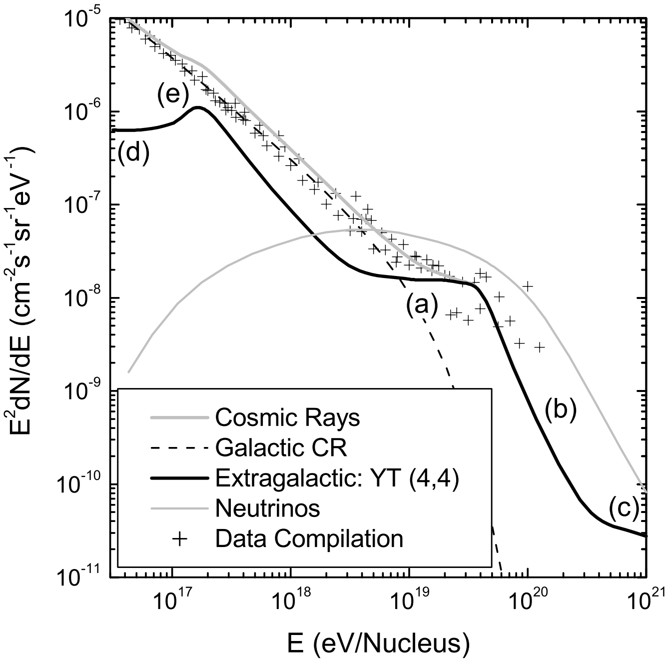

**FIGURE 1.** Neutrino and cosmic ray flux for model (4,4) of Yoshida and Teshima.

counts protons that originate within a few tens of Mpc. It therefore fixes $P_0$, but is independent of the evolution model. YT models are labeled by $(z_{max}, m)$.

In a homogeneous source model the GZK neutrinos are primarily produced at high red shift, so their flux depends both on $P_0$ and the source evolution. It follows that models with strong source evolution will produce more GZK neutrinos. In this regard, the model picked out for Figure 1 is the YT (4,4) model. This is the strongest source evolution model that YT consider and it gives a GZK neutrino flux approximately an order of magnitude stronger than their middle of the road (2,2) model. Even so it is interesting for several reasons.

First, the evolved cosmic ray flux shows clearly several generic features. (a) The shelf at $10^{19}$ eV is fixed by the normalization and reflects the current injection rate integrated over the age of the universe. It does not, qualitatively, include injection at high redshift ($z > 1$) and so is relatively insensitive to parameters other than $P_0$. It is also relatively insensitive to the assumption of homogeneity unless magnetic diffusion effects are strong and sources are long lived. (b) The roll off above $10^{19}$ eV is due to $dE/dX$ from photoproduction. (c) The shelf at $10^{21}$ eV reflects the current injection rate integrated over the energy loss time. The level of (c) relative to (a) is sensitive to the assumption that the sources are distributed homogeneously. (d) The shelf below $10^{17}$ eV is due to injection at high red shift of protons at low enough energy that the only energy losses are adiabatic. The level of (d) relative to (a) is sensitive to the evolution parameters. (e) The bump at $10^{17}$ eV contains protons injected with high energy at high redshift that quickly loose energy due to photoproduction followed by pair-production. This bump is directly related to the flux level of GZK neutrinos. Its height is sensitive to $m$ and its position to $z_{max}$.

Second, since publication of YT, it has become apparent that stronger source models are favored. For example, Engel and Stanev [2] argue for source evolution at least as strong as a (2,3) model, and they find conservative neutrino fluxes comparable to those from the YT (4,4) model. ES use a more detailed treatment of photoproduction than YT which may alter the evolution somewhat. They also use a different normalization, based on work by Waxman [3], which involves integrating the cosmic ray flux above $10^{19}$ eV. Comparing YT's integral spectra to Waxman's suggests normalization differences of ±20%. Taken together this suggests the YT flux in Figure 1 may not be unreasonable for homogeneous models.

Third, Figure 1 shows that when an extragalactic flux is combined with a reasonable galactic flux model interesting features relevant for consideration of GZK neutrinos may arise, beyond just the presence of a GZK cutoff. Specifically, in models of strong source evolution, the bump (e) should be noticeable as a distortion of the cosmic ray spectrum or its composition around $10^{17}$ eV. There is no hint of either effect in reviews by Gaisser [4].

The second half of the event rate calculation is the $\nu N$ cross section. Within the standard model, cross-sections at energies up to $10^{20}$ eV have been calculated by several authors [5–8]. All such calculations are extrapolations, and should be treated with some caution. Typical variation in the charged current cross-section at $10^{19}$ eV is 20% with larger variations in the neutral current cross-sections. Here, we use the results of Glück, Kretzer and Reya [7] (GKR), which are a bit above average for charged currents and a bit below for neutral currents.

Figure 2a shows event rates for different reactions assuming the ES flux and the GKR cross-sections. Rates assume $2\pi$ angular acceptance for downward going neutrinos, the upward flux being absorbed by the Earth, and are given in terms of neutrino energy, not shower energy. For charged current events total energy may be measurable based on known showering and $dE/dX$ properties of various leptons. Even $\tau$ leptons, at an EeV, lose some 7% of their energy per km of path length in ice [9]. For neutral current events only about 20% of the primary neutrino energy [5] goes into the hadronic recoil, so event rates should be estimated using a neutrino threshold energy $\sim 5$ times the detector threshold.

Figure 2b shows integral event rates for four YT models, as well as the ES flux. To achieve 100 events per yr requires roughly 1000 km$^3$ instrumented volume (or 1 Eg of mass) with threshold of 1 EeV. Pessimistic models, such as YT (2,2) may require 10 times the mass, but even then discovery could be accomplished on a modest 100 km$^3$ detector within a year or two of running.

## RICE AND OTHER TECHNOLOGIES

A summary of existing and proposed neutrino detectors is shown in Figure 3. The most widely deployed technique is to use optical Cherenkov photons to recon-

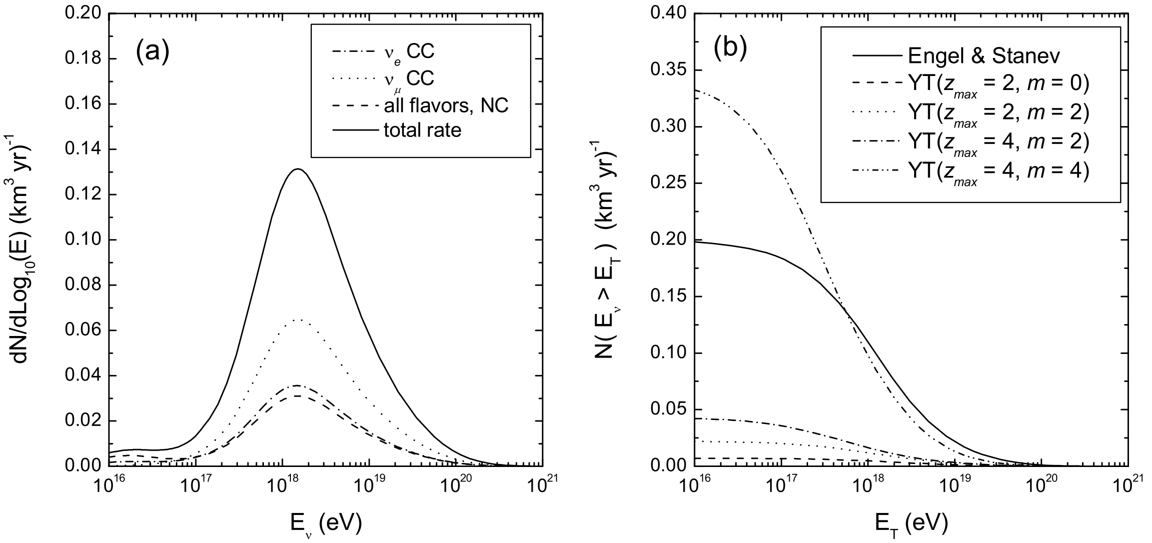

**FIGURE 2.** (a) Differential GZK neutrino interaction rates in ice, by flavor and event type, for the flux of Engel and Stanev. Rates for each flavor include both neutrinos and antineutrinos. The figure assumes no oscillations. (b) Integrated GZK neutrino event rates as a function of detector threshold. It is assumed that all energy is visible for charged current events and 20% is visible for neutral current events.

struct the tracks of muons produced in charged current reactions. In addition to muons, showers produced by the hadronic recoil in $\nu N$ scattering or by charged current electrons will produce intense concentrations of Cherenkov photons. Optical Cherenkov detectors are capable of energy determination for contained events and an extended sensitive volume for throughgoing heavy leptons. In the latter case, the energy resolution for the initial neutrino is likely to be quite poor. The largest optical Cherenkov detector constructed to date is AMANDA [10]. Cubic kilometer detectors are planned, such as Icecube, but even these are too small to adequately probe GZK neutrinos. In principle, the effective volume for throughgoing muons may exceed that for contained events by an order of magnitude; however, without energy resolution the technique at best can set upper limits on EeV neutrino fluxes, but claims of GZK neutrino detection will be problematic.

Air shower techniques have also been discussed for neutrino detection. Soon, the largest air shower array will be the AUGER [11] experiment including some 3000 km$^2$ active area. However, since the column density of air is about 10 m, the instrumented mass corresponds to only about 0.03 Eg. The mass shown in Figure 3 accounts for the efficiency to detect neutrino induced cascades via the ground array [11]. Air showers may also be detected via fluorescence techniques. To increase area, OWL [12]/EUSO [13] have proposed to look down on $\sim 1000 \times 1000$ km$^2$ of atmosphere from Earth orbit. The effective mass shown in the figure includes a 0.1 efficiency factor to include duty cycle and constraints on interaction depth and zenith angle so that the air shower can both fully develop and be cleanly separated from cosmic ray induced air showers. With these factors, space based fluorescence

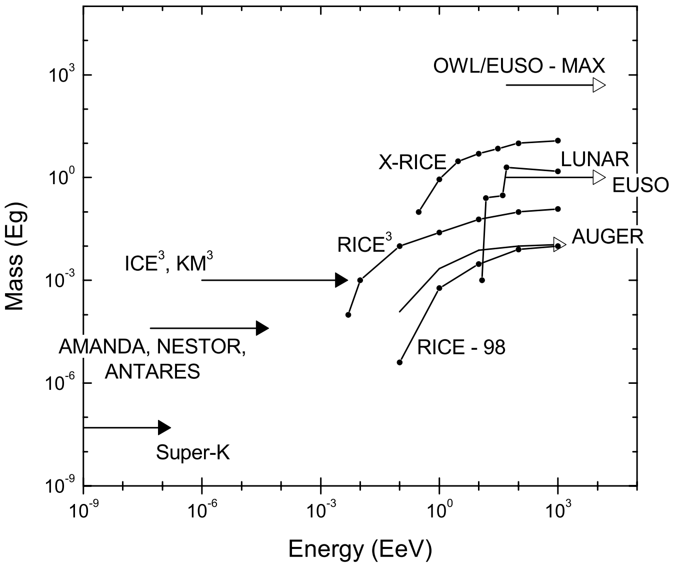

**FIGURE 3.** Effective mass of experiments proposed for detection of high energy neutrinos, as a function of neutrino energy. Experiments based on optical Cherenkov in water or ice are labeled by filled arrowheads. Open arrowheads denote air shower techniques. Radio Cherenkov experiments have dots overlayed and no arrowhead.

techniques can provide 1 Eg of detector mass. However, if the indicated threshold of $5 \times 10^{19}$ eV [13] is sharp, then using the ES flux would result in just 1 $\nu_e$ charged current event per yr, and less than one of other event types assuming that only the hadronic recoil is visible. For amusement, "OWL/EUSO Max" refers to the total mass of the atmosphere utilized with 10% efficiency.

A third option is to detect neutrinos through the coherent radio Cherenkov emission from the showers produced by neutrino interactions. Hopefully, it is not necessary, at this conference, to summarize the basic ideas behind the radio detection of high energy particles. One radio based technique involves the search for radio flashes from events in the lunar crust [14]. The effective mass shown in the figure is due to Alvarez-Müniz [15]. It falls somewhat short of the mass and energy thresholds required for GZK neutrino detection. Additionally, only those events that occur well away from the limb of the moon will be separable from more frequent cosmic ray events causing similar signals.

The figure also shows sensitivity for experiments based on the technique of deploying radio antennas in ice at the South Pole [16] (RICE). RICE-98 [17] shows the effective mass of the current pioneering effort as configured at the end of the 98 polar season. RICE$^3$ depicts an array as may be deployed with Icecube. The lower threshold for RICE$^3$ arises from a relatively dense spacing of over 300 radio antennas. The largest version, X-RICE, is a $10^4$ km$^2$ array suggested for the detection of GZK neutrinos. The result shown is for antennas on a rectangular grid of 1 km spacing [18]. 1 Eg of effective mass is achieved for $E > 1$ EeV. Increasing the antenna density tenfold lowers the threshold, and allows a 1 Eg detector from 1000

$km^2$ of ice. (This is about 50% efficiency since the ice is 2 km thick.) Allowing for detection of only electromagnetic and hadronic showers, such a detector would obtain approximately 30 $\nu_e$ and 25$\nu_\mu$ charged current, and 15 neutral current events from the Engel and Stanev GZK flux.

To summarize, optical Cherenkov experiments are too small, or too expensive, to ensure detection of GZK neutrinos. Air shower techniques require $10^5$ $km^2$ for particle detectors or $10^6$ $km^2$ for fluorescence detectors due to the low density of air, beyond the scope of current ground based efforts. Space based fluorescence experiments, as proposed, do not have a low enough threshold to detect GZK neutrinos. The lunar radio technique also has too high a threshold. Only the RICE technique seems to offer a suitable combination of mass and threshold to detect GZK neutrinos at the rate of $\sim$ 100 neutrinos per yr.

## DEPLOYMENT STRATEGIES WITH ICECUBE

The main difficulties with RICE are a) demonstrating that the physics of the technique is correctly described, b) establishing a calibration system for a deployed experiment, and c) overcoming the technical challenges of deploying on a remote basis up to 100 km from South Pole. (a) Recent experimental work by Saltzberg and collaborators [19], and continuing theoretical efforts on several fronts [20,21] suggests that the basic physics is sound, although there is still room for refinement. (b) One of the main points behind the $RICE^3$ plan is to provide explicit verification and calibration of a deployed experiment. (c) No serious work.

There are some flaws with the $RICE^3$ concept. First, Icecube is targeted toward detection of AGN neutrinos in the PeV region. Even with dense deployment, $RICE^3$ barely reaches below 10 PeV, although more sophisticated designs may improve on this situation. Second, the detectors do not really overlap. Optical transparency (bubbles) demands that Icecube be deployed in the bottom kilometer of ice, while radio transparency (geothermal warming) demands that RICE be deployed in the top kilometer. Since the Earth is opaque, most events in Icecube come from above or the side. The geometry of such events is such that the radio Cherenkov cone does not intersect a RICE array deployed above Icecube for most event vertecies contained in Icecube. The best geometry for coincident detection is charged current $\nu_\mu$ interactions where the muon passes through Icecube and $RICE^3$ gets the Cherenkov cone from the hadronic shower. For each zenith angle and impact parameter there is of order a linear km along the line of sight where the event geometry will satisfy this condition. Total effective overlap is about 1 $km^3$. Third, little progress is taken towards difficulty (c). Fourth, there may, in fact, be no AGN neutrinos, and fifth Icecube still cannot expect to see GZK neutrinos other than straggler external muons.

An alternative deployment strategy is to make $RICE^3$ look like the central part of X-RICE, i.e. deploy $\sim$ 100 antennas over 100 $km^2$ centered on Icecube. First off, such a deployment directly addresses difficulty (c). Second, such an array would provide vertex information for throughgoing muons detected by Icecube, allowing energy calibration of those events. Third, such an array would detect $\sim$ 10 GZK neutrinos per yr, which would be a significant discovery. On the down side, the threshold for radio detection would rise, so potential overlap for 10 PeV AGN neutrinos is eliminated. Also, it seems that overlapping detection of GZK neutrinos still seems unlikely. Simple geometry considerations indicate that none of the ten GZK events are likely to be detected by Icecube.

Which deployment strategy is better? In either case one cannot rely on the GZK neutrinos for calibration of RICE, even utilizing throughgoing muons. A bright AGN flux seems somewhat more likely than a bright flux in excess of GZK expectations at EeV energies. If neither bright option is present, then an independent confirmation and calibration of the radio technique is in order. Once achieved, the X-RICE prototype would likely give a first look at GZK neutrinos, while providing a technology development platform for the full X-RICE. On the other hand, the compact $\mathrm{RICE}^3$ lacks the sensitive volume for GZK detection, and would leave unsolved the daunting technical problems of a large area Antarctic deployment.

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## REFERENCES

1. Yoshida, S. and M. Teshiima, Prog. Theor. Phys. 89, 833 (1993).
2. Engel, R., and T. Stanev, astro-ph/0101216, (2001).
3. Waxman, E., Astrophys. J., 452, L1 (1995).
4. Gaisser, T.K., astro-ph/0011524, astro-ph/0011525 (2000).
5. Gandhi, R., C. Quigg, H. Reno, I. Sarkevic, Astropart. Phys. 5, 81 (1996).
6. Gandhi, R., C. Quigg, H. Reno, I. Sarkevic, Phys. Rev. D58 (093009) (1998).
7. Glück, M., S. Kretzer, and E. Reya, Astropart. Phys. 11, 327 (1999).
8. Kwiecinski, J., A.D. Martin, and A.M. Staso, Phys. Rev. D59, 093002 (1999).
9. Dutta, S.I., et al., Phys. Rev. D, In press. (astro-ph/0012350) (2001).
10. `http://amanda.berkeley.edu/amanda/amanda.html` (2001).
11. `http://www.auger.org/` (2001).
12. `http://owl.gsfc.nasa.gov/` (2001).
13. `http://www.ifcai.pa.cnr.it/~EUSO/` (2001).
14. Gorham, P.W., K.M. Liewer and C.J. Naudet, Proceedings 26th Int. Cos. Ray Conf., Salt Lake City (astro-ph/9906504) (1999).
15. Alvarez-Muniz, J. These proceedings, astro-ph/0102173. (2000).
16. Frichter, G., J. Ralston and D. McKay, Phys. Rev. D 53, 1684 (1996).
17. `http://kuhep4.phsx.ukans.edu/~iceman/index.html` (2001).
18. Seckel, D. and G. Frichter, Proc. 26th Int. Cos. Ray Conf., Salt Lake City (1999).
19. Saltzberg, D., et al., astro-ph/0011001 (2000).
20. Buniy, R.V. and J. Ralston, Phys. Rev. D, in Press, astro-ph/0003408 (2000).
21. Alvarez-Muniz, J. and E. Zas, Phys. Lett. B 411, 218 (1997); Phys. Lett. B 434, 396 (1998); Phys. Rev. D62, 063001 (2000).