Status of standard oscillation physics with IceCube DeepCore

J. P. Yanez for the IceCube Collaboration

Department of Physics, University of Alberta, Edmonton, Alberta T6G 2E1, Canada
E-mail: j.p.yanez@ualberta.ca

Abstract. The IceCube neutrino observatory is a cubic km neutrino telescope located at the geographic South Pole. DeepCore is an infill array within IceCube that enables the detection of atmospheric neutrinos with energies as low as 5 GeV. These lower energy atmospheric neutrinos make it possible to study a broad range of particle physics including the measurement of standard neutrino oscillations. In this talk I discuss the recent oscillation results from IceCube DeepCore and go over the future prospects of oscillation physics with this detector.

1. Introduction
Neutrino physics, in particular the study of neutrino oscillations, is in the process of transitioning from a discovery to a precision era. Atmospheric neutrinos have played a particularly important role in reaching this state [1, 2, 3]. The naturally occurring flux is dominated by muon neutrinos and antineutrinos, which undergo oscillations when $E_\nu \leq 100$ GeV for Earth-crossing trajectories. In the three-flavor paradigm, the oscillations pattern depends mainly on $\theta_{23}$ and $|\Delta m^2_{\text{large}}|$, with corrections coming from $\theta_{13}$ and the relative ordering of the neutrino masses [4]. IceCube, the largest neutrino detector in the world, has been recording atmospheric neutrino interactions for almost ten years in full configuration. The measurements made so far are discussed in what follows, as well as the status of the next generation of oscillation analyses.

2. Neutrinos in IceCube DeepCore
The IceCube Neutrino Observatory is an ice Cherenkov neutrino detector installed in the ice at the geographic South Pole between depths of 1.5 km to 2.5 km [5]. It consists of 5160 Digital Optical Modules (DOMs) that house a 10" PMT and all electronics for signal digitization and readout. The DOMs are arranged in vertical strings that are horizontally spaced between 40 m and 125 m. Within a string, DOMs have a separation of 7 m or 17 m. DeepCore is the region with the shortest distances between DOMs and is located in the lower center of the array [6]. The energy threshold for analysis in DeepCore is a few GeV, which makes it well suited for studying atmospheric neutrino oscillations.

IceCube detects neutrinos by recording the Cherenkov light produced by the secondary particles created in neutrino-nucleon interactions. The DOM spacing sets the energy threshold for detection: for DeepCore that is about 10 GeV, while for the bulk of IceCube it is close to 100 GeV. Because of this threshold, most of the interactions DeepCore observes are deep

1 http://icecube.wisc.edu
inelastic scattering, where the neutrino interacts with a single quark and the final states are a lepton and a hadronic shower. Charged current $\nu_\mu$ interactions produce muons that can look like tracks and can thus be tagged. Any other interaction looks like a particle shower.

3. Analysis strategy
The first step in all IceCube oscillation analyses is the rejection of the overwhelming atmospheric muon background. Even at a depth of 2 km, the rate of atmospheric muons is about $10^6$ higher than that of neutrinos. The other source of background are events created by random coincidences due to the noise from the DOMs themselves. Very low energy particle showers can be confused with this component. Atmospheric muons and pure noise events each account for roughly half of the rate in DeepCore at the trigger level. Pure noise is easily removed by means of cuts on causality and topology variables. Muons are suppressed by selecting only a sample of events whose interaction vertex is inside the instrumented DeepCore volume. Using IceCube as a veto, the muon background can be suppressed over five orders of magnitude with minimal signal sacrifice.

The geometry of the detector together with the complicated optical scattering introduced by the medium make it possible for muons to produce patterns that look very much like that of a starting neutrino. Removing this remaining, misreconstructed background has a significant impact on the neutrino efficiency of our samples. Even with these constraints, from ten to twenty thousand neutrinos between 5 and 56 GeV have been recorded and analyzed per year.

The most recent oscillation results were done analyzing two samples of three years of data and obtaining errors of about 5% in the mass splitting $\Delta m^2_{32}$ and about 15% in the mixing angle $\sin^2 \theta_{23}$ [7, 8]. The statistical component of the errors is larger or at-par as the systematic one. The next generation of analyses is thus focusing on increasing the rate of events selected for analysis and improving the description of systematic uncertainties that have been sub-leading until now.

4. Systematic uncertainties
The oscillation analysis is done in a 3D histogram in reconstructed energy, direction and event topology. Sources of uncertainty are modeled as variations either from first principle calculations or using simplified effective parameterizations. Most effects related to the flux of atmospheric neutrinos and neutrino interactions can be applied as corrections to the weight of the neutrino simulation. This strategy is very efficient, but cannot be applied to detection-related effects, the most important source of uncertainty in oscillation analyses.

Figure 1. Sketch of the construction of a hypersurface for modifying the expected number of counts of muons in one of the bins of the 3D histogram used in the analysis. Each point comes from a full simulation set. The surface is shown for the case of two dimensions.
Figure 2. Distribution of charge produced by single photoelectrons impinging the DOM. The previous template and the new, recalibrated template are shown together with in-situ calibration data.

In order to describe the impact of unknowns in the detector and medium, the detector response is evaluated at several values in a multi-dimensional space that includes three variables describing the optical efficiency of the DOMs and two variables that scale the global scattering and absorption coefficients of the ice. The predicted counts in every bin of the analysis histogram are then tabulated and a hyper-surface is fit through the simulated data. The dimensionality of the surface depends on the number of parameters included. The resulting functions make it possible to obtain expectations for any combination of parameters without the need of simulating an entire data set at every evaluation point. Since all the variations are included in the parameterization, correlations are naturally accounted for. Figure 1 sketches how the hypersurface is constructed for the expectation of atmospheric muons in one of the bins of the analysis histogram.

5. New developments

The latest DeepCore results employed these techniques to analyze three years of detector data and obtain high statistics samples to measure the atmospheric oscillation parameters [7, 8]. The studies were limited to three years due to a re-calibration campaign that introduced corrections in the data acquisition and made data taken after early 2015 incompatible with old simulation. The main goal of this was to obtain a better description of the charge deposited in a PMT when a photon is detected. The result can be observed in Figure 2, where the old and new expected charge spectrum is compared to data. This improved description has now been propagated to all years and also to the simulation chain, and it is being used in the development of the next generation of oscillation studies.

Another limiting factor that severely affected previous studies was the time required to fit the eight parameters used to describe a neutrino interaction\(^2\). Optimized procedures to obtain light expectations for particles and sample the allowed space have been developed in the meantime, resulting in similar resolutions across the board achieved in about a quarter of the time. Apart from this, the fast reconstruction method used for earlier results has also been reoptimized for efficiency.

A new event selection has also been developed as part of the updates to all DeepCore oscillation analyses. All variables used in the past were revisited, their agreement between data and simulation after recalibration was checked, as well as the correlations among them. Their separation power was tested in multivariate classifications, and the most powerful ones for separation of neutrinos from atmospheric muons and noise were used as input of two classifiers,

\(^2\) The interaction is described by \(E_{\mu}, E_{\text{had}}, \theta_{\mu}, \phi_{\mu}, \vec{x}_{\text{int}}\), where muons and hadrons are assumed to be collinear.
individually tailored to remove atmospheric muons and noise. Further straight cuts on single variables were introduced to remove known classes of problematic muons. At this point, where the sample is roughly 2/3 neutrinos and 1/3 atmospheric muons, the selection is split into two streams: one using the fast reconstructions but with low efficiency, and one with high efficiency but very time consuming reconstructions. Figures 3 and 4 demonstrate the agreement between data and simulation on the average charge per DOM and reconstructed direction for the fast stream. Both streams are well underway in the developing of final cuts to reach a muon contamination in the percent level.

6. Outlook
The analysis of IceCube DeepCore data has produced neutrino oscillation results in an energy range mostly unexplored. Now, a new generation of analyses is being developed that will take advantage of an improved detector calibration, faster reconstructions, and a unified background rejection strategy. Two data streams are being prepared to understand the new data and take advantage of the large number of events collected. As part of this endeavour, there are also renewed efforts studying sub-leading effects of cross section uncertainties, atmospheric flux calculations, and muon background modeling. All these improvements will go into the next generation of results, expected early next year, and will establish many of the techniques and methods to be used in the IceCube Upgrade.

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