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Short Baseline Neutrino Oscillation Experiments

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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 $\Delta m^2_{sterile} \sim 1$ eV^2 is the LSND experiment [3], where muon antineutrino (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.

$$\bar{\nu}_\mu \stackrel{oscillation}{\longrightarrow} \bar{\nu}_e + p \to \mathrm{e}^+ (Cherenkov) + n(capture) \ .$$

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 ($\bar{\nu}_\mu \to \nu_{sterile} \to \bar{\nu}_e$).

Meantime, the KARMEN experiment [4] excluded high Δm^2 region, and the Bugey experiment [5] excluded all low Δm^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 ~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.

$$\nu_\mu \overset{oscillation}{\longrightarrow} \nu_e + n \to p + e^+ (Cherenkov) ,$$
$$\bar{\nu}_\mu \overset{oscillation}{\longrightarrow} \bar{\nu}_e + p \to n + e^- (Cherenkov) .$$

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 $\bar{\nu}_\mu \to \nu_{sterile} \to \bar{\nu}_e$ 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 ν_μ charged current quasi-elastic (CCQE) events [13, 14], where measured ν_μ is related to intrinsic ν_e through the pion decay chain ($\pi^+ \to \nu_\mu + \mu^+$, $\mu^+ -> \bar{\nu}_\mu + e^+ + \bar{\nu}_e$) in their simulation.

The second largest background is the misID of neutral current (NC) events, mainly NC π° production. Although a π° 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 NCπ° production, and the measured information was used to correct π° 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.
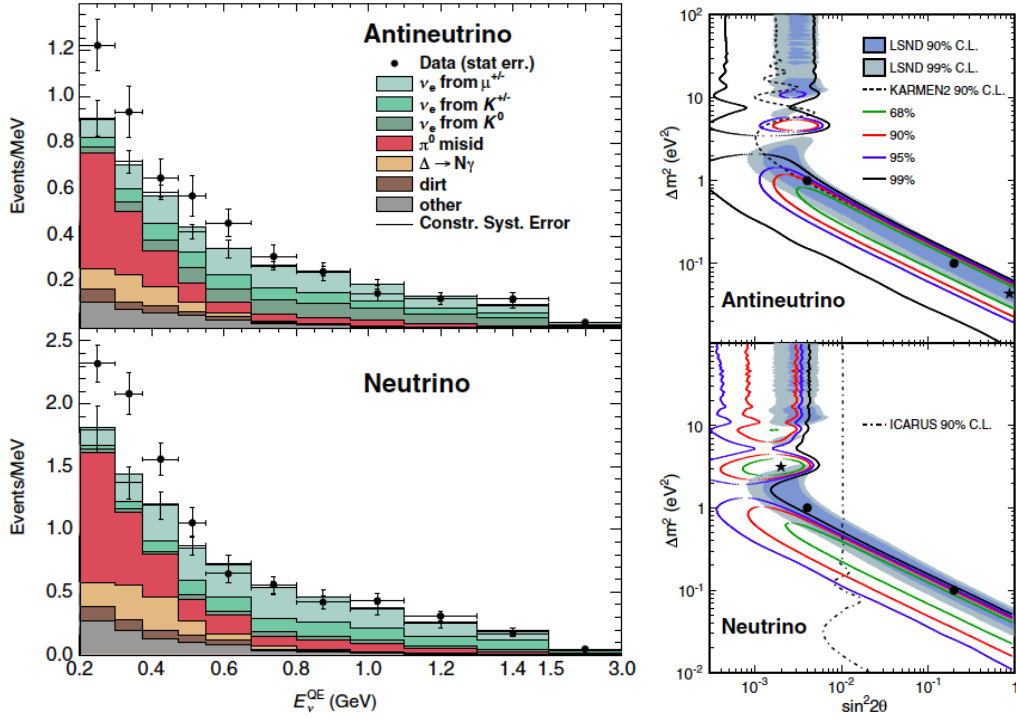
Figure 1. (color online) The final MiniBooNE oscillation results [16]. The top plots are antineutrino mode results, and bottom plots are neutrino mode results. The left plots show the reconstructed neutrino energy distribution of oscillation candidate events, and the right plots show the allowed region in Δm^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 ν_μNC 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 fulfil 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 ν_eCCQE interaction (higher proton multiplicity in the final state), and ν_μNC 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 (νSM) 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$15 m). To detect low energy reactor antineutrino ($\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], Nucifer [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 ν_e disappearance [24], instead of ν_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.

$$\nu_e +^{71} Ga \rightarrow^{71} Ge + e^- \ . \tag{1}$$

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 ν_μ 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 νSTORM [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.

Acknowledgement

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