Updated Limits on the Ultra-High-Energy Neutrino Flux from the RICE Experiment at the South Pole

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Abstract

We describe an updated search for ultra-high energy (UHE) neutrinos based on detection of radio-wavelength Cherenkov radiation resulting from neutrino-induced electromagnetic showers in cold Polar ice. We present upper limits on the UHE ν flux based on analysis of 1999-2001 data.

Introduction and Methods

The RICE experiment has goals similar to the larger AMANDA experiment - both seek to measure UHE neutrinos by detection of Cherenkov radiation produced by $\nu_l + N \rightarrow l + N'$. Whereas AMANDA is optimized for detection of penetrating muons resulting from $\nu_\mu + N \rightarrow \mu + N'$, RICE is designed to detect compact electromagnetic cascades initiated by $e^+(/e^-)$: $\nu_e(/\overline{\nu}_e) + N \rightarrow e^\pm + N'$. As the cascade develops, atomic electrons in the target medium are swept into the forward-moving shower, resulting in a net charge on the shower front of $Q_{tot} \sim E_s e/4$; E_s is the shower energy in GeV[4]. Such cascades produce broadband Cherenkov radiation – for $\lambda_{E-field}^{Cherenkov} >> r_{Moliere}$, the emitting region approximates a point charge of magnitude Q_{tot} and therefore emits fully coherently; fortuitously, the field attenuation length at such wavelengths $\sim$1 km. One calculation finds[3] that, for 1 PeV$< E_{\nu_e}$, radio detection of cascades becomes more cost-effective than PMT-based techniques. Using calculations presented elsewhere of the expected radio-frequency signal strength due to an electromagnetic shower[10,14], the RICE hardware, reconstruction software and simulation[5], and an initial ν_e-only analysis based on data taken in August, 2000[6], we now report on an expanded neutrino search based on all data taken in 1999, 2000, and 2001.

The RICE experiment presently consists of a 20-channel (16-channel for

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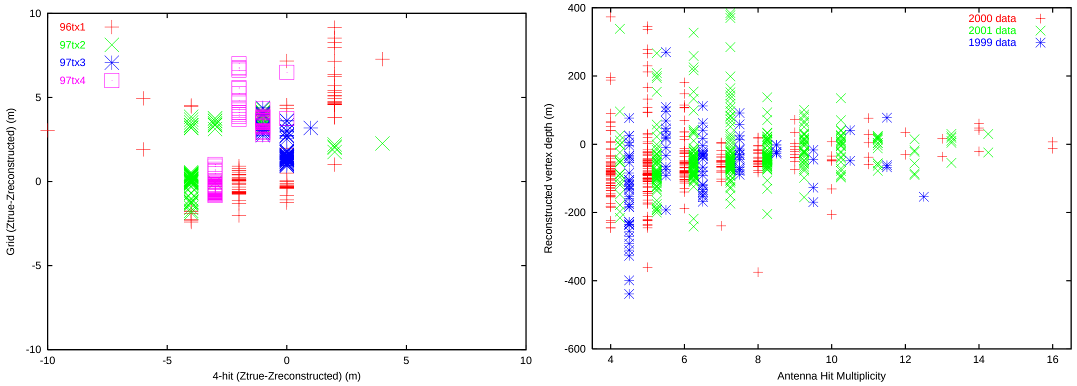

Fig. 1. Left (a): Deviation between true depth and reconstructed depth for four separate transmitters, for the two source reconstruction codes; Right (b): Distribution of reconstructed z-vertex vs. hit multiplicity for 1999, 2000, 2001 data, using analytic vertex reconstruction algorithm. Each point represents ∼50 events.

the data discussed herein) array of dipole radio receivers ("Rx"), scattered within a 200 m×200 m×200 m cube, at 100-300 m depths. The signal from each antenna is boosted by a 36-dB in-ice amplifier, then carried by coaxial cable to the surface observatory, where the signal is filtered (suppressing noise below 200 MHz), re-amplified (either 52- or 60-dB gain), and split - one copy is fed into a CAMAC crate to form the event trigger; the other signal copy is routed into one channel of an HP54542 digital oscilloscope. Short-duration pulses broadcast from under-ice transmitters provide the primary calibration signals, and are used to verify vertex reconstruction techniques. Figure 1a) illustrates the vertex reconstruction performance for our calibration transmitter data (transmitters are typically 100-200 m from receivers) using two vertex-reconstruction algorithms. One algorithm searches a cubic km. grid around the array for the source point most consistent with the observed hit times; the second technique analytically solves for the vertex using four-hit subcombinations of all the available hits. Typical differences between reconstructed and known depths are of the order a few meters. For non-calibration events, we expect reconstructed source vertices to cluster around the surface; smearing effects due to ray tracing through the firn may be considerable. Figure 1b) displays the reconstructed source depth for our "general" triggers for various hit multiplicities; source depths are observed to peak towards z=0 (consistent with surface anthropogenic activity).

To select neutrinos, we require events to: a) have at least 4 channels registering 5.5σ excursions in their waveforms, b) pass quality-of-vertex cuts, c) have reconstructed vertex depths below 150, c) a hit geometry consistent(/inconsistent) with a conically-(/spherically-) emitting source. Five candidate events pass all software filters; for all five events, hand-scanning reveals at least one hit clearly inconsistent with the time domain antenna response expected for a true neutrino.

After elimination of such spurious hits identified in the visual scan, all five candidate events reconstruct near the surface. Monte Carlo simulated waveforms (superimposed upon noise taken from data) are used to determine event selection efficiencies. Table 1 presents the results of our search.

Results and Discussion

Given the known experimental circuit gains and losses[5], the effective volume V_{eff} is calculated as a function of incident E_ν, as an exposure average of the detector configurations. The most important variable is the global discriminator threshold, which is adjusted to maintain an acceptable trigger rate under conditions of varying environmental noise. Knowing the total livetime for the full dataset (3300 hours), and based on observation of zero candidates, we calculate (Figure 2) an upper limit on the incident ν flux, as a function of incident energy.

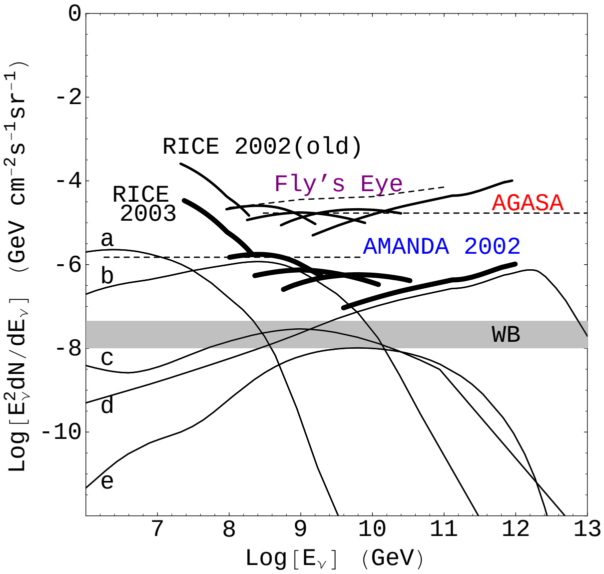

Figure 2) Neutrino flux model predictions (thin solid) and corresponding RICE calculated upper limits (95% confidence level; thick solid), as a function of E_ν. Predictions are: (a)=Stecker & Salamon[11] (b)=Protheroe[9], (c)=Mannheim (A)[7], (d)=Protheroe & Stanev[9], (e)=Engel *et al.* GZK-model.[3]; also shown is the Waxman-Bahcall upper-limit[12] (grey). Superimposed are also older upper limits from RICE, as well as the AMANDA[1] (old; an extended analysis should improve sensitivity ×10[4]) , AGASA[13], and the Fly's Eye experiments[2] (dashed).

Improvements in the RICE upper limit over the previous limit result from a nearly order-of-magnitude increase in the exposure, as well as inclusion of ν-induced hadronic showers.

Discussion

In addition to searches for neutrinos, the RICE detector offers sensitivity to other analyses (monopole detection, studies of neutrinos coincident with GRB's and air showers, searches for micro-black holes, etc.); results of such searches will be reported in the future. The 2002 and 2003 datasets comprise our highest-quality data thus far and should offer substantial improvement over the results presented herein. Beginning in 2004, we hope to take advantage of the scientific opportunity presented by IceCube hole drilling to substantially expand the current RICE array.

Cut imposed	Surviving Data Events (1999/2000/2001)	MC events left
Total triggers	297512/111586842/3174390	400
Passing surface veto	12674/406867/97357	400
Passing $4 \times 5.5\sigma_V$ cuts	393/3985/1464	400
(Z< -150 m) cut	5/33/18	396
Conical geometry	0/3/2	378
Passing Scanning	0/0/0	376

Table 1. Summary of 1999-2001 data analysis.

Acknowledgments

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