THE ICECUBE NEUTRINO OBSERVATORY

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IceCube is a kilometer-scale deep-ice neutrino observatory under construction at the South Pole. This paper presents a brief overview of the IceCube concept and components, its science goals, the expected performance and the present status of the project.

1. INTRODUCTION

The prime objective for the IceCube neutrino telescope [1] is the discovery of ultra-high energy cosmic neutrinos considered a promising tool for further exploration of the universe. Such observations would be expected to shed light on the mechanisms of acceleration of the highest energy cosmic rays and allow a mapping of their sources. They might also provide essential insights regarding the origin of the observed high-energy γ rays. Neutrino production requires hadronic processes for which two scenarios are implied in the literature [2]: in the top-down models neutrinos arise as decay products of massive ($M \sim 10^{23}$ eV) cosmological remnants; in the bottom-up models neutrinos originate in decays of pions which are produced when charged particles, accelerated to ultra-high energies by ”cosmic accelerators” driven by gravitational energy release, interact with dense clouds of radiation or matter surrounding the source. The possible ”accelerators” include Active Galactic Nuclei (AGN), microquasars, supernova remnants (SNR) and colliding neutron stars or black holes (GRB). Hence, search for steady, variable or transient sources of high-energy neutrinos is an important science goal for IceCube.

Apart from the astrophysics objectives, IceCube plans to investigate topics related to particle physics, such as signatures of dark matter or extra dimensions, and to search for magnetic monopoles and exotic superheavy objects like nuclearites or Q-balls [2]. In addition, owing to the low dark noise rate of the optical modules (OM) in ice (< 1 kHz), IceCube will be sensitive to a coherent OM rate increase due to MeV neutrinos from potential SN explosions within our galaxy. IceCube will participate in the SN alert network SNEWS [3].

2. THE ICECUBE CONCEPT

The conceptual design of IceCube is shown in figure 1. IceCube is an array of 80 strings – in total 4800 OMs – deployed in a hexagonal pattern over an area of ~ 1 km^2.

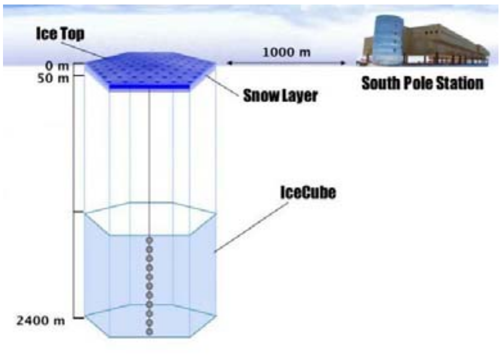

Figure1. IceCube and IceTop

The OMs are connected to the strings at depths between 1400 and 2400 m where the optical properties of the ice are well understood owing to measurements with the AMANDA set-up [4].

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The distance between strings, 125 m, and the distance between OM's in a string of about 17 m, is a result of an optimization for the principal energy range (TeV- PeV) of interest to IceCube [5].

The deep-ice detector is complemented by an Extensive Air Shower array on the surface – IceTop – consisting of 2 frozen water tanks with 2 OM's each on top of every string. In total 320 modules. The combination of IceCube with a surface array provides a unique possibility of tagging muons produced by cosmic rays in the atmosphere which penetrate to the deep-ice array. A valuable aspect is that the IceCube OMs can be surveyed and calibrated *in situ*. Also important is the possibility of vetoing some "background" events originating in the atmosphere. All events with $E > 300$ TeV can be vetoed when the shower passes the surface array. The geometrical reach of the veto increases with increasing shower energy. In addition IceTop/IceCube may be used for cosmic ray studies. IceTop has full efficiency in an energy range $< 10^{15} – 10^{18}$ eV. This includes the "knee" of the cosmic-ray spectrum around $3{\cdot}10^{15}$ eV as well as the likely beginning of the transition from galactic to extra-galactic cosmic rays above 10^{17}eV.

The fundamental component of IceCube is the Digital Optical Module, DOM, figure 2. Each DOM is a self-contained "mini" data acquisition system (DAQ) capable of recording signals from an optical sensor, digitizing and storing these with minimal loss of information and transmitting them to the surface at request. The optical sensor is a 10 inch diameter, 10 stage Hamamatsu R-7081 PMT coupled via an UV transparent optical gel to the glass pressure housing enclosing both the sensor and the electronics. The housing is designed to withstand a pressure of at least 600 bar.

The DOM digitizes the PMT waveform ensuring a dynamic range of 200 photoelectrons (p.e.) within the first 15 ns, a total of 2000 p.e. within 5 μs and a dead time < 1%. Each waveform is time-stamped locally, allowing to achieve a relative timing accuracy between modules of $\sigma \sim 7$ ns, making this contribution to the reconstruction efficiency for neutrinos small relative to the effects of light scattering. The basic performance of the IceCube design has been verified with the AMANDA string 18 deployed at the South Pole in January 2000, comprising 40 prototype digital optical modules connected both to the standard AMANDA DAQ and to a prototype digital DAQ. Waveforms have been recorded and analyzed, and down going muons detected. Also, the critical aspects of time stamping have been verified.

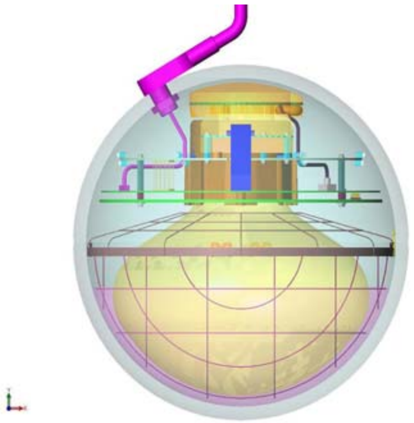

Figure 2. Schematics of a Digital Optical Module showing the PMT, the three electronics boards and the mu-metal shield enclosed in the pressure sphere.

3. PHYSICS PERFORMANCE

IceCube will be sensitive to all neutrino flavors over a large energy range. Muon tracks from ν_μ can be reconstructed above 10^{11} eV. Cascades from ν_e or ν_τ can be reconstructed from 10^{13} eV and ν_τ can be identified above 10^{15} eV. IceCube performance for muons at TeV – PeV energies has been investigated in detail in [6] whereas its performance at EeV energies has been studied in [7].

Figure 3 (top) shows the effective area for neutrino-induced muons as a function of the zenith angle for 4 different muon energy ranges. A generic E^{-2} ν_μ spectrum has been assumed and cuts have been applied to ensure track quality and suppress the down going atmospheric muon background by a factor of 10^6. An effective area of 1 km^2 will be achieved for upward-moving muons in the tens of TeV range. The sensitive aperture of the array increases with increasing energy and in the PeV range full sky observations become possible.

Figure 3 (bottom) shows the pointing resolution (median space angle error) for muons originating from ν_μ's as a function of the zenith angle, after application of background suppression cuts.

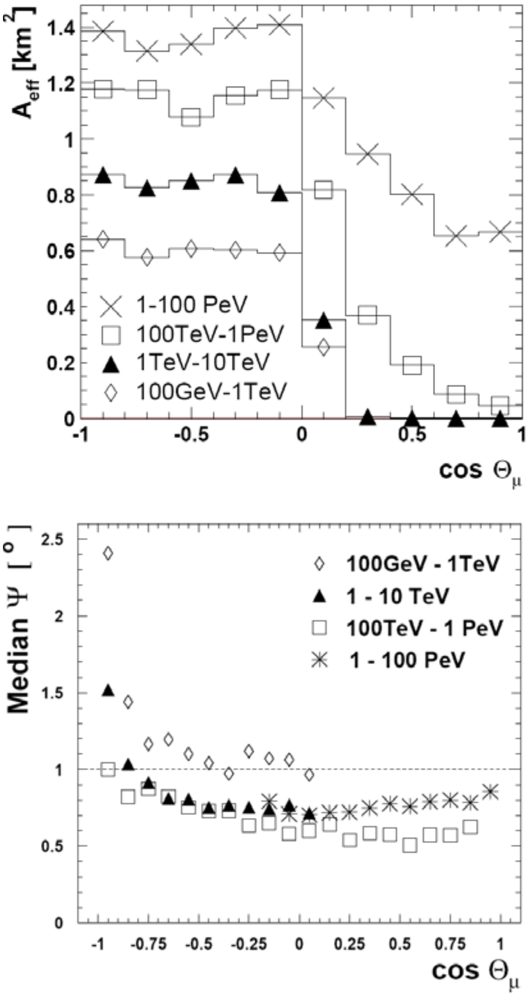

Figure 3. Effective area for muons originating from neutrinos as a function of zenith angle (top). Pointing resolution (median space angle error) for neutrino-induced muons as a function of zenith angle (bottom).

The resolution improves with energy, approaching 0.6° at the horizon for muons with energies of the order tens of TeV.

Figure 4 shows the sensitivity of IceCube for diffuse fluxes of astrophysical neutrinos. Assuming a generic diffuse E^{-2} ν_μ spectrum and optimizing the cuts for best sensitivity we obtain a 90% C.L. exclusion limit of $4.2 \cdot 10^{-9}$ cm^{-2} s^{-1} sr^{-1} GeV (horizontal full line) for 3 years of data taking. The second full line shows the corresponding limit for a generic E^{-1} ν_μ spectrum. The limits have been evaluated assuming the recombination quark-parton model for the charm contribution [8]. Other models for charm [9] would result in improved limits. The dashed (dotted) line in figure 4 indicates the expected diffuse ν flux from a model of photo-hadronic interaction in AGN cores (jets) [10, 11]. The model rejection factors (*mrf*) indicate a sensitivity of *mrf* · Φ at 90% C.L. for a model predicting a flux Φ after 3 years of data taking.

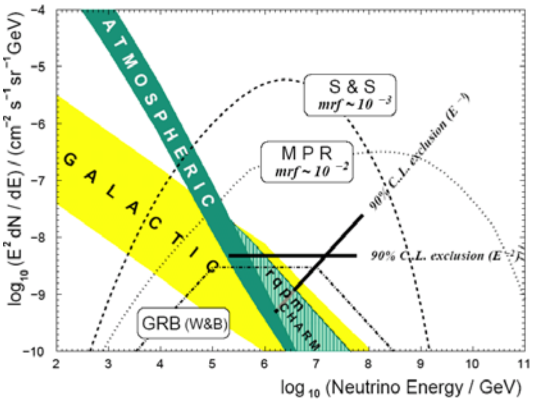

Figure 4. Expected sensitivity of IceCube (3 years of data taking) to a diffuse flux of neutrinos assuming a E^{-2} spectrum.

A considerable improvement of the overall sensitivity for diffuse sources is expected when exploiting IceCube capability to detect cascades from ν_e or ν_τ. An effective volume of ~ 1 km^3 will be achieved for cascades above 10 TeV.

Possible powerful sources of high-energy neutrinos like AGN's will be searched for by looking for an excess of events from within a limited region of the sky. An expected angular resolution in the sub-degree range will allow IceCube to restrict the search window, thereby reducing the background, while loosening other cuts to retain a larger fraction of the signal. Optimizing the cuts for best sensitivity we obtain a 90% C.L. exclusion limit of $2.4 \cdot 10^{-9}$ cm^{-2} s^{-1} GeV for 3 years of data taking.

Figure 4 also shows (dash-dotted) the prediction from the GRB model by [12]. Assuming independently available spatial and temporal information, IceCube expects after 1 year of data taking to achieve a sensitivity at the level of 20% of the flux predicted by this model.

4. DRILLING AND DEPLOYMENT

The IceCube strings will be deployed in 60 cm diameter holes drilled in the South Pole glacier utilizing water at 80 °C. The Enhanced Hot Water Drill (EHWD) represents a development of the drill technology used in the case of AMANDA, making it possible to drill a vertical hole to a depth of 2450 m within ~ 40 hours. Up to 18 holes per season are foreseen. Mounting, testing and lowering of a string with 60 DOMs is expected to take about 20 hours. All drill components have been dispatched to the South Pole, to be used for the first time during the 2004/2005 campaign.

Figure 5. The hose-reel for the IceCube Hot Water Drill assembled at the South Pole, January 2004.

5. STATUS OF THE ICECUBE PROJECT AND CONSTRUCTION.

The IceCube collaboration includes about 150 researchers from 26 institutions in Belgium, Germany, Japan, the Netherlands, New Zealand, Sweden, U.K., USA and Venezuela. The funding in the US is provided by the NSF, since 2004 through an MRE grant. Significant funding has also been granted in Germany, Belgium and Sweden. After an initial start-up phase, it is now foreseen to deploy the very first IceCube strings in January 2005.

The initial IceCube strings will be positioned in a pattern close to the AMANDA array, to provide both the possibility of calibration of IceCube with well-defined muon tracks and, more importantly, to ensure continuous science output during IceCube construction. Finally, AMANDA will become a fully integrated low threshold sub-array within IceCube. Construction of IceCube should be completed in January 2010.

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