Is there evidence for sterile neutrinos in IceCube data?

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Data from the LSND and MiniBooNE experiments, and revised expectations of the antineutrino flux from nuclear reactors suggest the existence of eV-mass sterile neutrinos. 3 + 2 and 1 + 3 + 1 scenarios accommodate all relevant short-baseline neutrino data except for the low-energy MiniBooNE anomaly. We analyze the angular distribution of upward going atmospheric neutrino events in the IceCube-40 dataset for evidence of sterile neutrinos within these scenarios. Depending on how systematic uncertainties are handled, we find strong evidence for, or weak evidence against sterile neutrinos. We show that future IceCube data will definitively settle the issue.

| δm² | | U_e4 | | U_µ4 | | U_τ5 | | U_µ5 | | δ/π |
|------|------|------|------|------|------|------|------|
| 3+2  | 0.47 | 0.87 | 0.128| 0.165| 0.138| 0.148| 1.64 |
| 1+3+1(a) | -0.47 | 0.87 | 0.129| 0.154| 0.142| 0.163| 0.35 |
| 1+3+1(b) | 0.47  | -0.87| 0.129| 0.154| 0.142| 0.163| 1.65 |

TABLE I. Global best-fit parameters to data from short-baseline experiments [4]. The two 1+3+1 cases correspond to either m4 or m5 being the lightest state. The active neutrinos have a normal hierarchy, and θ13 = 0.

δm² ~ 1 eV², resonant oscillations are possible for TeV atmospheric neutrinos [7]. In its 40-string configuration, IC has observed 12877 atmospheric muon neutrino events in the energy range 332 GeV–84 TeV [8].

In this Letter, we analyze the zenith-angle distribution of the IC data to see if it provides supporting evidence for sterile neutrino explanations of the SBL data and the reactor antineutrino anomaly as encapsulated by the scenarios of Table I and assess the future sensitivity of the IC detector. The energy window of the IC dataset is optimal as can be seen from Fig. 1. We expect IC data to not be very sensitive to the 3 + 2 case since the resonance occurs in the $\bar{\nu}_\mu$ channel which is subdominant in the atmospheric flux. In the 1 + 3 + 1 cases, the dominant $\nu_\mu$ flux is also suppressed so that these cases can be discriminated more readily from the 3ν case.

The muon events at IC can be classified as (i) ‘contained’ events, namely events with muon tracks that start within the instrumented volume, and (ii) ‘up-going’ events in which the muon is produced outside the detector. See Eqs. 8 and 10 of Ref. [10] for details and note that the incident $\nu_\mu$ flux includes a contribution from $\nu_e \rightarrow \nu_\mu$ oscillations.

For the points in Table I the muon neutrino flux is suppressed by ~ 10% above 100 GeV, with a corresponding reduction in the muon event rate. Thus, the 25% uncertainty in the atmospheric neutrino flux [11] is a serious impediment to a rate analysis. Instead, a distortion in the zenith-angle distribution of the detected muons would provide the strongest evidence for sterile neutrinos. As
most sub-TeV neutrinos do not distort the angular distribution, useful information may be extracted from high-energy events. It so happens that the cut at 332 GeV suppresses 90% of sub-TeV muon events while leaving a large sample of $10^4$ events.

To make it to the detector, up-going muons can travel at most the stopping distance which increases with energy. As a result, the effective volume for neutrinos is larger for high energy neutrinos that more readily produce energetic muons. In turn, the up-going sample has a larger fraction of high-energy events than the contained sample, making it particularly valuable in an analysis of a larger fraction of high-energy events than the contained events. To account for experimental efficiencies, we determine the theoretical zenith-angle spectrum as in Ref. [13]:

\[
S_i^{th} = a[1 + b(\cos \theta_z) + 0.5] \frac{N_i^{MC}}{N_i^{3\nu}} N_i^{th},
\]

where $N_i^{th}$ is the number of muon events in angular bin $i$, and $N_i^{MC}/N_i^{3\nu}$ is a bin-wise factor that scales our theoretical $3\nu$ prediction to IceCube’s Monte Carlo [8]. $a$ is an overall normalization and $b$ allows a systematic tilt of the spectrum. Both parameters are allowed to float in a $\chi^2$ analysis. Note that $S_i^{th} = N_i^{MC}$ in the $3\nu$ case with $a = 1, b = 0$.

The upper panel of Fig. 2 illustrates the event rate suppression and zenith-angle distributions in the scenarios under consideration. The large difference of the sterile neutrino scenarios from the IC data and from the $3\nu$ expectations in the near-vertical ($-1.0 \leq \cos \theta_z \leq -0.9$) bin promises much discriminating power. The near-horizon ($-0.1 \leq \cos \theta_z \leq 0$) bin has potentially large systematic errors from the misidentification of coincident downward events as horizontal events, and we do not include it in
our $\chi^2$ analysis. For our analyses we define

$$\chi^2 = \frac{(1-a)^2}{\sigma_a^2} + \sum_i (S_i^{th} - S_i^{exp})^2,$$

(2)

where $\sigma_a = 0.25$ is the percent uncertainty in the atmospheric flux normalization [11] and $S_i^{exp}$ denotes either real or simulated data. In what follows, we always fit $a$, and either set $b = 0$ or marginalize over $b$ without penalty. The lower panel of Fig. 2 shows the spectral distortion of the IC data and the sterile neutrino scenarios relative to $3\nu$ oscillations. In the latter case, $a = 1, b = 0$, while the best-fit value of $a$ is used for the sterile cases with $b = 0$.

The results of fitting the 9 non-horizontal ($\cos \theta_z < -0.1$) bins are shown in Fig. 3 and Table II. The $3\nu$ scenario gives a better fit provided the data are plagued by a large systematic tilt. If $|b|$ is restricted to be smaller than 0.11, the $3\nu$ fit yields a $\chi^2$ of 15.8, which is comparable to the values ($\sim 15$–16) of the sterile neutrino cases.

A natural question is if there are correlated signals in cascade events at IC. Interestingly, above 332 GeV, we find a comparable total number of $\nu_e$ plus $\nu_\tau$ events/km$^2$/year in the $3\nu$ ($\sim 890$) and sterile neutrino ($\sim 850$) cases. The corresponding number of induced cascade events can be obtained by folding with the IC efficiency which is not available to us.

That future IC data with systematics under control have the ability to reveal a deviation due to sterile neutrinos is evident from Fig. 4. The monotonically rising event ratio as a function of $\cos \theta_z$ in the up-going event sample is a striking signature of sterile neutrino oscillations. On the other hand, strong exclusions can also be obtained. Assuming a sample of $6.5 \times 10^4$ up-going events with no deviation from the $3\nu$ result, and fitting to all 10 angular bins with only a varied yields $\chi^2 = 111$, 386 and 331 for the $3+2$, $1+3+1(a)$ and (b) cases, respectively, compared to a $\chi^2 \sim 10$ for $3\nu$ oscillations. An interesting aspect of the contained event sample is that in all cases the zenith-angle distribution is almost flat for $-0.8 < \cos \theta_z < -0.2$ so that the features in the near-vertical and near-horizon bins are insensitive to a systematic tilt. With $6.5 \times 10^4$ contained events, we find $\chi^2 = 28, 165$ and 87 for the $3+2$ and $1+3+1(a)$ and (b) cases, respectively. With such sensitivity IC will easily confirm or exclude sterile neutrino scenarios.

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**References**

[1] A. Aguilar et al. [LSND Collaboration], Phys. Rev. D 64, 112007 (2001) [arXiv:hep-ex/0104049].

[2] A. A. Aguilar-Arevalo et al. [MiniBooNE Collaboration], Phys. Rev. Lett. 105, 181801 (2010) [arXiv:1007.1150 [hep-ex]].
[3] T. A. Mueller et al., Phys. Rev. C 83, 054615 (2011) [arXiv:1101.2663 [hep-ex]].
[4] J. Kopp, M. Maltoni, T. Schwetz, arXiv:1103.4570 [hep-ph].
[5] J. Hamann, S. Hannestad, G. G. Raffelt, Y. Y. Y. Wong, arXiv:1108.4136 [astro-ph.CO].
[6] T. K. Gaisser [for the IceCube Collaboration], arXiv:1108.1838 [astro-ph.HE].
[7] H. Nunokawa, O. L. G. Peres, R. Zukanovich Funchal, Phys. Lett. B562, 279-290 (2003) [arXiv:hep-ph/0302039]; S. Choubey, JHEP 0712, 014 (2007) [arXiv:0709.1937 [hep-ph]].
[8] R. Abbasi et al. [IceCube Collaboration], arXiv:1104.5187 [astro-ph.HE].
[9] A. M. Dziewonski, D. L. Anderson, Phys. Earth Planet. Interiors 25, 297-356 (1981).
[10] V. Barger, Y. Gao, D. Marfatia, Phys. Rev. D83, 055012 (2011) [arXiv:1101.4410 [hep-ph]].
[11] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, T. Sanuki, Phys. Rev. D 75, 043006 (2007) [arXiv:astro-ph/0611418].
[12] S. Grullon, private communication.
[13] S. Razzaque, A. Y. Smirnov, JHEP 1107, 084 (2011) [arXiv:1104.1390 [hep-ph]].