Search for sterile neutrinos with the IceCube Neutrino Observatory

THE ICECUBE COLLABORATION1,

1See special section in these proceedings

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Abstract: The IceCube Neutrino Observatory is a 1 km3 Cherenkov detector located at the geographic South Pole. It records atmospheric muon neutrinos with unprecedented statistics of several tens of thousands of identified neutrino events per year and has proven to be suitable for the measurement of muon neutrino disappearance due to neutrino oscillations. Similarly, IceCube is able to search for additional states of sterile neutrinos with mass differences on the order of 1 eV.

If additional sterile neutrino states exist, they will cause unique disappearance signatures for muon neutrinos in the energy range of a few TeV due to matter effects. The survival probability depends on the energy and the path of the neutrino through the Earth and thus its zenith angle. The high statistics and resolutions in the relevant range of energies and baselines make IceCube an ideal tool for testing models of one or more sterile neutrinos.

This work will present an analysis that investigates this signature, using one year of data taken with the IceCube 59-string configuration. It will also discuss the sensitivity that can be reached with five years of data, taken by the 86-string configuration.

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1 Introduction

Neutrino oscillations have become a large research topic over the last decades. The fact that neutrinos are not massless is well established and is the first obvious deviation from the current Standard Model of Particle Physics[1].

Recent results from different areas of neutrino oscillation experiments indicate that there might be effects that can not be explained well with the current model of neutrino oscillations. Examples for such results are the \( \nu_{\mu} \rightarrow \nu_e \) measurements of the two neutrino beam experiments LSND[2] and MiniBooNE[3], as well as various reactor neutrino rate measurements, which see fewer electron antineutrino events than expected within the current model[4]. One way to explain these results is to add additional flavors of neutrinos in a mass range of \( \Delta m_{32}^2 \approx 1 \text{eV}^2 \). These additional flavor states do not participate in the weak interaction, hence they are called sterile[5]. Because of this property, their existence would not violate the well-known limit on the number of light neutrinos from \( Z_0 \) branching ratio measurements at the LEP[6].

2 The IceCube Neutrino Observatory

The IceCube Neutrino Observatory is a neutrino detector located at the Amundsen-Scott South Pole Station. It uses the naturally clear ice of Antarctica as optical medium to observe Cherenkov radiation emitted by charged leptons that have been created by neutrino interactions in the ice. Its active volume of about one cubic kilometer lies at a depth of about 1.5 to 2.5 km beneath the surface of the ice and is instrumented with 5160 digital optical modules (DOMs) evenly distributed over 86 vertical cables called strings. IceCube was completed in December 2010, but it has already been taking data in the years before. The analysis presented here is conducted on data taken with the 59-string configuration between May 2009 and May 2010, called IC59.

Due to its large size, the IceCube detector is triggered by on the order of 100 000 neutrino events per year. However, because of the small interaction probability of neutrinos with matter, the rate with which muons generated in cosmic-ray air showers (i.e., atmospheric muons) trigger the detector is higher by many orders of magnitude. Atmospheric muons can reach IceCube only from above because they can not traverse more than a few kilometers of matter, so tracks that are upward-going are a good indication for neutrino-induced muons. Unfortunately, a small fraction of the atmospheric muon tracks is misreconstructed as upwards-going and – because of their much higher rates – dominates the triggered dataset.

To clean the dataset of atmospheric muons and badly reconstructed tracks, it is necessary to restrict it to high-quality events. The event selection used for this analysis yields approximately 22 000 muon neutrino events, contaminated by less than 70 atmospheric muon events and is discussed in detail in[7], where it is used in a search for extragalactic high-energy neutrinos.

3 Neutrino Oscillations in Matter

The analysis discussed here is a neutrino disappearance analysis, conducted with muon neutrinos that are created in cosmic-ray air showers in the Earth’s atmosphere. To illustrate the basic principle, it is helpful to first regard the simple formula for the probability of a flavor change for two-flavor oscillations in vacuum,

\[
P = \sin^2(2\theta_{\text{mix}}) \sin^2 \left( \frac{\Delta m^2_{\text{eff}} L}{2E} \right).
\]

This formula shows how the probability depends on the distance traveled for a given energy and mass difference.

In the case of IceCube, the matter effects are dominated by the interaction of the neutrinos with Earth’s nuclei, which is described by the so-called survival probability,

\[
P_s(E, L, \theta) = \frac{1}{1 + \Delta m^2_{\text{eff}} / 2E} \left( 1 - \frac{\Delta m^2_{\text{eff}}}{2E} - \frac{\Delta m^2_{\text{eff}} / 4E^2}{1 + \Delta m^2_{\text{eff}} / 2E} \right).
\]

This probability includes the effect of the Earth’s matter on the oscillation probability, which is important for IceCube due to the large depth of the detector.

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As IceCube measures atmospheric neutrinos that travel up the weak interaction, \( N \) flavors of neutrinos occur due to the \( N \) mass eigenstates \( \nu \), not being identical to the \( N \) flavor eigenstates regarding the weak interaction, \( \nu_{\alpha} \). Instead, the eigenstates can

\[ \theta_{\alpha i} = \sum_{i} U_{\alpha i} \theta_{i j} \]

be described as linear combinations of each other, given by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix \( U \):

\[ U = \prod_{i=1}^{N-1} \prod_{j=i+1}^{N} R_{ij}, \]

where \( \theta_{i j} \) are the mixing angles and \( \delta_{i j} \) are CP-violating Dirac phases. In general, \( U \) also gets multiplied by a diagonal matrix containing CP-violating Majorana phases, but these do not have any influence on oscillation effects and can therefore be ignored for this work. The parametrization has to be given explicitly because rotation matrices do not commute and for \( N > 3 \) there is no canonical parametrization. In total, \( U \) depends on \( \frac{1}{2} N(N-1) \) mixing angles, but only on \( \frac{1}{2} N(N-1)(N-2) \) Dirac phases because additional phases are redundant.

Using the PMNS matrix \( U \), the oscillation probabilities can then be computed numerically by solving the \( N \)-dimensional Schrödinger equation

\[ \frac{d}{dx} |\nu_{\text{flavor}}\rangle = \frac{1}{2E_\nu} (H_0 + A) |\nu_{\text{flavor}}\rangle, \]

where \( H_0 = U \cdot \text{diag}(\Delta m^2_{ij}) \cdot U^\dagger \) depends on the squared neutrino mass differences \( \Delta m^2_{ij} = m^2_i - m^2_j \). The choice of \( m^2_1 \) as point of reference is arbitrary, as every matrix proportional to identity does not influence the oscillation probabilities. \( A \) describes an effective squared mass, induced by the matter the neutrinos traverse. For this induced mass, only interactions are relevant in which the neutrino is preserved: The three conventional flavors can scatter on nucleons and electrons by neutral-current (NC) interactions, and electron neutrinos can additionally scatter by charged-current (CC) interactions on the many electrons present in Earth’s matter without the neutrino being absorbed. Analyses that investigate the first oscillation maximum between muon and tau neutrinos can typically neglect matter effects because muon and tau neutrinos see the same matter potential. However, sterile neutrinos lack possibilities to interact weakly by definition, which leads to

\[ \text{(θ}_{\text{rec}} - \text{θ}_\nu) / \text{θ}_\nu = \frac{1}{2E_\nu} \text{log}(E_{\nu} / \text{GeV}), \]

\[ \text{with IceCube.} \]
4 Analysis Method

As described above, the oscillation probability depends on the path the neutrino has taken through the Earth and on its energy \( E_\nu \). As the Earth can be approximated as a symmetrical sphere, the path of the neutrino only depends on the zenith angle \( \theta \) (fig. 1). The general analysis strategy is to employ a two-dimensional likelihood ratio test to check for the disappearance signature in the atmospheric muon neutrino distribution, binned in the reconstructed values for \( \cos(\theta) \) and \( E_\nu \). For the matter density \( \rho \) of the Earth, the Preliminary Reference Earth Model (PREM) is used\(^{[10]} \).

The oscillation probabilities have been calculated using the Python tool nuCRAFT\(^{[11]} \). For details such as the handling of the Earth’s atmosphere, please refer to \(^{[11]} \).

An example for the atmospheric muon neutrino disappearance signature given one sterile neutrino can be seen in fig. 4. The parameters of the sterile neutrino have been chosen to be \( \Delta m^2_{32} = 0.5 \text{eV}^2 \), \( \theta_{32} = 7^\circ \), and \( \theta_{34} = 0^\circ \), because these values have not been excluded by MINOS in 2011\(^{[12]} \), yet are large enough to serve well for illustrative purposes. The plot shows the survival probability averaged between muon neutrinos and antineutrinos. A strong oscillation minimum due to a resonance can be seen at about 4 TeV for the particles that traversed the inner core of the Earth. Variation of \( \Delta m^2_{32} \) leads to a shift of the minimum on the \( E_\nu \) axis, while variation of \( \theta_{32} \) shifts the minimum along the zenith angle axis and also steers the depth and shape of the minimum. \( \theta_{34} \) controls the mixing between electron and sterile neutrinos and is negligible for the atmospheric muon neutrino disappearance as seen by IceCube, whereas the tau-sterile angle \( \theta_{34} \) influences depth and shape roughly similar to \( \theta_{32} \), as long as \( \theta_{34} \neq 0^{[11]} \). A side-effect of \( \theta_{34} \neq 0 \) is that a large fraction of the muon neutrinos will not oscillate to sterile neutrinos, but to tau neutrinos instead. However, at the relevant energies of a few TeV, 85% of the tau neutrinos that interact produce cascade-like signatures and the remaining 15% produce faint muon tracks with large initial cascades, so they are strongly suppressed by the event selection that favors track-like signatures.

For this analysis, it was decided to limit the likelihood scan to the physics parameters \( \Delta m^2_{32} \) and \( \theta_{32} \). These two parameters suffice to reproduce all signatures 3+1 models can assume in IceCube, especially considering IceCube’s somewhat limited energy resolution. The analysis still remains sensitive to models with 3+2 or more neutrino flavors, because the signatures of these models can be approximated well as superposition of 3+1 signatures, and are therefore much more similar to 3+1 models than to 3+0 models. After the likelihood scan has been conducted, selected models that have not been considered in the scan will be examined.

Instead of a standard Poisson likelihood that only takes into account statistical uncertainties of the measured data, a formulation is used that also takes into account statistical uncertainties of the simulated reference histograms\(^{[13]} \). Using this likelihood, a scan is performed in the parameter range of \( \Delta m^2_{23} = 10^{-2} \text{eV}^2 \). The likelihood ratios, i.e., the differences between the logarithmic likelihood values for a given pair of parameters and the null hypothesis, \( LLH(\Delta m^2_{23}, \theta_{23}) = LLH(0, 0) \), are then used as a test statistic. According to Wilks’ theorem, two times the likelihood ratios follow a \( \chi^2 \) distribution with two degrees of freedom if the null hypothesis is true\(^{[14]} \). Although the preconditions of Wilks’ theorem are not clearly fulfilled by this analysis, the applicability of Wilks’ theorem has been verified empirically.

5 Systematic Uncertainties

Systematic uncertainties play an important role in this analysis, as it relies heavily on the agreement between simulated and measured data. All theoretical uncertainties that can have an effect on the energy or the zenith angle spectrum must be taken into account. In this analysis, this is achieved by parametrizing these effects and including them into the likelihood function as nuisance parameters as described in \(^{[15]} \). The meaning of nuisance parameters is that in contrast to the physics parameters in the likelihood function, the fit results for them will not be considered to be measurements of the physical quantities they describe, because they have not been tested to not be degenerate with other nuisance parameters that may or may not have been implemented in the fit. As required by likelihood ratio tests, nuisance parameters get minimized independently for both

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1. available at nuCRAFT.hepforge.org
null hypothesis and signal hypothesis at every point of the LLH scan [16].

The continuous nuisance parameters that are included in the likelihood function are the total neutrino flux, the cosmic-ray spectral index, the pion-kaon ratio in cosmic ray interactions, and the relative optical efficiency of IceCube's DOMs. Uncertainties in the optical model of the ice in which IceCube is embedded will be taken into account as a discrete nuisance parameter, which means that for every point in the physics parameter space the best-matching ice model will be chosen. The following plots do not yet include the ice model uncertainty.

6 Sensitivity and Outlook

The sensitivity of this analysis has been estimated using the so-called Asimov approach, in which it is derived from the most representative simulated dataset as described in [16]. Figure 5 shows the sensitivity with which IC59 can exclude certain pairs of Δm^2_{42} and θ_{24}, given the null hypothesis and the remaining oscillation parameters as in fig. It shows that for Δm^2_{42} ≈ 0.1 eV^2, θ_{24} mixing angles of 12° can be probed at a 90% confidence level. At smaller and larger Δm^2_{42}, the sensitivity diminishes due to the oscillation minimum moving into regions of lower statistics. It is expected that the sensitivity of the analysis improves significantly when priors on the nuisance parameters get implemented that restrict the uncertainties to parameter regions that have not yet been excluded.

Figure 6 shows a projection of this analysis to a five-year dataset taken with IC86, containing 200 000 muon neutrino events. It can be seen that the analysis on IC59 is currently limited by the statistics of the data and not by systematic uncertainties. The projection is conservative in the sense that the event selection could be modified to include more low-energy events, further boosting the sensitivity for low values of Δm^2_{42}. This should be fairly easy, because from the 79-string configuration onwards, IceCube's low-energy extension DeepCore is available to reach energies as low as 10 GeV. Also, the larger detector allows for better angular and especially energy reconstruction, which is not taken into account by this projection.

The next steps for this analysis are to finalize systematic studies and then to apply the analysis on the experimental data and calculate limits. Logical next steps are the extension to lower neutrino energies to increase the sensitivity for lower values of Δm^2_{42}, and to move on to multi-year datasets taken with newer configurations of IceCube as they become available.

References