Measurement of neutrino oscillations with the full IceCube detector

THE ICECUBE COLLABORATION

Abstract: We present preliminary results of the measurement of neutrino oscillations using the first year of data of the completed IceCube Neutrino Observatory. The DeepCore subarray is used to record atmospheric neutrinos that cross the Earth with energies as low as 10 GeV. The IceCube detector is employed to veto the background of muons produced by cosmic rays interacting in the atmosphere. The study benefits from tools designed to diminish the impact of systematic uncertainties and reliably reconstruct neutrinos at the detector’s energy threshold. In 343 days of livetime we find 1487 neutrino events. An analysis is performed on the shape of the two-dimensional energy-zenith angle distribution and, in the two flavor approximation, the oscillation parameters that best describe the data are $\sin^2(2\theta_{23}) = 1 (> 0.93)$ and $|\Delta m^2_{23}| = 2.4 \pm 0.4 \cdot 10^{-3}$ eV$^2$.

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1 Introduction

It is a well established phenomenon that neutrinos change their flavor eigenstate during propagation, known as neutrino oscillations. Experiments have tested a wide range of energies and propagation distances finding that a minimal extension to the standard model, with 3 massive neutrinos, can accommodate most measurements made.

The value of the parameters that govern this phenomenon have to be obtained from data. For certain experimental set-ups it is possible to assume, with an accuracy of up to a few percent, that only two neutrinos are involved. In such cases, the probability for observing a neutrino with a flavor different from the original is given by

$$P(\nu_a \rightarrow \nu_b) = \sin^2(2\theta) \sin^2(1.27\Delta m^2 L/E). \quad (1)$$

Here $\theta$ is the mixing angle between the two neutrino mass eigenstates, $\Delta m^2$ is the difference of the square of their masses in eV$^2$, $L$ is the distance traveled in kilometers, and $E$ the neutrino energy in GeV.

This proceeding describes a search for the disappearance of muon neutrinos produced in the atmosphere and detected by the IceCube+DeepCore detector. IceCube is a cubic-kilometer neutrino detector installed in the ice at the geographic South Pole between depths of 1450 m to 2450 m. The DeepCore subarray as used in this analysis includes 7 standard strings plus 8 with denser optical modules (DOMs) distributed on up to 4 strings.

Atmospheric neutrinos arise primarily from the decay of pions and kaons produced after interactions of cosmic rays with the atmosphere. They cover energies from a few MeV up to few hundred TeV, following a steeply falling spectrum. The flavors produced, in order of abundance, are $\nu_\mu$, $\nu_\tau$, $\nu_e$ and $\overline{\nu}_e$.

2 Analysis strategy

The current knowledge of oscillations indicates that maximum disappearance is expected for muon neutrinos of about 24 GeV after propagating 12,700 km, roughly the diameter of the Earth. For higher energies the disappearance effect is reduced, being less than 5% at 200 GeV. For lower energies the maximum is reached in shorter distances where the incoming direction is shifted towards the horizon.

Muon neutrinos are detected after they interact via charged current (CC) deep inelastic scattering. In a typical $\nu_\mu$ interaction at $E_\nu = 24$ GeV about half of the neutrino energy is transferred to the outgoing muon and half to the shower of hadrons at the interaction vertex. A 12 GeV muon in ice has a range of about 60 m, its primary energy loss mechanism being ionization. The shower has negligible elongation but is considerably brighter, with the hadrons depositing most of its energy as photons. The DeepCore subarray has string-to-string spacings from 40 m to 70 m in the plane parallel to the surface, and 7 m between photosensors in the vertical direction. The Cherenkov light from the detectable secondaries that constitute our signal can reach on average 15 digital optical modules (DOMs) distributed on up to 4 strings.

In this work, complementary techniques for reducing the background are implemented, which are discussed in Section 3. We introduce a method designed to reduce the influence of the medium details on the outcome of reconstruction, described in Section 4. Remaining systematic uncertainties are parametrized and included in the estimation of the oscillation parameters, as discussed in Section 5.

1. For a review of neutrino oscillations see chapter 13 in [4].
3 Background reduction

There are two kinds of background events that affect this search. The first and largest are atmospheric muons that trigger the detector at a rate $10^3$ higher than the neutrinos. The second comes from the neutrinos themselves where neutral current interactions from all neutrino flavors, as well as CC interactions from $\nu_e$, make the oscillation signature weaker.

The atmospheric muon background is reduced by selecting events that start inside the fiducial volume. The DeepCore fiducial volume is situated at the bottom half of the IceCube detector and is surrounded by three layers of standard strings, which define the veto volume for the analysis. Different algorithms are used to search for hits in the veto region that could be connected with the event that triggered DeepCore. They do so by analyzing the event’s topology: the position of the first hit of the trigger, the distribution of hits as a function of time and the existence of clusters of causally connected hits in the veto region and isolated hits along directions with sparse instrumentation. After applying these cuts the signal is reduced by half providing a signal to background ratio of 2:1.

Quality cuts are applied on the result of the directional fit, explained in the following section. Functions for the expectation of a track and cascade are fit; the $\chi^2_{\text{cascade}}/\chi^2_{\text{track}}$ ratio is used to remove all-flavor neutral currents and CC events where only photons from the cascade at the interaction point are seen. A loose cut on the reduced $\chi^2$ of the reconstruction is also applied to further reduce the number of poorly reconstructed events.

4 Selection and reconstruction of signal events

4.1 Event selection

When a Cherenkov light cone intersects a string, the arrival time of the photons at given depths may be described by a hyperbola. The exact shape depends on the orientation of the cone and the distance between the string and the cone’s axis. Figure 1 depicts the pattern expected for two different cone orientations; photons arriving without a significant time delay produce a pattern of hits with these unambiguous signatures.

The first step of the selection is the search for events that contain clusters of hits in hyperbolic patterns. The DOM with the largest photon count serves as a seed and from it a scan is performed to determine if adjacent modules are included. The criterion is entirely defined by causality conditions with respect to the surrounding modules accepted, and the typical jitter and noise rates.

For a given event, each string is independently scanned. A minimum of three accepted DOMs are necessary in order to form a cluster. Events are selected if they contain at least five accepted DOMs. This selection is the most stringent condition applied but assures good event quality and, since it focuses on photons without time delay, removes the need for detailed knowledge of scattering parameters in the ice.

4.2 Event reconstruction

The distance that an atmospheric neutrino has traveled to the detector depends on its incoming zenith angle, reconstructed using the previously mentioned clusters of hits. Due to the cluster selection, the fit may be performed without the need of assuming any scattering of the photons. The Cherenkov cone expectation is fit following the method presented in [6]. It is worthwhile to note that by means of using this procedure it is possible to obtain reliable zenith angle reconstructions for events with clusters of hits in only one string. This decreases the acceptance energy threshold of the analysis for up-going directions to about 7 GeV where the disappearance signal is strongest.

The total energy of the neutrino is estimated from the light deposition of the hadronic cascade at the vertex and the length of the muon track. Using a fixed direction from the previously described angular reconstruction, an algorithm searches for the first point where a cascade can be accommodated. Following the direction of the event, a subset of hits is extracted from which the average light expectation of a muon track has been removed. This subset is assumed to come from the hadronic cascade and the most likely cascade energy to produce this hit pattern is deduced. The fit algorithm then moves along the direction to search for the best fit point of the end of a muon track with pure Cherenkov emission (other processes, like stochastic energy losses, are not considered). Muon tracks at the energies under discussion here have a roughly constant energy loss of 0.2 GeV/m, so the total energy of the neutrino can be estimated from the cascade energy ($E_{\text{cascade}}$) and the track length ($R_\mu$) as $E_\nu = E_{\text{cascade}} + R_\mu/5 \times 10^{-6} \text{ GeV}$.

The energy distribution obtained for the final sample is shown in Fig. 2 after selection and reconstruction steps were applied. The sample, CC $\nu_\mu$ being the dominant component with close to 1/3 disappearing due to oscillations, peaks at an energy of 12 GeV.

Figure 3 shows the performance of the reconstructions used for the final event selection. A zenith angle resolution of 7 degrees, comparable with the kinematic angle between the neutrino and the muon in the sample, is obtained. The energy, resolved with an error of 0.25 in $\log_{10}(E)$, is also shown in Fig. 3 (bottom).
The data were fit by the method of likelihood inference in rate of observed events \(x\) is compared to the expectation \(\mu\), which depends on the oscillation parameters \(\theta_{23}, \Delta m_{32}^2\) and nuisance parameters \(q\). The subscript \(k\) runs over the list of nuisance parameters for which prior knowledge exists, penalizing deviations from the mean value \(\hat{q}_k\) in units of its uncertainty \(\sigma_{\hat{q}_k}\).

Table 1 contains the list of systematic uncertainties that were considered, as well as their priors and allowed ranges. The first four are related to the relative weight of an event with respect to the sample and can be implemented by modifying those quantities. The remaining systematics must be simulated individually and propagated through the analysis chain in order to be included.

The effects of uncertainties derived from simulation with the exception of the bulk ice properties are applied bin-wise in the energy-zenith angle histogram. The change in the expectation \(\mu\) is parametrized as a function of the single variable that describes the uncertainty. They are derived independently and applied as multiplicative factors \(g_l\), where \(l\) runs over the simulation-derived sources of uncertainty, to the baseline simulation. The number of events expected in the \(i,j\)-th bin is then

\[
\mu_{i,j} = \mu_{i,j}^{\text{baseline}} (\theta_{23}, \Delta m_{32}^2; q_w) \prod_l g_l(q_l),
\]  

where \(q_w\) denotes the dependence on the nuisance parameters that can be modified in the weights.

By using this parametrization it is possible to vary all the systematic uncertainties at once, which is a basic requirement for a correct minimization. This approach does assume that the effects of each change can be factorized, which is strictly correct only when discussing individual photons. The impact on event counts could be correlated, but this has not yet been included. Tests have been performed on control samples and, thus far, no abnormal effects have been observed.

The uncertainty on the description of the bulk ice is assessed using simulation generated with different ice models and the best fit oscillation parameters as inferred from the data. The simulation is fit and confidence regions

<table>
<thead>
<tr>
<th>Nuisance parameter</th>
<th>Prior</th>
</tr>
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<tbody>
<tr>
<td>Atm. (\mu) contamination</td>
<td>up to 10%</td>
</tr>
<tr>
<td>Atm. (\nu) flux</td>
<td>None</td>
</tr>
<tr>
<td>(\nu_e) deviation</td>
<td>(\sigma = 20%)</td>
</tr>
<tr>
<td>Spectral index</td>
<td>(\mu = 2.65, \sigma = 0.05)</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>(\sigma = 10%)</td>
</tr>
<tr>
<td>Relative DOM eff.</td>
<td>(\mu = 45%, \sigma = 3%)</td>
</tr>
<tr>
<td>Ice columns (\alpha)</td>
<td>(\mu = 0.02, \sigma = 0.01)</td>
</tr>
<tr>
<td>Bulk ice properties</td>
<td>See [8]</td>
</tr>
</tbody>
</table>
are constructed. The deviations of these confidence regions from the baseline simulation are calculated and added in quadrature to the confidence intervals obtained from the data. This can only be done because most of the the impact of the differences in the ice description are negligible and/or absorbed by the analysis chain. The correction that must be applied is small with respect to the effect of other systematic shifts. All results are shown with this correction clearly separated.

6 Results and Discussion

The analysis presented was applied to the first year of data taken by IceCube, from May 2011 until April 2012. In 343 days of livetime, 1487 neutrino events were found. A scan of the oscillation parameters was performed, the results of which are summarized in Fig. 4. The best fit, as well as the regions corresponding to the 68 % and 90 % confidence levels, as calculated from the LLH ratio, are shown. Two sets of confidence contours appear in Fig. 4, corresponding to those with all systematic uncertainties included (gray) and those without the uncertainties on the ice description (black).

The best fit values for single parameters obtained from the likelihood profile are 
\[ \sin^2(2\theta_{23}) = 1 \times 0.93 \text{ at 68 \% C.L.} \quad \text{and} \quad |\Delta m^2_{32}| = 2.4 \pm 0.4 \cdot 10^{-3} \text{ eV}^2. \]

Table 2 contains the values of the nuisance parameters at the best fit point.

<table>
<thead>
<tr>
<th>Nuisance parameter</th>
<th>Best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atm. ( \mu ) cont.</td>
<td>7.6 %</td>
</tr>
<tr>
<td>( \nu_e ) deviation</td>
<td>-0.5 % (0.02 ( \sigma ))</td>
</tr>
<tr>
<td>Spectral index</td>
<td>2.66 (0.2 ( \sigma ))</td>
</tr>
<tr>
<td>Optical efficiency</td>
<td>+2.7 % (0.3 ( \sigma ))</td>
</tr>
<tr>
<td>Relative DOM eff.</td>
<td>35.1 % (0.05 ( \sigma ))</td>
</tr>
<tr>
<td>Ice columns ( \alpha ) [1/cm]</td>
<td>0.018 (0.15 ( \sigma ))</td>
</tr>
</tbody>
</table>

Table 2: Values (and deviations in units of sigma) for the nuisance parameters at the best fit point between data and simulation.

![Fig. 4: Best fit, 68 % and 90 % confidence intervals. Contours including all systematic uncertainties (gray) and neglecting the uncertainties on the description of the bulk ice (black).](image)

![Fig. 5: Zenith angle and energy distributions of data and best fit simulation. Statistical errors are added to the data; systematic errors are attributed to the simulation.](image)

7 Summary and Conclusions

A method to measure neutrino oscillations with the full IceCube detector has been described. It uses reconstruction techniques that aim to reduce the impact of systematic uncertainties of the medium and implements the remaining uncertainties as nuisance parameters to be constrained by the data. Preliminary results are presented that show improvement with respect to a previous measurement [5]. Results will be updated when more data are available.

References