Review and Summary of Short Baseline Neutrino Experiments

Josh Spitz, University of Michigan
NuFACT 2019, 8/26/2019
Short baseline summary

- Why are there short baseline neutrino experiments?
  - Mainly: various hints of anomalous electron-flavor appearance and disappearance may be indicative of a new neutrino participating in oscillations and/or some other new physics.
  - But, also:
    - Neutrino cross sections for informing long-baseline oscillations measurements.
    - Neutrino cross sections for understanding the neutrino interaction with matter.
    - Exotic searches (e.g. dark matter production) with high luminosity, fixed target.
    - Detector R&D.
Outline

• Non-oscillation physics

• Short review of the existing anomalies at short-baseline

• Discussion of the MiniBooNE anomaly

• A quick tour of current/future experiments
Outline

- Non-oscillation physics
- Short review of the existing anomalies at short-baseline
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Why neutrino cross section measurements at short-baseline?
Reminder

$\nu_e : \nu_\mu$ ?

Compare these ratios as a function of energy

\[ \nu_e : \nu_\mu \]

Turning near and far rate measurements into flux evolution (oscillation) measurements requires cross section knowledge.
Why neutrino cross section measurements at short-baseline?

- Neutrino interactions with nuclei are complicated!
  - Fermi motion.
  - Correlations between nucleons.
  - Final state interactions.
  - One nucleus is different than the next.
- Detector limitations
  - Energy resolution.
  - Event classification issues.
  - Cerenkov threshold.

Adapted from K. McFarland
Why neutrino cross section measurements at short-baseline?

- Neutrino interactions with nuclei are complicated!
  - Fermi motion
  - Correlations between nucleons.
  - Final state interactions.
  - One nucleus is different than the next.
- Detector limitations
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Solving these problems for the purposes of informing oscillation physics requires neutrino-nucleus cross section measurements in all relevant interaction channels, nuclear targets, and energies.

Accelerator-based short-baseline experiments are tackling these issues.

Adapted from K. McFarland
A few new cross section results

MicroBooNE CC-inclusive measurement

First Measurement of Inclusive Muon Neutrino Charged Current Differential Cross Sections on Argon at $E_\nu \sim 0.8$ GeV with the MicroBooNE Detector

![Graphs showing differential cross sections for different cosine values of the measured muon polar angle.](image)

1905.09694 (accepted by PRL)
A few new cross section results

MiniBooNE KDAR measurement

\[ \omega = E_\nu - E_\mu \]

First Measurement of Monoenergetic Muon Neutrino Charged Current Interactions


(MiniBooNE Collaboration)

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20Yale University, New Haven, Connecticut 06520, USA

We report the first measurement of monoenergetic muon neutrino charged current interactions. MiniBooNE has isolated 236 MeV muon neutrino events originating from charged kaon decay at rest (K^+ \rightarrow \mu^+ \nu_\mu) at the NuMI beamline absorber. These signal \nu_\mu-carbon events are distinguished from primarily pion decay in flight \nu_\mu and \nu_\tau backgrounds produced at the target station and decay pipe using their arrival time and reconstructed muon energy. The significance of the signal observation is at the 3.9\sigma level. The muon kinetic energy, neutrino-nucleus energy transfer (\omega = E_\nu - E_\mu), and total cross section for these events are extracted. This result is the first known-energy, weak-interaction-only probe of the nucleus to yield a measurement of \omega using neutrinos, a quantity thus far only accessible through electron scattering.
Exotic searches at short-baseline

High luminosity proton beam (100s of MeV to 10s of GeV)

Simple idea: make a new particle with your $10^{20}$-something protons on target and then watch it decay or interact in your neutrino detector

Large boost means there are less kinematic constraints on the scattering, compared to traditional direct DM searches

$$\text{Br}(\pi^0 \rightarrow \gamma \gamma) \approx 0.99$$
$$\text{Br}(\eta \rightarrow \gamma \gamma) \approx 0.39$$
Exotic searches at short-baseline

example: vector portal

Short-baseline neutrino experiments are very competitive with other techniques when it comes to exotic searches.
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• Discussion of the MiniBooNE anomaly
• A quick tour of current/future experiments
A number of anomalies seem to indicate that there may be a new characteristic oscillation frequency mode (indicative of a new neutrino state).

<table>
<thead>
<tr>
<th>Experiment name</th>
<th>Type</th>
<th>Oscillation channel</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>Low energy accelerator</td>
<td>muon to electron (antineutrino)</td>
<td>3.8σ</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>High(er) energy accelerator</td>
<td>muon to electron (antineutrino)</td>
<td>2.8σ</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>High(er) energy accelerator</td>
<td>muon to electron (neutrino)</td>
<td>4.5σ</td>
</tr>
<tr>
<td>Reactors</td>
<td>Beta decay</td>
<td>electron disappearance (antineutrino)</td>
<td>(varies)</td>
</tr>
<tr>
<td>GALLEX/SAGE</td>
<td>Source (electron capture)</td>
<td>electron disappearance (neutrino)</td>
<td>2.8σ</td>
</tr>
</tbody>
</table>

(there are also various null results in this “high-frequency oscillation” parameter space); MINOS(+), IceCube, KARMEN, CDHS, OPERA, …
Pion and muon decay-at-rest neutrinos

(LSND anomaly)

\[ \pi^+ \rightarrow \mu^+ \nu_\mu \]
\[ \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu \]
The Liquid Scintillator Neutrino Detector anomaly

- LSND observed $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1 \text{ eV}^2$.

\[ \Delta m^2_{\text{LSND}} \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}) \]
The Liquid Scintillator Neutrino Detector anomaly

- LSND observed $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ at 3.8σ significance with a characteristic oscillation frequency of $\Delta m^2 \sim 1$ eV$^2$.

- That’s odd. There are two characteristic oscillation frequencies in the three neutrino picture and they are precisely measured.

$$\Delta m^2_{\text{LSND}} \gtrsim 0.2 \text{ eV}^2 \quad (\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}})$$
Pion decay-in-flight

(MiniBooNE anomaly)

\[
\mu^- \rightarrow \nu_e^? 
\]
The MiniBooNE anomalies

MiniBooNE Collab., PRL 122 221801 (2018)

Note: MiniBooNE does not have the ability to distinguish between electrons and single-gammas. That is, it’s not clear if the excess is electron-like or gamma-like.
MiniBooNE allowed region below approximately region, while the OPERA 90% C.L. limits disfavor the limits are outside the MiniBooNE 95% C.L. and OPERA agreement between the LSND and MiniBooNE signals.

Within the LSND 90% C.L. band, which demonstrates good best-fit point in the energy range $\Delta m^2 > 10^{-3} eV^2$. In addition, they do not affect the gamma [3,39].

The figure shows the MiniBooNE best fit point. Also shown are 90% C.L. POT data sets for events with $\nu$ mode and antineutrino mode ($\bar{\nu}$ mode). The shaded areas show the 90% C.L. and 99% CL LSND experiments. The KARMEN2 90% C.L. two-neutrino oscillation model. The shaded areas show the 90% C.L. and OPERA $\sigma$.

FIG. 4. MiniBooNE allowed regions for a combined neutrino and antineutrino mode ($\nu$ and $\bar{\nu}$). For this oscillation fit the entire data set is used and the neutrino fluxes, reconstructions, backgrounds, and systematics of NC oscillation fit. In addition, they do not affect the gamma [3,39].

The curves show fits to the MiniBooNE data, assuming two-neutrino oscillation from LSND and $\sigma$.) in the energy spectrum is, therefore, consistent with the LSND excess of events in both oscillation probability and distribution from LSND $\chi^2$. The MiniBooNE allowed region from a two-neutrino oscillation fit to the data, shown in Fig. 19.

The best oscillation fit and a ground-only fit has a probability of 0.02%, while the best fit point is $\sin^2 2\theta = 0.84$ with a probability of 21.1%, and the back-run point.

$\nu$ mode: $12.84 \times 10^{20}$ POT $\bar{\nu}$ mode: $11.27 \times 10^{20}$ POT LSND.
Lack of observed muon disappearance rules out a generic 1 sterile neutrino model

**IceCube, MINOS(+), NOvA, MiniBooNE, CDHS see no muon-flavor disappearance at high-$\Delta m^2$**

Taking the observed MiniBooNE+LSND results at face value and assuming the addition of 1 light sterile neutrino, muon-flavor disappearance should have been seen by now.

\[ P_{ee} = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]
\[ P_{\mu\mu} = 1 - 4|U_{\mu4}|^2(1 - |U_{\mu4}|^2) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]
\[ P_{\mu e} = 4|U_{\mu4}|^2|U_{e4}|^2 \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]

M. Dentler et al., JHEP **08**, 010 (2018), 1803.10661
What is going on?

• 3+1 doesn’t work.
  • A number of global-fit papers consider the removal of an experiment or class of experiments when performing a 3+1 or 3+0 fit. In general, it is still hard to perform a reasonable fit in these cases.

• It is fairly clear that any new physics explanation likely requires ‘multiple layers’ to explain all the results.
  • One sterile neutrino and a new interaction or decay? Two/three sterile neutrinos?

• There may be new physics here. But, the possibility of underestimated/unknown systematics (“bad data”) remains. Global fits suffer badly from this very real possibility. We shouldn’t forget: Neutrino experiments are hard.

• Unfortunately, we have entered the realm of ‘sigmas doesn’t matter’, recalling that the MiniBooNE+LSND combo (w/o considering others) is now 6.1σ.
  • A wiggle in L/E, observation in multiple channels with coherence among the results (and cosmology), or some other smoking gun, needs to be seen for discovery!

• What to do? Keep pushing with better detectors and better neutrino sources. We must figure this out!
  • Even in the absence of an actual light sterile neutrino or other new physics, short-baseline experiments remain highly compelling.
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What is the source of the MiniBooNE anomaly?

A good model for the excess must agree with all of these distributions simultaneously and the beam-dump mode results.
Ok, so 3+1 is ruled out. Can the MiniBooNE anomaly be due to something else exotic, perhaps not involving neutrinos?

The MiniBooNE beam dump null result provides a pretty good answer to this question.

**Answer: probably not.**

[The exotic particle should probably be produced in beam dump running as well, but no excess is seen]
What is the source of the MiniBooNE anomaly?


New Physics Model for the MiniBooNE Excess

How are the new particles responsible for the excess sourced in this model?

Neutral Meson Decays
- Ruled out by MiniBooNE beam dump mode data.

Continuum Processes

Charged Meson ($K^+$ or $\pi^+$) Decays

How does this model produce the electron-like excess in MiniBooNE?

Decay in the Detector
- Is the decay visible or semi-visible?

Visible
- Ruled out by MiniBooNE excess angular distribution.

Semi-visible

Is the scattering elastic or inelastic?

Elastic
- Ruled out by MiniBooNE excess angular distribution.

Inelastic
- Allowed, but with mild tension with the beam dump null result.
What is the source of the MiniBooNE anomaly?


The MiniBooNE excess is broadly consistent with having something to do with neutrinos sourced from charged pion/kaon decays in the beamline, rather than something else new (dark matter, millicharged particle, light scalar, etc.). New physics or systematics?

Also, it’s very hard to imagine new physics explaining both LSND and MiniBooNE simultaneously without invoking oscillations (and recalling that the LSND signal signature was a positron PLUS neutron capture).
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A quick tour of selected and representative running and ‘now or next-two-years’ short-baseline experiments

[w/ apologies to other experiments (adequately covered elsewhere at NuFACT)]

- SBN at Fermilab (pion decay-in-flight)
- JSNS\(^2\) (pion/muon/kaon decay-at-rest)
- PROSPECT (reactor)

Please see: C. Giunti, T. Lasserre, arXiv:1901.08330 for a recent review on eV-scale sterile neutrinos, including current/future experiments
SBN Program at Fermilab

3 LArTPCs in the Booster Neutrino Beamline, looking for (among other things) muon->electron flavor oscillations as a function of L/E


ICARUS-T600

600 m, 470 t

MicroBooNE

470 m, 86 t

SBND

110 m, 112 t

SBND (first data in 2021)
MicroBooNE (running since late-2015)
ICARUS (fill in late-2019; first data in 2020)

Note: these detectors also see a NuMI off-axis component
SBN Program at Fermilab

3 LArTPCs in the Booster Neutrino Beamline

SBN proposal:
1503.01520

See SBND/ICARUS NuFACT talks by:
Stephen Dennis, Jaehoon Yu
SBN’s LArTPC technology provides the ability to “see” all aspects of a neutrino interaction (w/ few exceptions) and differentiate between electrons and gammas.

LArTPC (compare to MiniBooNE)
Although the challenge of LArTPC hardware gets most of the attention, teaching a computer to reconstruct LArTPC events is just as difficult IMHO.
MicroBooNE is laying the groundwork for SBN+DUNE

So far: LArTPC hardware R&D, reconstruction and pattern recognition, detector physics and calibration, and cross section measurements...with lots more to come, including a detailed study of the MiniBooNE excess region.

See MicroBooNE NuFACT talks by:
Adrien Hourlier
Pip Hamilton
Mark Ross-Lonergan
JSNS$^2$: J-PARC E56 Sterile $\nu$ search
@MLF
http://research.kek.jp/group/mlfnu/

J-PARC Facility (KEK/JAEA)
South to North

Neutrino Beams (to Kamioka)

Materials and Life Experimental Facility

3 GeV RCS
400MeV

25Hz 500kW now & will be 1MW

30GeV MR

CY2007 Beams
JFY2008 Beams
JFY2009 Beams

Bird’s eye photo in January of 2008
J-PARC Sterile Neutrino Search at the J-PARC Spallation Neutron Source (JSNS²)

- Direct test of LSND
- Target volume is Gd-loaded liquid scintillator
  - Phase 0: 17 tons w/ ~150 10” PMTs @ 24 m
  - Future phases: multi-detector
- Energy resolution $\sim 15\% / \sqrt{E} \text{ (MeV)}$
- Beam: 525 kW @ 3 GeV (w/ duty factor $\sim$5x10⁻⁶)
  - Ramping up to 700 kW in early-2020, eventually 1 MW.
- First data in early-2020!

See JSNS² NuFACT talks by:
Tomoyuki Konno
Fumihiko Suekane

JSNS² TDR: 1705.08629
Signal and background

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e, \quad \bar{\nu}_e + p \rightarrow e^+ + n \]

Signal

- Direct fast neutron
- Cosmic ray muons
- Fast neutron

Background

- Concrete, Iron, etc
- Gd loaded LS
- Capture gammas
- Recoil proton; 20-60MeV (mimics IBD prompt)
Using the Geant4-based simulation package RAT [52] for detector simulation and oscillation sensitivity results, we compare the difference in the muon kinematic predictions among the previously employed by other liquid scintillator experiments, such as KamLAND. The processes that are considered include scintillation, absorption, and reemission. The reflectivity dependence of surfaces in the detector is simulated using the models built into Geant4. All three have wavelength dependence.

While NuWro is the only generator used to produce simulated events, we did compare it to NuWro and employed for the event rate estimate here. The KDAR signal muons along with the non-KDAR muons. Fig. 4 shows the kinetic energies of the resulting events, mainly coming from kaon decay-in-flight.

**FIG. 4:** The charged current (CC) cross section on carbon at 236 MeV according to the RPA model [50], +np/nh). While NuWro is the only generator used to produce simulated events, we did compare it to NuWro and employed for the event rate estimate here.

**FIG. 5:** The muon and total kinetic energy (KE) distributions given by NuWro to that provided by JSNS². The ratio of integrated signal to background (red) is 66:1.

### IBD signature:

<table>
<thead>
<tr>
<th>Prompt signal</th>
<th>Time from beam</th>
<th>Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;T_p&lt;10μs</td>
<td>20&lt;E&lt;60MeV</td>
<td></td>
</tr>
<tr>
<td>Delayed signal</td>
<td>T_p&lt;T_d&lt;100μs</td>
<td>7&lt;E&lt;12MeV</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Global time (ns)</th>
<th>Flux (arbitrary units)</th>
<th>Event type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10⁰</td>
<td>ν total</td>
</tr>
<tr>
<td>200</td>
<td>10¹</td>
<td>ν from π</td>
</tr>
<tr>
<td>400</td>
<td>10²</td>
<td>ν from µ</td>
</tr>
<tr>
<td>600</td>
<td>10³</td>
<td>ν from K</td>
</tr>
<tr>
<td>800</td>
<td>10⁴</td>
<td>Prompt signal</td>
</tr>
<tr>
<td>1000</td>
<td>10⁵</td>
<td>Delayed signal</td>
</tr>
<tr>
<td>1200</td>
<td>10⁶</td>
<td>IBD Signal in the detector</td>
</tr>
</tbody>
</table>

The signal window is from 236 MeV to 400 MeV. Only neutrinos with KE from n capture on Gd.arrivetime ~ 30 μs. Only neutrinos with KE from all other protons.

**Beam structure:** @25 Hz
JSNS2 is sensitive to the smoking gun signature of oscillations: a wiggle in L/E

\[
\bar{\nu}_\mu \rightarrow \bar{\nu}_e, \quad \bar{\nu}_e + p \rightarrow e^+ + n
\]

Expected spectrum

Case $\Delta m^2 = 2.5eV^2$, $\sin^2 2\theta = 0.003$

Case $\Delta m^2 = 1.2eV^2$, $\sin^2 2\theta = 0.003$

(3 years of running)
JSNS² status
(first data will be taken in early-2020)
PROSPECT

- Segmented liquid scintillator (4 tons in Phase 1)
- Highly-enriched uranium reactor @ 85 MW
- Moveable w/ 7-12 m baselines
- Initial oscillation results reported for 33 days of reactor-on (750 IBD events/day).
- First oscillation analysis excludes Reactor Antineutrino Anomaly best-fit at 2.3σ.

Anomaly best-fit at 2.3σ.
In general, it’s a great time to be a reactor neutrino physicist. There are lots of reactor experiments taking/reporting data. As usual, though: need more data for definitive statements about reactor anomaly!
Conclusion

• A number of neutrino anomalies at short baseline may be indicative of new physics.

• The parameter space of new oscillations/interactions continues to be explored with accelerator-based, including decay-in-flight and decay-at-rest, and reactor-based experiments.

• We can look forward to many more results with short-baseline experiments in the future, including impactful cross section measurements, exotic searches, and R&D, all in addition to the anomaly probes.
Backup
Reactor anomaly

The oscillation modes associated with reactor neutrinos

1 - (oscillation probability) vs Reactor To Detector Distance (m)

- Known oscillation frequency modes
- Anomalous data (new frequency mode?)

3ν, 4ν
Update: recent reactor results

DANSS and NEOS
Update: recent reactor results

\[ \Delta m^2 = 7.22 \text{eV}^2, \sin^2(2\theta) = 0.35 \]

\[
\begin{array}{ccc}
\chi^2/\text{DoF} & 18.84/25 & \text{GoF} 0.80 \\
\chi^2/\text{DoF} & 30.15/27 & \text{GoF} 0.31 \\
\end{array}
\]

Neutrino-4

arXiv:1809.10561
SBN sensitivity

Figure 7: SBN sensitivities to a light sterile neutrino in the $\nu_\mu \rightarrow \nu_e$ appearance (left) and $\nu_\mu \rightarrow \nu_\mu$ disappearance (right) channels. For comparison, the LSND preferred regions at 90% and 99% C.L. (shaded blue and gray) are presented (19). Moreover, the global $\nu_\mu \rightarrow \nu_e$ appearance (shaded red) and global $\nu_\mu \rightarrow \nu_\mu$ disappearance (black line) regions from Ref. (33) are also included. Finally, the global best fit regions from Ref. (35) are shown in green. The sensitivities are reproduced from the SBN proposal (15).

The capability to search for evidence of oscillation through muon neutrino disappearance is a very important feature of the SBN program, owing to the intense muon neutrino beam and multiple detectors. The severe tension between existing $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_\mu \rightarrow \nu_\mu$ disappearance data, as discussed in Section 2, presents a major challenge to the sterile neutrino interpretation at present. The observation of muon neutrino disappearance, commensurate with an appearance signal, would be essential to the interpretation of any electron neutrino excess as being due to the existence of sterile neutrinos.

Focusing on a 3+1 sterile neutrino scenario, the SBN sensitivities are presented as solid and dotted red lines, respectively, in Fig. 7. To put the SBN sensitivity into perspective, several related results are superimposed for comparison. To start with, SBN was designed to cover, at 5$\sigma$, the full 99% allowed region of the original LSND appearance result reported in 2001 (19) in the $(\sin^22\theta_{\mu e}, m^2_{41})$ plane. This is presented as the blue (90% C.L.) and gray (99% C.L.) regions in the left panel.

The shielding and CRTs provide a powerful combination for cosmic background mitigation that is essential to the physics goals of SBN.

The projected sensitivities to $\nu_\mu \rightarrow \nu_e$ conversion and $\nu_\mu \rightarrow \nu_\mu$ disappearance oscillation signals are shown in Fig. 7. The analysis is presented in the context of a 3+1 sterile neutrino model according to Eqs. 4 and 6. Event rates and systematic uncertainties and their correlations were determined from the full BNB and GENIE simulation codes, as described above. An uncorrelated detector systematic uncertainty at the level of 3% is assumed. Statistical errors are derived assuming an exposure of $6 \times 10^{20}$ protons delivered to the BNB target, which corresponds to approximately three years of operation, for both the near and far detectors.

The Seoane shielding and CRTs provide a powerful combination for cosmic background mitigation that is essential to the physics goals of SBN.

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JSNS$^2$ sensitivity

Figure 73 shows the 90% C.L sensitivities with this condition.

We expect to have the preliminary result in 2021 because our background and energy reconstruction uncertainty is small using the DAR neutrino flux and IBD signal. The calibration scheme is relatively straightforward (with only 200 PMTs). Compared to the world experiments, especially, the SBN program, it is possible to have competitive results from JSNS$^2$.

6 Summary

The JSNS$^2$ experiment can provide timely, competitive results in the sterile neutrino search via the $\bar{\nu}_\mu \leftrightarrow \nu_e$ mode by utilizing the best existing facility (the J-PARC MLF) and established detector techniques. JSNS$^2$ is a direct test of LSND and can have a large impact on our current picture of neutrino physics. JSNS$^2$ can also provide measurements.
Sterile neutrino limits

\[ \Delta m^2 \] (eV^2)

\[ \sin^2 2\theta_{\mu e} \]
Dark Neutrino Portal Model

\[ \mathcal{L} \supset \frac{m_{Z_D}^2}{2} Z_D \mu Z_D^\mu + g_D Z_D \bar{\nu}_D \gamma_\mu \nu_D + e \epsilon Z_D^\mu J^\text{em}_\mu + \frac{g}{c_W} \epsilon' Z_D^\mu J^Z_\mu \]