A search for sterile neutrinos with IceCube DeepCore

Andrii Terliuk\textsuperscript{1} for the IceCube Collaboration\textsuperscript{2}

\textsuperscript{1}Deutsches Elektronen-Synchrotron, Platanenallee 6, 15738 Zeuthen, Germany
\textsuperscript{2}http://icecube.wisc.edu
E-mail: andrii.terliuk@icecube.wisc.edu

Abstract. The DeepCore detector is a densely instrumented part of the IceCube Neutrino Observatory that lowers the neutrino detection threshold down to approximately 10 GeV resulting in the ability to measure atmospheric neutrino oscillations. The standard three neutrino mixing scenario can be tested by searching for an additional light sterile neutrino state, which does not interact via the standard weak interaction, but mixes with the three active neutrino states. This leads to an impact on the atmospheric neutrino oscillations below 100 GeV. We present improved limits to the sterile mixing element $|U_{\tau 4}|^2$ using three years of the DeepCore data taken during 2011-2013.

1. Sterile neutrino mixing

Neutrino oscillations is a phenomenon that changes the flavour of neutrinos as they travel through space\textsuperscript{[1]}. For atmospheric neutrinos with energies above 10 GeV the leading effect is a transition of $\nu_\mu$ to $\nu_\tau$. The muon neutrino survival probability can be approximated as

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23}) \sin^2 \left( \frac{\Delta m^2_{32} L}{4E_\nu} \right), \quad (1)$$

where $\theta_{23}$ is the neutrino mixing angle, $\Delta m^2_{32}$ is the mass splitting, $L$ is the distance between production and detection point, and $E_\nu$ is the neutrino energy. Values of $\theta_{23}$ and $\Delta m^2_{32}$ determine the amplitude and period of the neutrino oscillations. The effect leads to almost complete disappearance of muon neutrinos with energies around 25 GeV that cross the Earth along its diameter. Survival probabilities for atmospheric muon neutrinos are shown in the left part of Figure 1.

Some neutrino experiments have found results that do not fit within the three flavour mixing paradigm\textsuperscript{[2]}, suggesting the existence of additional neutrino species beyond the Standard Model. Such “sterile” neutrinos do not interact via the standard (left-handed) weak interactions, however they can mix with the active neutrino states, and therefore still participate in neutrino oscillations. The simplest extension of the standard paradigm is “3+1” model with one additional sterile neutrino. If CP-violating phases are assumed to be absent the elements of the mixing matrix $U_{\mu 4}$ ($U_{\tau 4}$), corresponding to the mixing between muon (tau) and sterile neutrinos, can be expressed as\textsuperscript{[3]}:

$$|U_{\mu 4}|^2 = \sin^2 \theta_{24},$$
$$|U_{\tau 4}|^2 = \cos^2 \theta_{24} \cdot \sin^2 \theta_{34}. \quad (2)$$
The presence of an additional sterile neutrino modifies the position and amplitude of the oscillation minimum [4]. An example of such a modification is shown in the right part of Figure 1. The change is proportional to the amount of matter along the neutrino trajectory, leading to strong modifications for neutrinos crossing the Earth ($\cos \theta_Z = -1$), while neutrinos from the horizontal direction ($\cos \theta_Z = 0$) are almost unaffected. The experimental effects of sterile neutrino mixing for neutrinos with energies below 100 GeV are independent of the sterile neutrino mass splitting $\Delta m^2_{31}$ for values above 0.3 eV$^2$. Larger mass splittings result in rapid oscillations, which IceCube DeepCore cannot resolve and do not modify the sterile neutrino signal.

2. DeepCore and IceCube

DeepCore [5] is a densely instrumented area of the IceCube Neutrino Observatory [6] designed for particle physics studies. Digital Optical Modules (DOM) with 35% higher quantum efficiency are used in this region. The horizontal spacing between DOMs is reduced from 125 to 40-60 meters and vertical spacing is 7 meters compared to 17 m in other parts of the detector. This increases the detection efficiency for charged particles produced by neutrino interactions and lowers the energy threshold for neutrino detection to $\sim 10$ GeV. The outer layers of the IceCube detector are used to reject atmospheric muons.

3. Data selection and analysis

Three years of DeepCore data were used to constrain the mixing parameters $\theta_{23}$ and $\Delta m^2_{23}$ [7]. This study uses essentially the same event selection with minor improvements in background rejection to search for sterile neutrino mixing.

The event selection is designed to identify events with long distinguishable muon tracks produced by the charged current interactions of muon neutrinos. The existence of a long track yields a median zenith resolution of $12^\circ$ at 10 GeV, which improves to $5^\circ$ at 40 GeV. The full energy of neutrinos in CC interactions can be reconstructed as the neutrino loses all of its energy in such interactions. Another task of the event selection is to reject the background of atmospheric muons. This is achieved by studying the light signals outside the DeepCore region. The muon background was reduced using slightly stricter fiducial volume

![Figure 1](image1.png)

**Figure 1:** Survival probability for standard neutrino oscillations (left) and the “3+1” model (right). The values assumed for the standard atmospheric mixing are $\Delta m^2_{31} = 2.6 \times 10^{-3}$ eV$^2$, $\sin^2 \theta_{23} = 0.51$.

![Figure 2](image2.png)

**Figure 2:** Ratio between the expected event rates for the standard three neutrino mixing hypothesis and the “3+1” hypothesis.
criteria than in [7]. A data driven template is used to estimate the impact of the remaining atmospheric muons.

Three years of data (2011-2013), comprising 5118 events in total [8], are used in this study. The data are binned in a two-dimensional histogram of reconstructed energy, $E_{\text{reco}}$, and direction, $\cos \theta_2$. Figure 2 illustrates the impact of an additional sterile neutrino family on the expected event count in the experimental binning. The probabilities of neutrino oscillations are calculated with GLoBES [9].

A Poisson likelihood with nuisance parameters is maximized to find the best estimate of the sterile neutrino mixing parameters. There are 12 nuisance parameters to account for the systematic uncertainties from the standard neutrino mixing parameters, atmospheric neutrino fluxes, detector parameters, cross sections and background. Confidence levels (C.L.) are estimated using Wilk’s theorem [10].

4. Results

The data show good agreement with predictions from simulations with $\chi^2 = 52.5/51$ d.o.f. The best estimate of the sterile neutrino mixing matrix elements are

$$|U_{\mu 4}|^2 = 0.0, \ |U_{\tau 4}|^2 = 0.075. \quad (3)$$

The best fit for the standard atmospheric mixing parameters are $\Delta m_{42}^2 = 2.52 \times 10^{-3}$ eV$^2$ and $\sin^2 \theta_{23} = 0.54$. The fitted values are consistent with the expectation from the Standard (three neutrino) Model with a log-likelihood (LLH) difference of $-2\Delta$LLH = 0.7, which corresponds to 70% probability to observe the fitted value from pure statistical fluctuations. Therefore we set limits on the sterile neutrino mixing elements

$$|U_{\mu 4}|^2 < 0.12 \ (90\% \ \text{C.L.}),$$
$$|U_{\tau 4}|^2 < 0.15 \ (90\% \ \text{C.L.}) \quad (4)$$

The exclusion contours for the mixing matrix elements are shown in Figure 3 in comparison to the corresponding limits from Super-Kamiokande experiment [11].

This study provides the best current limit on the $|U_{\tau 4}|$ mixing element. The present study is statistics limited and extending the event selection to include more years of data and additional event topologies may lead to a significant improvement in sensitivity.

References
1. Gonzalez-Garcia M C, Maltoni M and Schwetz T 2014 Journal of High Energy Physics 2014 52
2. Kopp J, Machado P A N, Maltoni M and Schwetz T 2013 Journal of High Energy Physics 2013 1–52
3. Razzaque S and Smirnov A Y 2011 Journal of High Energy Physics 2011 1–36
4. Razzaque S and Smirnov A Y 2012 Phys. Rev. D 85(9) 093010
5. Abbasi R et al. (IceCube collaboration) 2012 Astropart. Phys. 35 615
6. Achterberg A et al. (IceCube collaboration) 2006 Astropart. Phys. 26 155
7. Aartsen M et al. (IceCube collaboration) 2015 Phys. Rev. D 91 072004
8. http://icecube.wisc.edu/science/data/nu_osc/
9. Wilks S 1938 Ann. Math. Statist. 9 60–62
10. Abe K et al. (Super-Kamiokande Collaboration) 2015 Phys. Rev. D 91(5) 052019