From the First Neutrino Telescope, the Antarctic Muon and Neutrino Detector Array AMANDA, to the IceCube Observatory

F. Halzen, for the AMANDA Collaboration

E. Andres[11], P. Askebjer[4], G. Barouch[8], S. W. Barwick[6], X. Bai[11], K. Becker[9], R. Bay[5], L. Bergström[4], D. Bertrand[12], D. Besson[13], A. Biron[2], J. Booth[6], O. Botner[14], A. Bouchta[2], S. Carius[3], M. Carlson[8], W. Chinowsky[10], D. Chirkin[5], J. Conrad[14], C. Costa[8], D. F. Cowen[7], E. Dalberg[4], J. Dewulf[12], T. DeYoung[8], J. Edsjö[4], P. Ekström[4], G. Frichter[13], A. Goobar[4], L. Gray[8], A. Hallgren[14], F. Halzen[8], Y. He[5], R. Hardtke[8], G. Hill[8], P. O. Hulth[4], S. Hundertmark[2], J. Jacobsen[10], V. Kandhadai[8], A. Karle[8], J. Kim[6], B. Koci[8], M. Kowalski[2], I. Kravchenko[13], J. Lamoureux[10], P. Loaiza[14], H. Leich[2], P. Lindahl[3], T. Liss[5], I. Liubarsky[8], M. Leuthold[2], D. M. Lowder[5], J. Ludvig[10], P. Marciniewski[14], T. Miller[1], P. Miocinovic[5], P. Mock[6], F. M. Newcomer[7], R. Morse[8], P. Niessen[2], D. Nygren[10], C. Pérez de los Heros[14], R. Porrata[6], P. B. Price[5], G. Przybylski[10], K. Rawlins[8], W. Rhode[5], S. Richter[11], J. Rodriguez Martino[4], P. Romenesko[8], D. Ross[6], H. Rubinstein[4], E. Schneider[6], T. Schmidt[2], R. Schwarz[11], A. Silvestri[2], G. Smoot[10], M. Solarz[5], G. Spiczak[1], C. Spiering[2], N. Starinski[11], P. Steffen[2], R. Stokstad[10], O. Streicher[2], I. Taboada[7], T. Thon[2], S. Tilav[8], M. Vander Donckt[12], C. Walck[4], C. Wiebusch[2], R. Wischnewski[2], K. Woschnagg[5], W. Wu[6], G. Yodh[6], S. Young[6]

(1) Bartol Research Institute, University of Delaware, Newark, DE, USA
(2) DESY-Zeuthen, Zeuthen, Germany
(3) Dept. of Physics, Kalmar University, Sweden
(4) Dept. of Physics, Stockholm University, Stockholm, Sweden
(5) Dept. of Physics, UC Berkeley, Berkeley, CA, USA
(6) Dept. of Physics, UC Irvine, Irvine, CA, USA
(7) Dept. of Physics, University of Pennsylvania, Philadelphia, PA, USA
(8) Dept. of Physics, University of Wisconsin, Madison, WI, USA
(9) Dept. of Physics, University of Wuppertal, Wuppertal, Germany
(10) Lawrence Berkeley Laboratory, Berkeley, CA, USA
(11) South Pole Station, Antarctica
(12) ULB - IIHE - CP230, Boulevard du Triomphe, B-1050 Bruxelles, Belgium
(13) University of Kansas, Lawrence, KS, USA
(14) University of Uppsala, Uppsala, Sweden

Abstract

With an effective telescope area of order 10,000 meter squared for very high energy neutrinos, a threshold near 50 GeV and a pointing accuracy of 2.5 degrees per muon track, the AMANDA detector represents the first of a new generation of high energy neutrino telescopes, reaching a scale envisaged over 25 years ago. We describe the calibration of natural deep ice as a particle detector as well as AMANDA's performance as a neutrino telescope. We discuss its expansion to AMANDA II in the coming Antarctic summer and, subsequently, to a kilometer-scale detector ICECUBE.

1 Introduction: Multidisciplinary Science

The excellent scientific infrastructure of the U. S. Amundsen-Scott South Pole Station, soon to be modernized and expanded and situated on kilometers of extraordinarily transparent ice, provides us with the unique opportunity to study the history and nature of the Universe in a novel way (Gaisser, Halzen, & Stanev 1995; Protheroe 1998; Gandhi et al. 1996). Using optical sensors buried in the deep clear ice, the expanded AMANDA collaboration proposes to attack major problems in astronomy, astrophysics, cosmic ray physics and particle physics by building the IceCube observatory. According to estimates covering a wide range of scientific objectives, a neutrino telescope with effective telescope area of 1 kilometer squared is required to address the most fundamental questions (Halzen 1994 & 1996). Planning is already underway to instrument a cubic volume of ice, 1 kilometer on the side, as a neutrino detector.

Many of the outstanding mysteries of astrophysics may be hidden from sight at any wavelength of the electromagnetic spectrum by the matter and radiation between Earth and the source. Among the many problems which a high energy neutrino telescope will address are the origin of cosmic rays, the engines which power active galaxies, and the nature of gamma ray bursts. We will search for the annihilation products of halo cold dark matter particles, galactic supernovae and, more speculatively, the birth of the supermassive black holes which power quasars. Coincident experiments with earth- and space-based gamma ray telescopes, cosmic ray observatories and gravitational wave detectors such as LIGO can be contemplated. The best justification for creating the IceCube high-energy neutrino observatory is based on history: the opening of each new astronomical window has led to unexpected discoveries.

Although traditionally Nature has been more imaginative than scientists, active galactic nuclei (AGN) and gamma ray bursts (GRB) must be considered well-motivated sources of high energy neutrinos simply because they are the sources of the most energetic photons. They may also be the accelerators of the highest energy cosmic rays. If they are, their neutrino flux can be calculated in a relatively model-independent way because the proton beam will photoproduce pions and, therefore, neutrinos on the high density of photons in the source. We have a beam dump configuration where both the beam and target are constrained by observation: the beam by the observed cosmic ray spectrum and the photon target by astronomical measurements of the high energy photon flux. Based on modelling of AGN and GRBs, we anticipate order 10 neutrinos per year will be detected from such sources with a 1 km^2 telescope. The neutrino energies cluster indeed in the vicinity of 100 TeV for GRBs and 100 PeV for neutrinos originating in AGN jets. These estimates are rather uncertain and in some models one obtains much higher rates. The effective area of a detector instrumented over 1 km should be larger for such high energy events.

With cosmological sources such as active galaxies and GRBs we will be observing ν_e and ν_μ neutrinos over a baseline of 10^3 Megaparsecs. Above 1 PeV these are absorbed by charged-current interactions in the Earth before reaching the detector at the opposite surface. However, the earth never becomes opaque to ν_τ since the τ^- produced in a charged-current ν_τ interaction decays back into ν_τ before losing significant energy. This penetration of tau neutrinos through the Earth provides an experimental signature for neutrino oscillations. The appearance of a ν_τ component in a pure $\nu_{e,\mu}$ beam would be evident because the source intensity would be independent of the zenith of the source, even at the highest neutrino energies where $\nu_{e,\mu}$, on the contrary, are absorbed by the Earth. Such a flat zenith angle dependence for the farthest sources is a signature for tau neutrino mixing with a sensitivity to Δm^2 as low as 10^{-17} eV^2 for large mixing angles. With IceCube we will also search for ultrahigh-energy neutrino signatures from topological defects and magnetic monopoles; for properties of neutrinos such as mass, magnetic moment, and flavor-oscillations; and for clues to entirely new physical phenomena. The potential of neutrino “telescopes" to do particle physics is evident.

2 From AMANDA to IceCube

Currently, the only proven technology to build a neutrino detector in a reliable, expandable and affordable way is to look for Cherenkov radiation associated with secondary electrons and muons in ice. With an effective telescope area of order 10^4 m^2 (the area actually ranges from several times 10^3 m^2 for atmospheric neutrinos – produced by cosmic rays interacting in Earth's atmosphere – to a larger area for the high energy neutrinos from gamma ray bursts) the operating AMANDA detector represents the first of a new generation of high energy neutrino telescopes to reach a scale which has been a community goal for over 25 years.

The most striking demonstration of the quality of natural ice as a Cherenkov detector medium is the observation of atmospheric neutrinos with the partially deployed AMANDA detector in data taken with only eighty 8 inch photomultiplier tubes. Analysis of 6 months of data obtained with the first 80 deep optical modules, a subset of the existing $\sim$400, has demonstrated the capability to reject the background of downgoing cosmic ray muons to the level required to identify up-going muons generated by atmospheric neutrinos. Despite the fact that the rates are extremely low with only several events per year, reconstructed up-going muons are found at a rate consistent with the expected flux of atmospheric neutrinos (AMANDA 1999). Preliminary analysis of the 1997 data taken with the full detector has produced neutrino candidates at a rate of about 10^2 per year. All features of the neutrino events, including the observed rate, are consistent with expectations from Monte Carlo simulation of the atmospheric neutrino flux (Karle 1999). The first search for neutrinos from point sources, gamma ray bursts, and for a cold dark matter signal from the center of the Earth, are in progress.

3 Technology

In early 1998 three 2,400 m deep strings, with optical modules spread over the lowest kilometer, were deployed. They allow us to test a variety of technologies for IceCube. The 3 strings also form part of an intermediate detector, AMANDA II, which will almost double the photocathode area of the present detector, and result in a more symmetric acceptance. It will be completed in 99-00 with the addition of six more strings. Construction of IceCube will be staged over approximately five deployments (possibly 01-02 to 05-06; reducing this time period by using “summer camps" for drilling crews is under study) of 16 strings per year for a total of $\sim$5000 optical modules. A straw-man design for IceCube calls for 60 to 100 photomultipliers (PMT) per hole, instrumented with phototubes from $\sim$1.5 to 2.5 km, with 80 holes spaced laterally by 100 m.

All data analysis this far has been performed with photomultiplier signals transmitted to the surface over coaxial or twisted pair electrical cables. The amplitude of the high gain, 14 dynode Hamamatsu R5912-0 photomultiplier, typically 0.5 to 1.5 V, is large enough to be transmitted over a 2 km coaxial cable. A PMT pulse of 1 V and 7 nsec FWHM is attenuated to a few mV. The risetime is degraded to 180(60) nsec and the FWHM is 600(280) nsec for coaxial (twisted pair) cable. Twisted pair transmission from larger photomultipliers represents a robust and attractive default technology for IceCube.

The collaboration is investigating alternative fiber optic methods, which have already been tested as part of the AMANDA B and II deployments. PMT pulses are transmitted over a multi-mode optical fiber. The anode current pulse is converted by a LED into a 1300 nm light pulse. The transmitter in the OM is a InGaAsP LED, the receiver an InGaAs PIN photodiode with an integrated low-noise transimpedance pre-amplifier. The attenuation is only 1.5 dB/km. The high fidelity of signal reproduction at the surface eliminates the distortion while preserving the conservative design features introduced by analog transmission over electrical cables. Reconstruction of events should benefit from multiple photon resolution.

If the results from further deployments are satisfactory, OMs with analog optical fiber transmission of PMT signals may become the default technology for constructing ICECUBE. Its robustness will be thoroughly tested in the final 99-00 AMANDA II deployment. The dynamic range should be larger than 50 photoelectrons (pe) over 7nsec. The arrival time distribution of light pulses in ice is, on average, broader than the width of the PMT signal. Therefore the dynamic range per pulse may be larger than 1000 pe. Individual pe are counted if separated by 10 nsec.

The total cost of the detector is \$6$\sim$7K per optical module, not including inflation and contingency. This number is obtained after separating actual cost from R&D cost and includes cables and data acquisition system.

It is the nature of pioneering astroparticle experiments that they depend on the development of new and improved technologies for deployment, particle detection, fast processing of electronic signals and large amounts of electronic data. Because of the staged construction of the detector over relatively short Antarctic summers, the instrument evolves with the science and technology developments. Ongoing R&D includes trigger system and front-end electronics, and the use of larger photomultipliers and wavelength shifting films in order to exploit the large attenuation length in ice near and below 300 nm.

Also part of the R&D effort is the construction and deployment of an AMANDA II string equipped with digital optical modules in order to investigate waveform digitization at depth as a scalable solution for IceCube. The waveform of the PMT, digitized in the OM, is transmitted with a serial link to the surface. The method, including triggering, is technologically challenging, especially because all OMs have to be synchronized on a nanosecond time scale for event building at the surface.

4 IceCube: Exploiting the Advantages of Ice

A main advantage of deploying neutrino telescopes in ice, is that the technology is proven and the cost understood. For blue Cherenkov light, deep ice has longer attenuation and absorption lengths than ocean water. Because photons are detected over a large absorption length, their scattering is important. The AMANDA experiment has demonstrated that the problems associated with scattering in bubble-free ice below 1500 m can be solved. Extrapolating from the performance of AMANDA, achieving degree resolution of long muon tracks in ICECUBE has been demonstrated by Monte Carlo. It should be noted that the nominal resolution per muon track of 2° for AMANDA and 1° for IceCube is already smaller than the average neutrino-muon angle at the respective energy thresholds of these two detectors.

IceCube will offer great advantages over AMANDA and AMANDA II beyond its larger size: it will have a much higher efficiency to reconstruct tracks, map showers from electron- and tau-neutrinos (events where both the production and decay of a τ produced by a ν_τ can be identified) and, most importantly, measure neutrino energy. Initial simulation of a strawman ICECUBE design indicate that the direction of showers can be reconstructed to better than 10° in both θ, ϕ above 10 TeV. Energy reconstruction is expected to be superior in ice, in part because of the scattering. Energy resolution is critical because, once one establishes that the energy exceeds 100 TeV, there is, in practice, no background in a kilometer-scale detector. Simulations predict a linear response in energy of about 25%. This has to be contrasted with the logarithmic energy resolution of first-generation detectors.

The cost of ice detectors is expected to be lower than the cost of water-based detectors because of intrinsic advantages (no potassium decay noise, no bioluminescence, easier deployments and proven longevity in the inert solid ice environment), but also because of the larger absorption length of Cherenkov light in ice which determines, to a first approximation, the spacing of the optical modules for a kilometer-scale detector.

Acknowledgments

This research was supported by the following agencies: 1. U.S. National Science Foundation, Office of Polar Programs; 2. U.S. National Science Foundation, Physics Division; 3. University of Wisconsin Alumni Research Foundation; 4. U.S. Department of Energy; 5. U.S. National Energy Research Scientific Computing Center (supported by the Office of Energy Research of the U.S. Department of Energy); 6. Swedish Natural Science Research Council; 7. Swedish Polar Research Secretariat; 8. Knut and Alice Wallenberg Foundation, Sweden; 9. German Ministry for Education and Research.

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