29th International Cosmic Ray Conference Pune (2005) **00**, 101–106

Simulation of a Hybrid Optical/Radio/Acoustic Extension to IceCube for EeV Neutrino Detection

D. Besson[a], S. Böser[b], R. Nahnhauer[b], P.B. Price[c], and
J. A. Vandenbroucke[c] (justin@amanda.berkeley.edu) for the IceCube Collaboration
(a) Dept. of Physics and Astronomy, University of Kansas, Lawrence, KS 66045-2151, USA
(b) DESY, D-15738 Zeuthen, Germany
(c) Dept. of Physics, University of California, Berkeley, CA 94720, USA
Presenter: R. Nahnhauer, ger-nahnhauer-R-abs1-og25-oral

Astrophysical neutrinos at ∼EeV energies promise to be an interesting source for astrophysics and particle physics. Detecting the predicted cosmogenic ("GZK") neutrinos at 10^{16} - 10^{20} eV would test models of cosmic ray production at these energies and probe particle physics at ∼100 TeV center-of-mass energy. While IceCube could detect ∼1 GZK event per year, it is necessary to detect 10 or more events per year in order to study temporal, angular, and spectral distributions. The IceCube observatory may be able to achieve such event rates with an extension including optical, radio, and acoustic receivers. We present results from simulating such a hybrid detector.

1. Introduction

Detecting and characterizing astrophysical neutrinos in the 10^{16} eV to 10^{20} eV range is a central goal of astro-particle physics. The more optimistic flux models in this range involve discovery physics including topological defects and relic neutrinos. Detecting the smaller flux of cosmogenic (or Greisen, Zatsepin, and Kusmin, "GZK") neutrinos produced via ultra-high energy cosmic ray interaction with the cosmic microwave background would test models of cosmic ray production and propagation and of particle physics at extreme energies. With ∼100 detected events, their angular distribution would give a measurement of the total neutrino-nucleon cross section at ∼100 TeV center of mass, probing an energy scale well beyond the reach of the LHC. Hence, as a baseline, a detector capable of detecting ∼10 GZK events per year has promising basic physics potential. If any of the more exotic theories predicting greater EeV neutrino fluxes is correct, the argument in favor of such a detector is even stronger.

To detect ∼10 GZK events per year, a detector with an effective volume of ∼100 km^3 at EeV energies is necessary. In addition to the possibility of identifying neutrino-induced inclined air showers, there are three methods of ultra-high energy neutrino detection in solid media: optical, radio, and acoustic. Optical Cherenkov detection is a well-established technique that has detected atmospheric neutrinos up to 10^{14} eV and set limits up to 10^{18} eV [1]. Radio efforts have produced steadily improving upper limits on neutrino fluxes from 10^{16} eV to 10^{25} eV [2]. Acoustic detection efforts are at an earlier stage, with one limit published thus far from 10^{22} to 10^{25} eV [3].

The currently planned 1 km^3 optical neutrino telescopes expect a GZK event rate of ∼1 per year. It is possible to extend this by adding more optical strings for a modest additional cost [4], but it's difficult to imagine achieving 10 or more events per year with optical strings alone. The radio and acoustic methods have potentially large effective volumes with relatively few receivers, but the methods are unproven in that they have never detected a neutrino. Indeed, if radio experiments claim detection of a GZK signal, it may be difficult to confirm that it is really a neutrino signal. However, it may be possible to bootstrap the large effective volumes of radio and acoustic detection with the optical method, by building a hybrid detector that can detect a large rate of radio or acoustic events, a fraction of which are also detected by an optical detector. A signal seen in coincidence between any two of the three methods would be convincing. The information from multiple methods can be combined for hybrid reconstruction, yielding improved angular and energy resolution.

We simulated the sensitivity of a detector that could be constructed by expanding the IceCube observatory currently under construction at the South Pole. The ice at the South Pole is likely well-suited for all three methods: Its optical clarity has been established by the AMANDA experiment [1], and its radio clarity and suitability for radio detection in the GZK energy range has been established by the RICE experiment [2]. Acoustically, the signal in ice is ten times greater than that in water. Theoretical estimates indicate low attenuation and noise [5], and efforts are planned to measure both [6] with sensitive transducers developed for glacial ice [7]. Here we estimate the sensitivity of such a detector by exposing all three components to a common Monte Carlo event set and counting events detected by each method alone and by each combination of multiple methods.

2. Simulation

IceCube will have 80 strings arrayed hexagonally with a horizontal spacing of 125 m. In [4], the GZK sensitivity achieved by adding more optical strings at larger distances ("IceCube-Plus") was estimated, and the possibility of also adding radio and acoustic modules was mentioned. Here we consider an IceCube-Plus configuration consisting of a "small" optical array overlapped by a "large" acoustic/radio array with a similar number of strings but larger horizontal spacing. The optimal string spacing for GZK detection was found to be $\sim$1 km for both radio and acoustic strings. This coincidence allows the two methods to share hole drilling and cable costs, both of which are dominant costs of such arrays.

The geometry of the simulated array is shown in Fig. 1. We take the optical array to be IceCube as well as a ring of 13 optical strings with a 1 km radius, surrounding IceCube. All optical strings have standard IceCube geometry: 60 modules per string, spaced every 17 m, from 1.4 to 2.4 km depth. Encompassing this is a hexagonal array of 91 radio/acoustic strings with 1 km spacing. Each radio/acoustic hole has 5 radio receivers, spaced every 100 m from 200 m to 600 m depth, and 300 acoustic receivers, spaced every 5 m from 5 m to 1500 m depth. At greater depths both methods suffer increased absorption due to the warmer ice. The large acoustic density per string is necessary because the acoustic radiation pattern is thin (only $\sim$10 m thick) in the direction along the shower. The array geometry was designed to seek an event rate of $\sim$10 GZK events per year detectable with both radio and acoustic independently. To obtain rough event rate estimates, a very simple Monte Carlo generation scheme was chosen. Between 10^{16} and 10^{20} eV, the neutrino interaction length ranges between 6000 and 200 km [8], so upgoing neutrinos are efficiently absorbed by the Earth and only downgoing events are detectable. A full simulation would include the energy-dependent slow rolloff at the horizon. Here we assume all upgoing neutrinos are absorbed before reaching the fiducial volume, and no downgoing neutrinos are; we generate incident neutrino directions isotropically in 2π sr. Vertices are also generated uniformly in a fiducial cylinder of radius 10 km, extending from the surface to 3 km depth.

The Bjorken parameter $y = E_{had}/E_{\nu}$ varies somewhat with energy and from event to event, but we choose the mean value, $y = 0.2$, for simplicity. The optical method can detect both muons and showers, but here we only consider the muon channel; simulation of the shower channel is in progress. The radio and acoustic methods cannot detect muon tracks but can detect electromagnetic and hadronic showers. Under our assumptions of constant y and no event-to-event fluctuations, all flavors interacting via both CC and NC produce the same hadronic shower. Electron neutrinos interacting via the charged current also produce an electromagnetic cascade which produces radio and acoustic signals superposed on the hadronic signals. However, at the energies of interest here, electromagnetic showers are lengthened to hundreds of meters by the Landau-Pomeranchuk-Migdal effect. This weakens their radio and acoustic signals significantly, and we assume they are negligible.

For simulation of the optical response, the standard Monte Carlo chain used in current AMANDA-IceCube

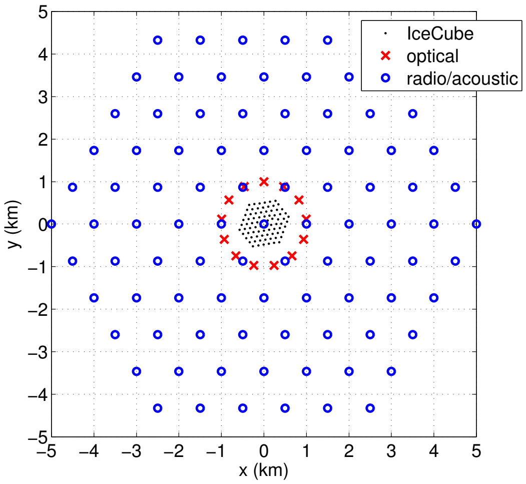

Figure 1. Geometry of the simulated hybrid array.

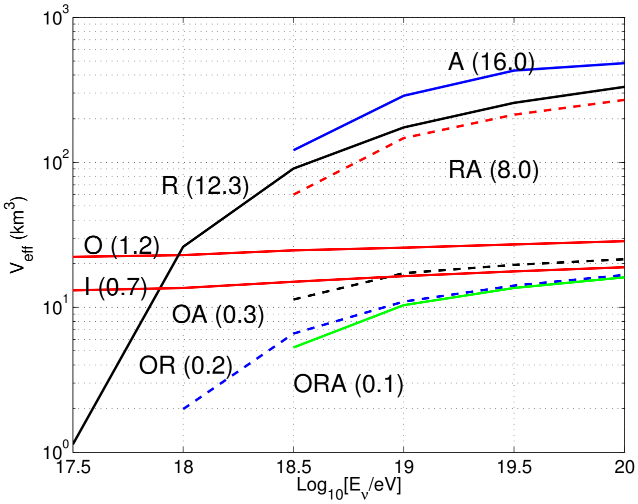

Figure 2. Effective volume for each of the seven combinations of detector components, as well as for IceCube alone ("I"). GZK event rates per year are given in parenthesis. Note that different channels were used for different combinations (see text).

analyses [1] was performed. After the primary trigger requiring any 5 hits in a 2.5 μs window, a local coincidence trigger was applied: Ten local coincidences were required, where a local coincidence is at least two hits on neighboring or next-to-neighboring modules within 1 μs. Compared with [4], we used an updated ice model with increased absorption, which may account for our factor of $\sim$2 lower effective volume.

Each simulated radio "receiver" consists of two vertical half-wave dipole antennas separated vertically by 5 m to allow local rejection of down-going anthropogenic noise. We assume an effective height at the peak frequency (280 MHz in ice) equal to 10 cm, with ±20% bandwidth to the –3 dB points. As currently under development for RICE-II, we assume optical fiber transport of the signal to the DAQ, with losses of 1 dB/km (measured) through the fiber. The electric field strength $E(\omega)$ is calculated from the shower according to the ZHS prescription [9, 10]. Frequency-dependent ice attenuation effects are incorporated using measurements at South Pole Station [11]. The signal at the surface electronics is then transformed into the time domain, resulting in a waveform 10 ns long, sampled at 0.5 ns intervals, at each antenna. Two receivers with signals exceeding 3.5 times the estimated rms noise temperature σ_{kT} (thermal plus a system temperature of 100 K) within a time window of 30 μs are required to trigger.

The unattenuated acoustic pulse $P(t)$ produced at arbitrary position with respect to a hadronic cascade is calculated by integrating over the cascade energy distribution. The cascade is parametrized with the Nishimura-Kamata-Greisen parametrization, with λ (longitudinal tail length) parametrized from [10]. The dominant mechanism of acoustic wave absorption in South Pole ice is theorized [5] to be molecular reorientation, which increases with ice temperature. Using a temperature profile measured at the South Pole along with laboratory absorption measurements, an absorption vs. depth profile was estimated. The predicted absorption length ranges from 8.6 km at the surface to 4.8 km at 1 km depth to 0.7 km at 2 km depth. The frequency-independent absorption is integrated from source to receiver and applied in the time domain.

South Pole ice is predicted to be much quieter than ocean water at the relevant frequencies ($\sim$10-60 kHz), because there are no waves, currents, or animals. Anthropogenic surface noise will largely be waveguided back up to the surface due to the sound speed gradient in the upper 200 m of uncompactified snow ("firn"). For the current simulation we assume ambient noise is negligible compared to transducer self-noise. Work is underway to produce transducers with self-noise at the 2-5 mPa level [7]. For comparison, ambient noise in the ocean is $\sim$100 mPa [3]. The acoustic trigger used in this simulation required that 3 receivers detect pressure pulses above a threshold of 9 mPa.

3. Results and Conclusion

Ten-thousand events were generated at each half-decade in neutrino energy in a cylinder of volume 942 km^3. For each method and combination of methods, the number of detected events was used to calculate effective volume as a function of neutrino energy (Fig. 2). This was folded with the GZK flux model of [12, 13] and the cross-section parametrizations of [8] to estimate detectable event rates (Fig. 2). We use a flux model which assumes source evolution according to $\Omega_\Lambda = 0.7$. This model is a factor of $\sim$2 greater than that for $\Omega_\Lambda = 0$ evolution; it is unclear which model is correct [13]. For radio and acoustic, and their combination, all flavors and both interactions were included. For those combinations including the optical method, only the muon channel has been simulated thus far; including showers will increase event rates for these combinations.

It may be possible to build an extension like that considered here for a relatively small cost. Holes for radio antennas and acoustic transducers can be narrow and shallow, and both devices are simpler than photo-multiplier tubes. The necessarily large acoustic channel multiplicity is partially offset by the fact that the acoustic signals are slower by five orders of magnitude, making data acquisition and processing easier.

The IceCube observatory will observe the neutrino universe from 10's of GeV to 100's of PeV. Our simulations indicate that extending it with radio and acoustic strings could produce a neutrino detector competitive with other projects optimized for high-statistics measurements of GZK neutrinos but with the unique advantage of cross-calibration via coincident optical-radio, optical-acoustic, and radio-acoustic events.

References

[1] K. Woschnagg for the AMANDA Collaboration, Nucl. Phys. B 143, 343 (2005).
M. Ackermann et al., Astropart. Phys. 22, 339 (2005).
[2] I. Kravchenko et al., Astropart. Phys. 20, 195 (2003).
P. Gorham et al., Phys. Rev. Lett. 93, 041101 (2004).
N. Lehtinen et al., Phys. Rev. D 69, 013008 (2004).
[3] J. Vandenbroucke, G. Gratta, and N. Lehtinen, ApJ. 621, 301 (2005).
[4] F. Halzen and D. Hooper, J. Cosmol. Astropart. Phys. 01, 002 (2004).
[5] P. B. Price, astro-ph/0506648.
[6] S. Böser et al., IceCube internal note.
S. Böser, ARENA workshop, http://www-zeuthen.desy.de/arena
[7] S. Böser et al., these proceedings.
[8] R. Gandhi et al., Phys. Rev. D 58, 093009 (1998).
[9] E. Zas, F. Halzen, and T. Stanev, Phys. Lett. B 257, 432 (1991).
E. Zas, F. Halzen, and T. Stanev, Phys. Rev. D 45, 362 (1992).
[10] J. Alvarez-Muñiz and E. Zas, Phys. Lett. B 434, 396 (1998).
[11] S. Barwick, D. Besson, P. Gorham, and D. Saltzberg, to appear in J. Glac.
[12] R. Engel, D. Seckel, and T. Stanev, Phys. Rev. D 64, 093010 (2001).
[13] R. Engel, D. Seckel, and T. Stanev, ftp://ftp.bartol.udel.edu/seckel/ess-gzk/