Short Baseline Neutrino Oscillation Experiments

Teppei Katori
Queen Mary University of London, London E1 4NS, UK
E-mail: t.katori@qmul.ac.uk

Abstract. Series of short baseline neutrino oscillation experiments provided unexpected results, and now they are called short baseline anomalies, and all indicates an existence of sterile neutrinos with a mass scale around 1 eV. The signals of short baseline anomalies are reported from 4 different classes of experiments. However, at this moment, there is no convincing theoretical model to explain such sterile neutrinos, and a single experiment to confirm 1 eV sterile neutrinos may be challenging. In this short note, we describe classes of short baseline neutrino oscillation experiments and their goals.

Classification of short baseline neutrino oscillation experiments

The short baseline anomalies come from 4 different classes of experiments [1]. Based on this, we can classify short baseline neutrino oscillation experiments into following 5 groups;

(i) test of LSND signal,
(ii) test of MiniBooNE signal,
(iii) test of reactor antineutrino anomaly,
(iv) test of Gallium anomaly, and
(v) others.

We discuss each of the above group in following sections. The last group is all other experiments, they are mainly experiments motivated by 1 eV sterile neutrinos and not short baseline anomalies themselves. Therefore many experiments in (v) are not short baseline oscillation experiments.

The short baseline anomalies are unsolved mysteries in this community, and they attract many theorists and experimentalists. The search of 1 eV sterile neutrino is one of the big branches of the neutrino experiment community [2]. Therefore, it is rather impossible to cover all experiments in this note, however, we try to cover most of experiments planned in the near future.
1. LSND signal and experiments designed to test to it

**LSND experiment**

The origin of $\Delta m^2_{\text{sterile}} \sim 1 \text{ eV}^2$ is the LSND experiment [3], where muon antineutrinos (0 to 53 MeV) are produced by pion decay-at-rest (DAR), and detected by a liquid scintillator detector at 31 m from the target. The LSND experiment measured $\bar{\nu}_e$ candidate events by utilizing the coincidence of the prompt Cherenkov radiation from the positron and the delayed neutron capture by a hydrogen.

$$\bar{\nu}_\mu \overset{\text{oscillation}}{\longrightarrow} \bar{\nu}_e + p \rightarrow e^+(\text{Cherenkov}) + n(\text{capture}) .$$

The LSND experiment observed an excess of $\bar{\nu}_e$ candidate events. This small (< 1% oscillation probability) but statistically significant signal is consistent with the presence of sterile neutrinos ($\bar{\nu}_\mu \rightarrow \nu_{\text{sterile}} \rightarrow \bar{\nu}_e$).

Meantime, the KARMEN experiment [4] excluded high $\Delta m^2$ region, and the Bugey experiment [5] excluded all low $\Delta m^2$ region of the LSND signal region in $\Delta m^2 - \sin^2 2\theta$ plane. The combined result suggests the LSND signal is most likely due to sterile neutrinos around 1 eV region.

**Experiments to test LSND signal**

The LSND experiment has limited statistics, also, the duty cycle (nominal run, $\sim$25 Hz) was high with a wide pulse. This allows LSND to accept large amount of cosmic backgrounds. Also, the detector was located to the direction of the primary beamline, and neutrinos from pion decay-in-flight (DIF) made additional backgrounds. Therefore, to test LSND signal, experiments are desired to have:

- LSND beam energy, baseline, and the detector which can tag $\bar{\nu}_e$ candidate events,
- higher statistics,
- known and narrow beam structure, and
- detector located on off-axis.

The promising experiments are off-axis liquid scintillator experiments at various neutron spallation sources in the world. The high pion-DAR $\bar{\nu}_\mu$ flux is available (and free!) from Oak Ridge National Laboratory (ORNL) [6], J-PARC Materials and Life Science Experimental Facility (MLF) [7], and European spallation source (ESS) [8]. On top of the high neutrino flux, proton pulses hitting the target to produce neutrons have well known beam structure. Therefore these experiments cover the desired features to test the LSND signal. Presently, OscSNS [6] is about to write a proposal, and J-PARC group [7] submitted proposal to J-PARC.
2. MiniBooNE signal and experiments designed to test it

*MiniBooNE experiment*

The MiniBooNE experiment is designed to test the LSND signal within the two massive neutrino oscillation hypothesis. However, muon (anti)neutrinos are now made by pion DIF at the Fermilab Booster neutrino beamline [9], and the baseline is 541 m from the target (pion decay length is $\sim 18$ m). The MiniBooNE detector is a spherical mineral oil based Cherenkov detector [10], and the $\nu_e (\bar{\nu}_e)$ candidate signals are measured as single isolated electron-like Cherenkov ring. In this way, the systematics of MiniBooNE is completely different from the LSND experiment, but MiniBooNE can test 1 eV sterile neutrino hypothesis, because of similar L/E with LSND.

\[
\nu_\mu \to \nu_e + n \to p + e^+ (\text{Cherenkov}), \\
\bar{\nu}_\mu \to \bar{\nu}_e + p \to n + e^- (\text{Cherenkov}).
\]

The Booster neutrino beamline can run either in neutrino mode or in antineutrino mode, by focussing either positive or negative mesons. Since LSND signal was interpreted $\bar{\nu}_\mu \to \nu_{\text{sterile}} \to \bar{\nu}_e$ oscillations, running in antineutrino mode is more interesting. However, the antineutrino mode run suffers from lower statistics and higher backgrounds [11] (especially from the muon-neutrino contamination in the antineutrino mode beam [12]), therefore the experiment started in neutrino mode prior to the antineutrino mode running, and in the meantime systematics (the neutrino flux, neutrino interactions, and the detector response) were studied.

Unlike the LSND experiment, expected signal to noise is much lower. There are 2 dominant backgrounds of $\nu_e (\bar{\nu}_e)$ candidate events. The first one is the intrinsic $\nu_e (\bar{\nu}_e)$ contaminated in the beam. The majority of them are made by muon decay, therefore, MiniBooNE constrains them by simultaneously measuring $\nu_\mu$ charged current quasi-elastic (CCQE) events [13, 14], where measured $\nu_\mu$ is related to intrinsic $\nu_e$ through the pion decay chain ($\pi^+ \to \nu_\mu + \mu^+\mu^-$, $\mu^+\mu^- \to \bar{\nu}_\mu + e^+ + \bar{\nu}_e$) in their simulation.

The second largest background is the misID of neutral current (NC) events, mainly NC $\pi^0$ production. Although a $\pi^0$ decays to two gamma rays which should be distinguishable from an electron (positron) Cherenkov ring, sometimes decay kinematics make two gamma rays look like one gamma ray (asymmetric decay, gamma rays are too close). Then, the Cherenkov ring from one gamma ray is indistinguishable from an electron (positron). For this, MiniBooNE internally measured NC $\pi^0$ production, and the measured information was used to correct $\pi^0$ production rates in the simulation [15].

After the 10 years running in both neutrino and antineutrino mode, the MiniBooNE experiment observed excesses in both neutrino and antineutrino mode runs [16]. The final result is shown in Figure 1.
Figure 1. (color online) The final MiniBooNE oscillation results [16]. The top plots are antineutrino mode results, and bottom plots are neutrino mode results. The left plots show the reconstructed neutrino energy distribution of oscillation candidate events, and the right plots show the allowed region in $\Delta m^2 - \sin^2 2\theta$, where the best fit points are shown in black stars. Both modes show excesses in the low energy region, while the neutrino mode has higher statistical significance. On the other hand, the compatibility with the LSND signal is better in antineutrino mode.

Experiments to test MiniBooNE signal

The measured signal, especially in neutrino mode, does not quite agree with the expected sterile neutrino signal. The MiniBooNE detector cannot distinguish an electron (positron) and a gamma ray, therefore $\nu_\mu$ NC interaction with single gamma ray in the final state is a potential misID background. Therefore, to test the MiniBooNE signal, experiments are desired to have;

- MiniBooNE beam energy and baseline,
- ability to distinguish NC or CC interaction, or
- ability to distinguish an electron (positron) and a gamma ray.

The MiniBooNE+ was proposed to fulfill these criteria [17]. By doping scintillator (PPO) in the MiniBooNE detector mineral oil, MiniBooNE+ can measure scintillation light from the neutron capture. This allows statistical separation between $\nu_e$ CCQE interaction (higher proton multiplicity in the final state), and $\nu_\mu$ NC interactions (protons and neutrons are half-and-half in the final state). However, the proposal of MiniBooNE+ was not accepted by Fermilab recently.
The MicroBooNE experiment [18] is a new experiment on the Fermilab Booster neutrino beamline to test the MiniBooNE signal. It is also an important project for the future large liquid argon (LAr) TPC experiment, such as LBNE [19]. The MicroBooNE LArTPC detector has an ability to separate an electron from single gamma ray, by utilizing vertex-shower separation and dE/dx before developing the shower. This clearly tells if MiniBooNE excess is by an electron (positron) or a gamma ray [20]. The MicroBooNE experiment is under commissioning stage, and they expect beam data at the end of 2014.

Although the T2K experiment [21] is designed to measure the neutrino Standard Model ($\nu_{\text{SM}}$) parameters and it does not use the Booster neutrino beam, J-PARC neutrino beam [22] has a similar beam peak ($\sim$600 MeV) as the Booster neutrino beam but is narrower, and the baseline to the near detector complex [23] is close (280 m) to what MiniBooNE has. Therefore, T2K is sensitive to the MiniBooNE signals ‡. The magnetic field in the near detector is a great advantage. It can allow the sign selection of the signal. The NC background (mostly ambient gamma rays) can be understood from the internal measurement [25].

3. Reactor antineutrino anomaly and experiments designed to test it

Reactor antineutrino anomaly

The re-evaluation of reactor electron antineutrino flux calculation provides consistently lower rate than world reactor data (about 6%) [26]. This, so called reactor antineutrino anomaly can be interpreted as neutrino oscillations with 1 eV sterile neutrinos [27].

Experiments to test Reactor anomaly

Reactor anomaly can be tested by small scale experiments, by measuring neutrino flux with small detectors with very short baseline ($\sim$15 m). To detect low energy reactor antineutrinos ($\sim$4 MeV), detector needs to be sensitive to low energy events. The common choice is the liquid scintillator detector, where large mass can be prepared at a relatively low cost.

There are number of such experiments designed for R&D of neutrino reactor monitoring for nuclear non-proliferation (SCRAAM [28], Nuifer [29], etc). These experiments are naturally served to test reactor antineutrino anomaly. Due to affordable cost of the experiments, several new experiments are also proposed to test the reactor antineutrino anomaly (DANSS [30], PROSPECT [31], STEREO [32], etc).

‡ Current sterile neutrino search analysis in T2K is looking for $\nu_e$ disappearance [24], instead of $\nu_e$ appearance.
4. Gallium anomaly and experiments designed to test

**Gallium anomaly**

The two of pp-solar neutrino experiments, SAGE [33] and GALLEX [34], used highly radioactive sources to calibrate gallium detectors.

\[ \nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^- \]  

But some of these measurements using mega-curie $^{51}$Cr or $^{37}$Ar sources showed lower event rates than expected, and this so-called **Gallium anomaly** can be understood by neutrino oscillations with 1 eV sterile neutrinos [35].

**Experiments to test Gallium anomaly**

To test Gallium anomaly, a highly radio-active neutrino source and a very sensitive detector are required. Existing high sensitivity solar or reactor neutrino detectors (Borexino as “SOX” [36], KamLAND as “Ce-LAND” [37], SNO+ [39], DayaBay [38], etc) are good candidates for this purpose. Similarly, SAGE group proposed to build a new detector but reuse the liquid gallium from old detectors [40]. Proposed solar neutrino experiment (LENS [41], etc) and coherent scattering experiment (RICOCHET [42], etc) can look for 1 eV sterile neutrinos, too.

5. Others, 1 eV sterile neutrino searches

**Tests by existing facilities**

Once we assume 1 eV sterile neutrinos, some existing facilities are also sensitive to signals, even though the experiments are not originally designed to test 1 eV sterile neutrinos. The IceCube experiment [43] is designed to measure astrophysical ultra high energy neutrinos, however, 1 eV sterile neutrinos cause disappearance signals for >100 GeV high energy atmospheric neutrinos [44]. MINOS+ experiment [45] is an extension run of MINOS experiment [46, 47] during NOvA beam configuration era (medium energy NuMI, ~7 GeV peak at Sudan mine) [48]. One of physics goal of MINOS+ is to look for $\nu_\mu$ disappearance signal due to 1 eV sterile neutrinos.

**Tests by R&D facilities**

Many R&D experiments for other purposes often look for 1 eV sterile neutrinos. For example IsoDAR experiment [49] look for sterile neutrino oscillation using $^8$Li isotope made by the high power cyclotron. This cyclotron is a part of the R&D for the DAEδALUS experiment [50]. The $\nu$STORM [51] experiment uses the muon storage ring, which is an important step for the future neutrino factory [52]. KDAR experiment [53] uses mono-energetic kaon DAR muon neutrinos (236 MeV), and the detector requires high resolution, such as LArTPC. This can be considered a part of LArTPC technology R&D, and in fact, all LArTPC sterile neutrino searches, such as MicroBooNE [18],...
LAr1-ND [54], and NESSiE [55], have detector R&D aspects for future large LArTPC experiments.

Ultimate 1 eV sterile neutrino search experiments

Experiments including precise measurement of oscillation probability with function of L/E can be considered in this group. LSND reloaded [56] was proposed to test short baseline neutrino oscillations by measuring oscillations with function of L/E in a large detector, such as gadolinium doped Super-Kamiokande. Similar concept may be applied to reactor antineutrino anomaly experiments and gallium anomaly experiments, where neutrino sources are small and low energy. In those experiments, precise L/E dependence measurement may be possible by either using a large detector or multiple small detectors, or moving sources and/or detectors. The precise oscillation measured in this way is a strong evidence of sterile neutrinos and it is a missing part from past experiments.

Aknowledgement

The author thanks Ranjan Dharmapalan for the careful reading of this manuscript. The author thanks to the organisers of “NuPhys2013, prospects in neutrino physics, (Institute of Physics, London, UK)” for the invitation to the conference.

References

[1] Abazajian K, Acero M, Agarwalla S, Aguilar-Arevalo A, Albright C et al. 2012 (Preprint 1204.5379)
[2] de Gouvea A et al. (Intensity Frontier Neutrino Working Group) 2013 (Preprint 1310.4340)
[3] Aguilar-Arevalo A et al. (LSND Collaboration) 2001 Phys.Rev. D64 112007 (Preprint hep-ex/0104049)
[4] Armbruster B et al. (KARMEN Collaboration) 2002 Phys.Rev. D65 112001 (Preprint hep-ex/0203021)
[5] Declais Y, Favier J, Metref A, Pessard H, Achkar B et al. 1995 Nucl.Phys. B434 503-534
[6] Allen R et al. (OscSNS Collaboration) 2013 (Preprint 1307.7097)
[7] Harada M et al. 2013 (Preprint 1310.1437)
[8] Baussan E et al. (ESSnuSB Collaboration) 2013 (Preprint 1309.7022)
[9] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2009 Phys.Rev. D79 072002 (Preprint 0806.1449)
[10] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2009 Nucl.Instrum.Meth. A599 28–46 (Preprint 0806.4201)
[11] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2013 Phys.Rev. D88 032001 (Preprint 1301.7067)
[12] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2011 Phys.Rev. D84 072005 (Preprint 1102.1964)
[13] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2008 Phys.Rev.Lett. 100 032301 (Preprint 0706.0926)
[14] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2010 Phys.Rev. D81 092005 (Preprint 1002.2680)
[15] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2008 Phys. Lett. B664 41–46 (Preprint 0803.3423)
[16] Aguilar-Arevalo A et al. (MiniBooNE Collaboration) 2013 Phys. Rev. Lett. 110 161801 (Preprint 1207.4809)
[17] Dharmapalan R et al. (MiniBooNE Collaboration) 2013 (Preprint 1310.0076)
[18] Camilleri L (MicroBooNE Collaboration) 2013 Nucl. Phys. Proc. Suppl. 237-238 181–183
[19] Alkire T et al. (LBNE Collaboration) 2011 (Preprint 1110.6249)
[20] Fleming B T 2011 J. Phys. Conf. Ser. 308 012007
[21] Abe K et al. (T2K Collaboration) 2014 Phys. Rev. Lett. 112 061802 (Preprint 1311.4750)
[22] Abe K et al. (T2K Collaboration) 2013 Phys. Rev. D88 032002 (Preprint 1304.0841)
[23] Abe K et al. (T2K Collaboration) 2011 Nucl. Instrum. Meth. A659 106–135 (Preprint 1106.1238)
[24] SGALABERNA D 2014 PoS EPS-HEP2013 011
[25] Abe K et al. (T2K Collaboration) 2014 (Preprint 1403.2552)
[26] Mueller T, Lhuillier D, Fallot M, Letourneau A, Cormon S et al. 2011 Phys. Rev. C83 054615 (Preprint 1101.2663)
[27] Mention G, Fechner M, Lasserre T, Mueller T, Lhuillier D et al. 2011 Phys. Rev. D83 073006 (Preprint 1101.2755)
[28] Bowden N, Bernstein A, Dazeley S, Svoboda R, Misner A et al. 2008 J. Appl. Phys. (Preprint 0808.0698)
[29] Porta A (Nucifer Collaboration) 2010 Journal of Physics: Conference Series 203 012092
[30] Danilov M (DANSS Collaboration) 2013 (Preprint 1311.2777)
[31] Djuricic Z, Hans S, Yeh M, Blucher E, Johnson R et al. 2013 (Preprint 1309.7647)
[32] Lhuillier D 2014 PoS EPS-HEP2013 522
[33] Abdurashitov J et al. (SAGE Collaboration) 2009 Phys. Rev. C80 015807 (Preprint 0901.2200)
[34] Hampel W et al. (GALLEX Collaboration) 1999 Phys. Lett. B447 127–133
[35] Giunti C and Laveder M 2011 Phys. Rev. C83 065504 (Preprint 1006.3244)
[36] Bellini G et al. (Borexino Collaboration) 2013 (Preprint 1304.7721)
[37] Gando A, Gando Y, Hayashida S, Ikeda H, Inoue K et al. 2013 (Preprint 1309.6805)
[38] Dwyer D, Heeger K, Littlejohn B and Vogel P 2013 Phys. Rev. D87 093002 (Preprint 1109.6036)
[39] O’Keefe H, Kraus C, Wan Chan Tseung H and Wilson J (SNO+ Collaboration) 2012 Nucl. Phys. Proc. Suppl. 229-232 552
[40] Gorbachev V, Veretenkin E, Gavrin V, Dan’shin S, Ibragimova T et al. 2013 Phys. Atom. Nucl. 76 1507–1511
[41] Grieb C, Link J and Raghavan R 2007 Phys. Rev. D75 093006 (Preprint hep-ph/0611178)
[42] Anderson A, Conrad J, Figueroa-Feliciano E, Scholberg K and Spitz J 2011 Phys. Rev. D84 013008 (Preprint 1103.4894)
[43] Aartsen M et al. (IceCube) 2013 Science 342 1242556 (Preprint 1311.5238)
[44] Barger V, Gao Y and Marfatia D 2012 Phys. Rev. D85 011302 (Preprint 1109.5748)
[45] Evans J (MINOS) 2013 Adv. High Energy Phys. 2013 182537 (Preprint 1307.0721)
[46] Adamson P et al. (MINOS Collaboration) 2013 Phys. Rev. Lett. 110 251801 (Preprint 1304.6335)
[47] Adamson P et al. (MINOS Collaboration) 2011 Phys. Rev. Lett. 107 011802 (Preprint 1104.3922)
[48] Messier M (NOvA Collaboration) 2013 (Preprint 1308.0106)
[49] Bunge A, Adelmann A, Alonso J, Barletta W, Barlow R et al. 2012 Phys. Rev. Lett. 109 141802 (Preprint 1205.4419)
[50] Aberle C, Adelmann A, Alonso J, Barletta W, Barlow R et al. 2013 (Preprint 1307.2949)
[51] Adiy D et al. (nuSTORM Collaboration) 2014 Phys. Rev. D89 071301 (Preprint 1402.5250)
[52] Tunnell C D, Cobb J H and Bross A D 2011 (Preprint 1111.6550)
[53] Spitz J 2012 Phys. Rev. D85 093020 (Preprint 1203.6050)
[54] Adams C et al. 2013 (Preprint 1309.7987)
[55] Antonello M, Bagliani D, Baudissinov B, Bilokon H, Boffelli F et al. 2012 (Preprint 1203.3432)
[56] Agarwalla S K and Huber P 2011 Phys. Lett. B696 359–361 (Preprint 1007.3228)