The Precision IceCube Next Generation Upgrade

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The IceCube Neutrino Observatory, completed in December 2010 and located at the geographic South Pole, is the largest neutrino telescope in the world. IceCube includes the more densely instrumented DeepCore subarray, which increases IceCube’s sensitivity at neutrino energies down to 10 GeV. DeepCore has recently demonstrated sensitivity to muon neutrino disappearance from atmospheric neutrino oscillation. A further extension is under consideration, the Precision IceCube Next Generation Upgrade (PINGU) which would lower the energy threshold below about 10 GeV. In particular, PINGU would be sensitive to the effects of the neutrino mass hierarchy, which is one of the outstanding questions in particle physics. Preliminary feasibility studies indicate that PINGU can make a high significance determination of the mass hierarchy within a few years of construction.

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For the full IceCube author list see http://icecube.wisc.edu/collaboration/authors/current.
1 Introduction

One of the outstanding problems in neutrino physics is the nature of the neutrino mass hierarchy (NMH), or the sign of $\Delta m^2_{13}$. A number of experiments at accelerators are in planning for the purposes of determining the NMH. Megaton Cherenkov neutrino detectors in ice or water provide another potential path to the NMH measurement.

1.1 IceCube DeepCore

The IceCube Neutrino Observatory, located at the geographic South Pole, is the largest neutrino detector in the world, designed to detect ultra high-energy neutrinos from astrophysical sources such as active galactic nuclei and gamma ray bursts. IceCube consists of 86 cables called “strings”, each instrumented with 60 Digital Optical Modules (DOMs). The DOMs are deployed between 1450 m and 2450 m deep in the Antarctic ice. Each DOM consists of a glass pressure vessel containing a 10-inch photomultiplier tube (PMT), digitizing electronics, and LED flashers for calibration. IceCube includes a surface component (IceTop) and a more densely instrumented inner array called DeepCore, which was designed to improve IceCube’s sensitivity to neutrinos at low energies \(^1\). DeepCore strings are located in the center of IceCube, with smaller string-to-string and DOM-to-DOM spacing than the surrounding IceCube strings, as shown in Figure \(^1\). DeepCore DOMs are concentrated below 2000 m depth, where the ice is the most transparent to light deposited by neutrino interactions in the ice. Most DeepCore DOMs contain PMTs which have 35% higher quantum efficiency than standard IceCube PMTs. The closer spacing and higher efficiency increase DeepCore’s sensitivity to neutrinos below 50 GeV in energy. DeepCore’s physics program includes indirect detection of dark matter \(^2\), galactic supernovae \(^3\), and atmospheric neutrino physics \(^4\).

The amount and pattern of light detected by IceCube DOMs is used to reconstruct the properties of the incident particle: direction, position, time, and energy. Neutrino event topologies in IceCube fall into two categories: track-like events from charged current (CC) muon neutrino interactions, and shower-like events, or cascades, from electron and tau neutrino CC events and neutral current (NC) events of all flavors. To detect neutrino events in DeepCore, the surrounding IceCube strings are used to veto the background from cosmic ray-induced muons which has a $10^6$ times higher rate at trigger level than atmospheric neutrinos.

1.2 Atmospheric Neutrino Physics in DeepCore

DeepCore recently reported the first statistically significant observation of muon neutrino disappearance at energies above 20 GeV \(^4\). The disappearance signature in DeepCore is a deficit of muon neutrino tracks at upgoing zenith angles due to a
minimum in the survival probability of Earth-crossing muon neutrinos at 25 GeV. The fitted oscillation parameters from the muon neutrino deficit are consistent with the world average values for $\Delta m^2_{23}$ and $\sin^2(2\theta_{23})$. IceCube also successfully isolated low energy cascades from atmospheric electron neutrinos and NC interactions in DeepCore, reporting the first measurement of the atmospheric electron neutrino flux between 80 GeV and 6 TeV [5].

Figure 1: Left: IceCube including DeepCore as seen from the top and side. Black circles: standard IceCube strings. Red stars and black triangles: DeepCore. Right: 20-string and 40-string PINGU geometries under study. Black circles: standard IceCube strings. Red triangles: DeepCore strings. Blue crosses: PINGU strings.

2 PINGU

The Precision IceCube Next Generation Upgrade (PINGU) is a proposed infill extension of IceCube. PINGU would add strings with 60-100 additional DOMs each inside of the DeepCore volume. Detector geometries with 20 and 40 additional strings are under study, shown in Figure 1. These strings can be deployed within 2-3 years for a relatively modest cost, based on the construction experience of IceCube [12]. The basic design of PINGU is that of IceCube, with several improvements planned including a simplified digitization scheme, an upgraded system of calibrated in situ light sources, and degassing of the drill water during the drilling process in order to mitigate the formation of bubbles in the PINGU holes. PINGU would increase IceCube’s effective volume for neutrinos at energies below 20 GeV.
2.1 Neutrino Mass Hierarchy with PINGU

Neutrinos oscillating in the Earth undergo the MSW effect [6], which modifies the oscillation probability of neutrinos propagating through matter. The oscillation probability of (anti-)neutrinos is enhanced in the normal (inverted) mass hierarchy. Neutrino oscillation probabilities also undergo parametric enhancement at density boundaries, such as the boundary between the core and the mantle [7]. For Earth-crossing neutrinos, the enhancement is strongest below 10 GeV. The relatively large value of $\theta_{13}$ [8] makes the measurement of the NMH feasible in PINGU [9, 10, 11]. The muon neutrino survival probability in PINGU as a function of zenith angle and energy, for both normal and inverted hierarchies, is shown in Figure 2. Although PINGU cannot distinguish between neutrinos and antineutrinos, differences in the cross section and fluxes for neutrinos vs. antineutrinos produce a measurable difference in the muon neutrino flux as a function of energy and zenith angle for the normal and inverted hierarchies.

The distinguishability metric defined in [11] may be used to quantify the observable difference between the normal and inverted hierarchies:

$$S_{tot} = \sqrt{\frac{(N_{i,j}^{IH} - N_{i,j}^{NH})^2}{N_{i,j}^{IH}}}$$  \hspace{1cm} (1)

where $N_{i,j}$ is the number of muon neutrino events in the $i,j$th bin in neutrino energy and cosine of zenith angle ($\cos(\theta_Z)$). The distinguishability metric indicates which regions in the $E_\nu - \cos(\theta_Z)$ plane have the most sensitivity to the NMH. The significance of a NMH measurement in PINGU is computed taking reconstruction efficiency and systematic uncertainties into account.

To determine the energy and angular resolution, low-energy reconstruction algorithms developed for DeepCore data analysis have been applied to simulated PINGU events. Results from these algorithms with the baseline 40-string geometry are shown in Figure 3. A direction reconstruction algorithm using unscattered light from muons yields a median angular resolution of 15° at 5 GeV, improving to 8° at 20 GeV. A maximum likelihood energy reconstruction yields an energy resolution of 0.7 GeV + $0.2E_\nu$(GeV). Flavor identification algorithms are under study which identify the muon track by its speed, which is near the speed of light in vacuum, as opposed to light from cascade-like events which travels at the speed of light in ice.

Three independent analyses have estimated the sensitivity of PINGU to the NMH. Systematic effects used in these studies include: ±$2\sigma$ variation on the world average values of $\theta_{23}, \theta_{13}, \Delta m_{atm}^2$ and $\delta_{CP}$; 30% uncertainty in the effective volume; ±0.05 in the atmospheric neutrino spectral index; 10% error in the energy and direction reconstruction; and 10% error in the energy and angular resolution. The effects of nonzero $\delta_{CP}$ and uncertainties in $\theta_{12}$ and $\delta m_{12}^2$ are under investigation, but are expected to be small [11]. These studies indicate that the wide range of energies and
Figure 2: Left: muon neutrino survival probability as a function of neutrino energy and the cosine of the zenith angle ($\cos(\theta_Z) = -1$ for upgoing neutrinos) in the normal and inverted hierarchies, with enhanced oscillation probabilities due to neutrino propagation through the Earth visible in the normal hierarchy. For antineutrinos, enhancements would occur in the inverted hierarchy. Right: significance of NMH measurement in PINGU as a function of time. The band encompasses the results of three independent studies.

baselines available to PINGU allows control of systematic errors.

The sensitivity as a function of detector livetime, displayed as a band encompassing the range of results from the various sensitivity studies, is shown in Figure 2. We estimate that PINGU will have roughly 3σ sensitivity to the neutrino mass hierarchy within 2 years of completing construction [12].

3 Summary

PINGU has the potential to measure the neutrino mass hierarchy on a relatively short timescale for a relatively modest cost. This measurement would be complementary to long baseline accelerator neutrino experiments in planning or under construction. Further studies of systematic effects are under investigation and a letter of intent is in preparation, with a full proposal to follow.

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Figure 3: Left: energy resolution as a function of energy in the PINGU 40-string geometry, using a maximum likelihood reconstruction algorithm. Right: angular resolution as a function of energy using an algorithm which detects unscattered light from muons.

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