

Exotic Physics with IceCube

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Abstract

The IceCube neutrino observatory, currently under construction at the South Pole, will be used to search for particles and interactions beyond the standard model. These searches include both direct and indirect searches for dark matter, searches for non-standard neutrino interactions, searches for supersymmetric particles, and searches for both relativistic and non-relativistic monopoles. The expected sensitivity of IceCube to exotic physics will be discussed.

1. Introduction

The IceCube neutrino observatory will be the largest volume instrumented detector ever constructed. Nearly one cubic kilometer of South Pole ice will be instrumented with highly sensitive photomultiplier tubes and associated readout electronics. The large size is driven by the desire to detect high-energy (TeV-PeV) extraterrestrial neutrinos. A detector of this size can also open up new possibilities for exotic physics searches.

High energy neutrinos have many properties that make them ideal probes for physics beyond the standard model. The small standard model neutrino interaction cross-section means that any new types of interactions will have pronounced effects on the observed neutrino spectra. At this conference, we heard talks on several new types of neutrino interactions, including TeV scale gravity [1], micro black-holes[2], and supersymmetric stau production [3]. The observation of these signatures requires the existence of a high-energy extra-terrestrial neutrino flux. Once IceCube establishes the existence and makes quantitative measurements of a high energy extra-terrestrial neutrino flux we will use this lepton beam to probe physics beyond the reach of accelerators.

IceCube will also be a unique instrument for dark matter searches. There is a long history of indirect dark matter searches in neutrino telescopes utilizing neutrinos produced in neutralino annihilations in the center of the Earth or Sun (for a review of such searches in AMANDA and IceCube, see the contribution by Hubert[4]). There are also dark matter candidates where IceCube has sensitivity for direct detection. They are generally very massive and therefore have extremely low fluxes due to the dark matter bound, are expected to have virial velocities ($\beta \approx 10^{-3}$), and emit photons via non-Cherenkov mechanisms. Three potential candidates are: **Supersymmetric Q-balls.** These are coherent states of squarks and Higgs fields that may be produced during the decay of the proposed Affleck-Dine condensate[5]. Q-balls carry large baryon number but would evade the non-baryonic constraint on dark matter from Big Bang Nucleosynthesis. The observation of

these objects would validate the Affleck-Dine mechanism as the origin of the baryon-antibaryon asymmetry in the universe. These states are only stable for masses $> 10^{15}$ GeV. They produce light via the catalysis of nucleon decay (which leads to pion production and finally photons).

Heavy Strangelets. These objects are states with nearly equal numbers of up, down, and strange quarks [6]. As they become very massive, they have sizes of order atomic dimensions or above. Objects this size passing through ice will trigger a thermal shock and produce light via black-body radiation.

Massive Magnetic Monopoles. The limits on massive monopoles with masses $> 10^{16}$ GeV can be improved by IceCube. These objects also register in the detector via the catalysis of nucleon decay.

A search for slowly moving massive particles using AMANDA is in progress [7].

As with other Cerenkov neutrino telescopes, IceCube will be highly sensitive to relativistic monopoles. A fast monopole with unit Dirac charge will produce ~ 8300 times as much Cerenkov radiation as an identical particle with unit electric charge.

2. Detector

The possibility of using the South Pole Ice as a neutrino detector was first demonstrated by AMANDA [8]. The South Pole has several obvious and non-obvious advantages as a location for high energy neutrino detection. The ice thickness at the South Pole is ~ 2800 m, which allows the active instrumentation to be shielded from the vast majority of cosmic-ray muons. At depths below ~ 1400 m the trapped air bubbles in the ice convert to an air hydrate crystal form with a substantially increased scattering length. Below 1500m, the effective scattering length varies between ~ 15 -45m for wavelengths between 300 and 600nm except near the dust peak at ~ 2100 m[9]. For wavelengths less than 400 nm the absorption length averages ~ 110 m.

Although the optical properties of water (effective scattering lengths ~ 200 m and average absorption length ~ 50 m) are superior to ice, South Pole Ice has several technical advantages for operation of a neutrino telescope. For the instrumented depths (1450m to 2450m), the temperature of the ice varies from -40 C at the highest point to -15 C at the lowest point. At these low temperatures, the dark noise rates in the photomultiplier tubes are reduced (averaging about 450 Hz for the IceCube DOMs). The lack of bioluminescence allows the optical modules to be deployed in isolation rather than in pairs. While it is difficult to deploy the optical modules in ice, once the IceCube strings are installed they are mechanically stable and do not require constant alignment. Several AMANDA strings have been operated for nearly 10 years with minor optical module failures.

IceCube is both larger and technologically superior to AMANDA. The instrumented volume of AMANDA is ~ 0.015 km³, while IceCube will eventually approach 1 km³ once all 70-80 strings are installed (as of this conference, IceCube has 9 deployed strings). IceCube, however, is more sparsely instrumented with a horizontal spacing between strings of 125m compared to 55-75 m for AMANDA. Vertically, the modules are spaced every 17m in IceCube versus 10-20m in AMANDA. In addition to the in ice optical modules, a surface array (IceTop) based on the same optical module technology will be installed. The acceptance of the surface/deep ice joint array will approach ~ 0.3 km²sr and will allow cosmic ray composition studies from below the knee up to 1 EeV.

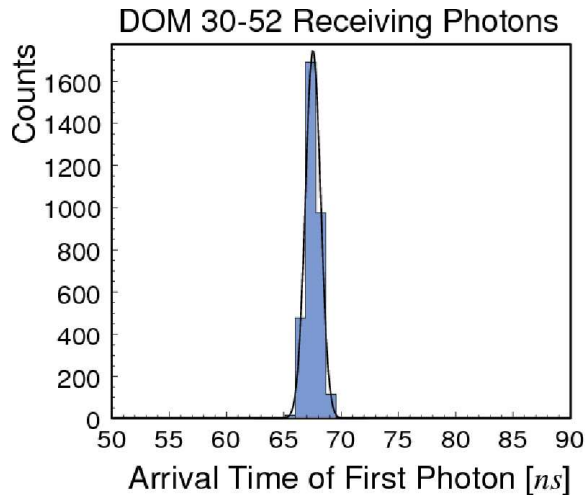


Fig. 1. Plot of the arrival time of the first photoelectron in the DOM 17m above an LED flasher.

Both AMANDA and IceCube utilize large (10" in the case of IceCube) photomultiplier tubes encased in spherical pressure spheres as the active optical elements. In the case of IceCube, however, each digital optical module (DOM) acts as an autonomous data collection unit. Each DOM has its own high voltage power supply and waveform digitization electronics. The digitized waveforms can be buffered in the DOMs, and are communicated digitally at a rate of up to 1 MBit/s over the cable. In the case of AMANDA, HV was provided from the surface, and the photomultiplier signals were sent to the surface analog communications (with corresponding signal degradation).

For the purposes of exotic physics studies, the in-ice signal digitization will give a improvement in the sensitivity of the detector. The waveform digitization is done by three analog transient waveform digitizers (ATWDs) that run at three different gain settings. This leads to a large increase in dynamic range and will reduce saturation for the brightest events (e.g. relativistic monopoles). In addition to the ATWDs which record 128 waveform samplings with a sampling rate between 200 and 700 MHz, each DOM is equipped with a slow 40 MHz digitizer that records the waveform for up to $6.4\mu\text{s}$. This ability to record multiple photoelectrons over an extended period will allow for improved background rejection.

In the case of slowly moving massive particle searches, the IceCube hardware opens up new possibilities as well. The DOMs operate essentially dead-time free. Particles moving at $10^{-3}c$ will spend a few milliseconds crossing the detector and the DOMs are able to record signals during this entire period. The IceCube trigger is entirely software based and topological triggers for slow particles are under development. The minimum velocity to which IceCube is sensitive is largely determined by the dark noise rates, and these are substantially lower than similar water based Cerenkov detectors.

3. Detector Performance and Sensitivity Estimates

As of 2006, 9 IceCube strings have been deployed with 540 DOMs. A total of 16 IceTop stations have been constructed with 64 DOMs. Extensive testing has been done on the deployed hardware to verify the performance of the IceCube DOMs and

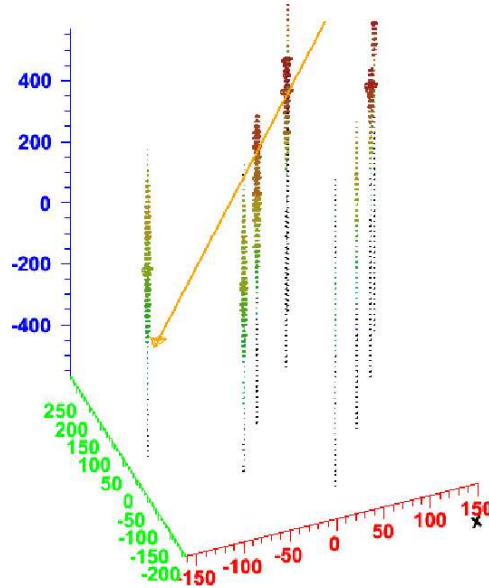


Fig. 2. Simulation of a mass =1 PeV/c² monopole with $\gamma = 10$ passing through the 2006 nine-string IceCube detector.

data acquisition system[10]. The detector has been used to reconstruct down-going muons as well as up-going atmospheric neutrinos. Additionally, LEDs in each DOM have been used to test the performance of the array. Figure 1 shows the arrival time distribution of the first photon recorded in the DOM 17m above a flashing LED. This shows that the timing resolution of the deployed DOMs is better than 2ns.

First simulations are underway to determine the sensitivity of the IceCube array to exotic physics signals. The simulations use a detailed model of South Pole Ice, simulations of the photon propagation through the pressure sphere and glass, detailed modeling of the photomultiplier tube response and electronics, and a simulation of the detector trigger. Figure 2 shows a simulated event consisting of a $M=1$ PeV/c², $\gamma = 10$ monopole passing through the 2006 IceCube configuration. As monopole events are very bright, the large cross-sectional area of IceCube will allow even the present detector stage with 9 strings to perform monopole searches with increased sensitivity over existing limits. It is expected that analysis of the 2006 IceCube data for will have a flux sensitivity of $\sim 10^{-17}$ cm⁻²s⁻¹sr⁻¹. This will represent a factor of 3-4 improvement of the current best limits from Baikal[11]. The full IceCube detector operated for several years will have a sensitivity to relativistic monopoles of $\sim 10^{18} - 10^{19}$ cm⁻²s⁻¹sr⁻¹.

IceCube will have a similar flux sensitivity to slowly moving massive particles. Figure 3 shows the current limits as well as future IceCube sensitivity to massive strangelets, neutral Q-balls, and GUT monopoles that catalyze nucleon decay. In this case the flux limit is shown versus the mass of the slowly moving massive particle. The diagonal black line is the local dark matter limit ($\rho = 0.3$ GeV/cm³) assuming a velocity $\beta = 10^{-3}$. The black line horizontal line (IceCube24) is for the expected 21-23 string 2007 IceCube configuration, and the blue line is for three years of full IceCube. The strongest current limits on monopoles are from searches for nuclear tracks in ancient mica [12]. IceCube should exceed that sensitivity level

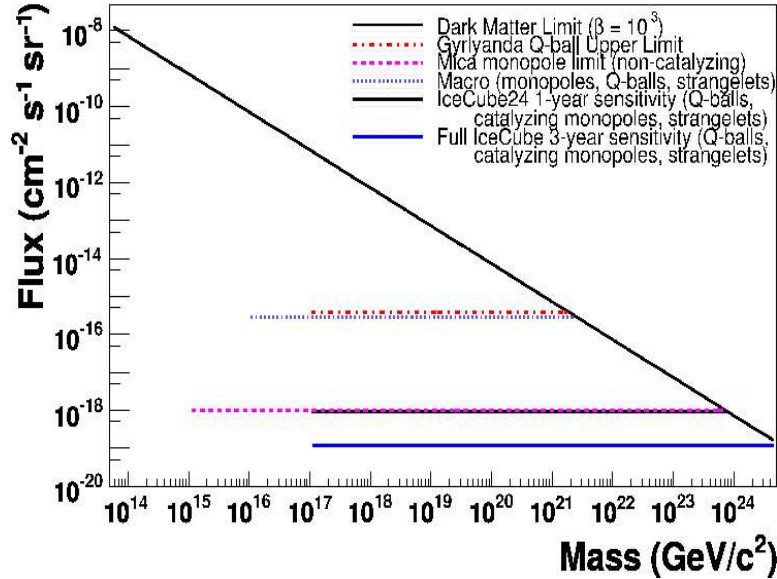


Fig. 3. Current flux limits on $\beta = 10^{-3}$ massive particles and predicted flux sensitivity for 2007 24 string IceCube configuration and full IceCube configuration.

and will not be subject to the same theoretical uncertainties.

4. Conclusions

The IceCube neutrino observatory will be the most sensitive detector for many of the exotic physics topics discussed at this conference. Extraterrestrial neutrino beams will probe particles and interactions beyond the standard model. IceCube will conduct both indirect and direct searches for dark matter. The initial experience with the IceCube hardware indicates that a rich exotic physics program is feasible.

References

- [1] J. Illana, these proceedings.
- [2] M. Kowalski, these proceedings.
- [3] I. Albuquerque, these proceedings.
- [4] D. Hubert, these proceedings.
- [5] A. Kusenko, these proceedings.
- [6] J. Madsen, these proceedings.
- [7] A. Pohl and H. Wissing, these proceedings.
- [8] E. Andrés *et al.*, *Nature* **441**, 441, 2001.
- [9] M. Ackermann *et al.*, *J. Geo. Res.* **111**, D13203, 2006.
- [10] A. Achterberg *et al.*, *Astropart. Phys.* **26**, 155, 2006.
- [11] E. Osipova, these proceedings.
- [12] P. B. Price and M. H. Salamon, *Phys. Rev. Lett.* **56**, 1226, 1986.