**LSND $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance**

Energy range: 20 to 55 MeV  
Baseline: 30 m  
$L/E \sim 1 \text{ m/MeV}$

**Golden Mode:** 
$\pi^+ \rightarrow \mu^+ \nu_\mu$  
$\bar{\nu}_e p \rightarrow e^+ n$

**Signature**  
Scintillation  
Čerenkov  
$2.2 \text{ MeV neutron capture}$

Event Excess: $32.2 \pm 9.7$

Phys. Rev. D64, 112007 (2001)
MiniBooNE used a $\pi^+$ ($\pi^-$) decay in flight beam and a liquid Cherenkov detector to search for $\nu_e$ ($\bar{\nu}_e$) appearance in a $\nu_\mu$ ($\bar{\nu}_\mu$) beam.

Baseline $\sim 500$ m

$\langle E_\nu \rangle \sim 500$ MeV

$L/E \sim 1$ m/MeV
MiniBooNE used a $\pi^+ (\pi^-)$ decay in flight beam and a liquid Cherenkov detector to search for $\nu_e (\bar{\nu}_e)$ appearance in a $\nu_\mu (\bar{\nu}_\mu)$ beam

Baseline ~ 500 m
$\langle E_\nu \rangle$ ~ 500 MeV
L/E ~ 1 m/MeV

MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Appearance Search

MiniBooNE used a $\pi^+ (\pi^-)$ decay in flight beam and a liquid Cherenkov detector to search for $\nu_e (\bar{\nu}_e)$ appearance in a $\nu_\mu (\bar{\nu}_\mu)$ beam

Baseline $\sim 500$ m
$\langle E_\nu \rangle \sim 500$ MeV
$L/E \sim 1$ m/MeV


Event Excess: $78.4 \pm 28.5$
MiniBooNE used a $\pi^+$ ($\pi^-$) decay in flight beam and a liquid Cherenkov detector to search for $\nu_e$ ($\overline{\nu}_e$) appearance in a $\nu_\mu$ ($\overline{\nu}_\mu$) beam. 

Baseline $\sim 500$ m 
$\langle E_\nu \rangle \sim 500$ MeV 
$L/E \sim 1$ m/MeV 

Event Excess: 162.0 ± 47.8 

MiniBooNE used a $\pi^+$ ($\pi^-$) decay in flight beam and a liquid Cherenkov detector to search for $\nu_e$ ($\bar{\nu}_e$) appearance in a $\nu_\mu$ ($\bar{\nu}_\mu$) beam.

Baseline $\sim 500$ m

$\langle E_\nu \rangle \sim 500$ MeV

$L/E \sim 1$ m/MeV

Event Excess: $162.0 \pm 47.8$

Excess? Yes, but it’s not very consistent with LSND

Gallium Anomaly ($\nu_e$ Disappearance)

The solar radiochemical detectors GALLEX and SAGE used intense electron capture sources ($^{51}$Cr and $^{37}$Ar) to "calibrate" the $\nu_e^{71}$Ga interaction/detection rate.

A reanalysis, based on new cross section calculations, suggests that were too few events.


Recent calculations of the reactor $\bar{\nu}_e$ flux and spectrum predict a higher rate than the earlier calculation. This resulted in an apparent deficit of reactor neutrinos across all experiments.

Although the T2K beam is predominantly a $\nu_\mu$ beam, the small $\nu_e$ component can be used in the near detector for a $\nu_e$ disappearance search.

Short-baseline $\nu_e$ appearance from the much larger $\nu_\mu$ component of the beam could fill in the exact region depleted by disappearance, so it is assumed to be zero in this analysis.
Relating Appearance and Disappearance Probabilities

With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.
Relating Appearance and Disappearance Probabilities

With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\nu_s
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\nu_4
\end{pmatrix}
\]

\[U_{e4}^2 \quad U_{\mu 4}^2 \quad U_{\tau 4}^2 \quad U_{s4}^2\]

Solar $\Delta m_{21}^2$

Atmospheric $\Delta m_{32}^2$

Sterile $\Delta m_{43}^2$
With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.

$U_{e4}^2 + U_{\mu 4}^2 + U_{\tau 4}^2 + U_{s4}^2 = 1$ (PMNS Unitarity)
With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.

\[ \begin{pmatrix} v_e \\ v_\mu \\ v_\tau \\ v_s \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} \end{pmatrix} \begin{pmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \end{pmatrix} \]

The appearance probability:

\[ P_{\mu e} = \sin^2 2\theta \sin^2 (1.27 \Delta m_3^2 L/E) \]
With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.

The appearance probability:

$$P_{\mu e} = 4 U_{e4}^2 U_{\mu 4}^2 \sin^2(1.27 \Delta m_{32}^2 L/E)$$
With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.

\[
\begin{pmatrix}
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    U_{s1} & U_{s2} & U_{s3} & U_{s4}
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\begin{pmatrix}
v_1 \\
v_2 \\
v_3 \\
v_4
\end{pmatrix}
\]
With a single sterile neutrino we get a 4×4 PMNS mixing matrix and 3 independent $\Delta m^2$s.

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U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
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\nu_3 \\
\nu_4
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\]

The appearance probability:

\[
P_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2 \sin^2(1.27\Delta m_3^2 L/E)
\]

The $\nu_e$ disappearance probability:

\[
P_{e\bar{e}} \approx P_{\bar{e}s}
\]
With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.

\[
\begin{pmatrix}
V_e \\
V_\mu \\
V_\tau \\
V_s
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{pmatrix}
\begin{pmatrix}
V_1 \\
V_2 \\
V_3 \\
V_4
\end{pmatrix}
\]

\[
P_{\mu e} = 4U_{e4}^2 U_{\mu 4}^2 \sin^2(1.27 \Delta m_{32}^2 L/E)
\]

\[
P_{e}\bar{\nu} \approx P_{e\bar{\nu}_s} = 4U_{e4}^2 U_{s4}^2 \sin^2(1.27 \Delta m_{32}^2 L/E)
\]
With a single sterile neutrino we get a $4 \times 4$ PMNS mixing matrix and 3 independent $\Delta m^2$s.

The appearance probability:

$$P_{\mu e} = 4 U_{e4}^2 U_{\mu 4}^2 \sin^2(1.27 \Delta m^3 L/E)$$

The $\nu_e$ disappearance probability:

$$P_{e\nu} \approx P_{e\bar{\nu}} = 4 U_{e4}^2 U_{s4}^2 \sin^2(1.27 \Delta m_3^2 L/E)$$

The $\nu_{\mu}$ disappearance probability:

$$P_{\mu \bar{\nu}} \approx 4 U_{\mu 4}^2 U_{s4}^2 \sin^2(1.27 \Delta m_3^2 L/E)$$
1. Since any 4th mass state is predominantly sterile \((U_{s4} \approx 1)\),

\[
P_{\mu e} \approx \frac{1}{4} P_{e\nu} \times P_{\mu\nu} \quad \text{or} \quad \sin^2 \theta_{\mu e} = \frac{1}{4} \sin^2 \theta_{ee} \sin^2 \theta_{\mu\mu}
\]
Appearance vs. Disappearance

1. Since any 4th mass state is predominantly sterile (U_{s4} \approx 1),
   \[ P_{\mu e} \approx \frac{1}{4} P_{e\emptyset} \times P_{\mu\emptyset} \]
   or \[ \sin^2 \theta_{\mu e} = \frac{1}{4} \sin^2 \theta_{ee} \sin^2 \theta_{\mu\mu} \]

2. Since \( P_{\mu e} \) depends on both \( U_{e4} \) and \( U_{\mu4} \), you can have \( \nu_e \) disappearance without \( \nu_e \) appearance, but you can’t have \( \nu_e \) appearance without \( \nu_\mu \) disappearance.
Appearance vs. Disappearance

1. Since any 4th mass state is predominantly sterile ($U_{s4} \approx 1$),

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2. Since $P_{\mu e}$ depends on both $U_{e4}$ and $U_{\mu4}$, you can have $\nu_e$ disappearance without $\nu_e$ appearance, but you can’t have $\nu_e$ appearance without $\nu_\mu$ disappearance.

Global fit from Kopp et al. JHEP 1305, 050 (2013)
Appearance vs. Disappearance

1. Since any 4th mass state is predominantly sterile \((U_{s4} \approx 1)\),

\[
P_{\mu e} \approx \frac{1}{4} P_{e\bar{e}} \times P_{\mu\mu} \quad \text{or} \quad \sin^2 \theta_{\mu e} = \frac{1}{4} \sin^2 \theta_{ee} \sin^2 \theta_{\mu\mu}
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2. Since \(P_{\mu e}\) depends on both \(U_{e4}\) and \(U_{\mu4}\), you can have \(\nu_e\) disappearance without \(\nu_e\) appearance, but you can’t have \(\nu_e\) appearance without \(\nu_\mu\) disappearance.

\(\nu_e\) Disappearance \hspace{1cm} \(\nu_\mu \rightarrow \nu_e\) Appearance \hspace{1cm} \(\nu_\mu\) Disappearance

Global fit from Kopp et al. JHEP 1305, 050 (2013)

The absence of \(\nu_\mu\) disappearance is a huge problem for the LSND and MiniBooNE signals, while the \(\nu_e\) disappearance anomalies are consistent with all existing data.
Ongoing & Future Short-Baseline Experiments

**Accelerator Decay-in-Flight:**
- Fermilab Short-Baseline (SBND, MicroBooNE (Toups), ICARUS (Varanini))
- T2K Near Detector
- nuSTORM

**Accelerator Decay-at-Rest:**
- OscSNS
- IsoDAR
- KDAR/KPipe

**Reactor Experiments:**
- Nucifer
- Stereo (Haser)
- Solid (Yarmia)
- DANSS
- POSIDON
- Neutrino-4
- CARR
- Korean SBL
- Prospect (Heeger)
- NuLAT
- CHANDLER
- …

**Radioactive Neutrino Sources:**
- SOX (Vivier)
- LZ-Cr (McKinsey)
- RICCOCHET

**Sterile Searches that are not Short-Basline:**
- OPERA (Di Crescenzo)
- IceCube (Salvado)
- SHiP (De Serio)
- MINOS+ (Holin)
- Plank (Lattanzi)
- KATRIN (Mertens)
Ongoing & Future Short-Baseline Experiments

**Accelerator Decay-in-Flight:**
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T2K Near Detector nuSTORM

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OPERA (Di Crescenzo) IceCube (Salvado) SHiP (De Serio)
MINOS+ (Holin) Plank (Lattanzi) KATRIN (Mertens)
The liquid argon TPC pattern recognition is expected to significantly reduce misID backgrounds.

The near detector provides an inclusive measure of beam and misID backgrounds.

The ICARUS T600 at a third baseline significantly boosts the statistics and the dynamic range in L/E.
The liquid argon TPC pattern recognition is expected to significantly reduce misID backgrounds.

The near detector provides an inclusive measure of beam and misID backgrounds.

The ICARUS T600 at a third baseline significantly boosts the statistics and the dynamic range in L/E.
The Fermilab Short-Baseline Program

Oscillation Channels:

- $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$
- $\nu_\mu$ & $\bar{\nu}_\mu$ disappearance

The liquid argon TPC pattern recognition is expected to significantly reduce misID backgrounds.

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The liquid argon TPC pattern recognition is expected to significantly reduce misID backgrounds.

The ICARUS T600 at a third baseline significantly boosts the statistics and the dynamic range in L/E.

Baseline | Mass
---|---
110 m | 112 t
470 m | 89 t
600 m | 476 t
nuSTORM is a low-energy muon storage ring that produces pure and well-characterized beams of $\nu_\mu$ and $\bar{\nu}_e$, or $\bar{\nu}_\mu$ and $\nu_e$ depending on which sign muons are stored.

In the $\nu_\mu$ appearance channel, the sign of the outgoing muon is all that’s needed to establish oscillations.

Oscillation Channels & Detection Mechanism

| $\nu_e \rightarrow \nu_\mu$ & $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ | Golden Mode | $\nu_\mu$ CC |
| $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ | $\nu_e$ CC |
| $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_e$ & $\bar{\nu}_e$ disappearance | $\nu_\mu$ CC |
OscSNS is direct test of LSND using the Spallation Neutron Source as a pion decay-at-rest source.

LSND is individually the most significant evidence for sterile neutrinos.

Neither the beam nor the detector is particularly innovative, but they have the opportunity to fix certain weaknesses of LSND:

- Detector located upstream of the target
- Possible use of Gd to tag neutrons
- Covers a wider range in L/E

Oscillation Channels & Detection Mechanism

\[
\begin{align*}
\bar{\nu}_\mu \rightarrow \bar{\nu}_e & \quad \text{(Golden Mode) Inverse } \beta\text{-decay} \\
\nu_\mu \rightarrow \nu_e & \quad \nu_e +^{12}\text{C} \rightarrow e^- (12.5 \text{ MeV}) +^{12}\text{N} \\
\nu_e \text{ disappearance} & \quad \nu_e +^{12}\text{C} \rightarrow e^- +^{12}\text{N}
\end{align*}
\]
The IsoDAR proposal uses an intense beam of protons to produce $^8$Li. The $^8$Li decays producing $\bar{\nu}_e$ with a $\beta$-spectrum.

Neutrinos are detected via inverse $\beta$-decay. KamLAND and RENO-50 are possible host detectors.

Oscillations observed through a disappearance channel.

Oscillation Channels & Detection Mechanism

$\bar{\nu}_e$ disappearance  Inverse $\beta$-decay

Golden Mode
Requirement for Disappearance Experiments

“It don’t mean a thing if it ain’t got that swing”
–American jazz great Duke Ellington

**Oscillometry**, noun, The observation and measurement of oscillations.

In disappearance experiments the existence of sterile neutrinos can only be convincingly established through oscillometry.
**Bring the Source vs. Bring the Detector**

**Reactor Experiments:** the detector is brought to a pre-existing source

1. Nuclear reactors are the most prolific terrestrial neutrino sources, producing $6 \times 10^{17} \bar{\nu}_e$ per second per MW\textsubscript{th}.

2. It is unlikely that a reactor would ever be constructed specifically for use as a neutrino source, nevertheless, neutrino experiments can use existing reactors without any impact on their normal operations.

3. Once the detector has been delivered, neutrino statistics accumulate with minimal operational costs.

**Radioactive Source Experiments:** the source is brought to a pre-existing detector

1. Leverages detectors built for other applications (e.g. solar neutrinos, dark matter).

2. Often these detectors have existing reconstructions, well measured backgrounds and a well understood energy response.

3. The source decays away, so to accumulate additional statistics requires a new investment on the scale of the original deployment.
Source Experiment: SOX

Combines the Borexino detector with a $^{144}\text{Ce}$ $\bar{\nu}_e$ source and/or a $^{51}\text{Cr}$ $\nu_e$ source.

At the typical sterile $\Delta m^2$, multiple oscillation wavelengths may be observed inside the detector.

See talk by Vivier
Source Experiment: SOX

Combines the Borexino detector with a $^{144}\text{Ce} \bar{\nu}_e$ source and/or a $^{51}\text{Cr} \nu_e$ source.

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See talk by Vivier
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See talk by Vivier

At the typical sterile $\Delta m^2$, multiple oscillation wavelengths may be observed inside the detector. $^{144}\text{Ce} \bar{\nu}_e$ neutrinos have a $\beta$ spectrum with a 3 MeV endpoint and are observed by inverse beta decay. Mono-energetic $^{51}\text{Cr} \nu_e$ oscillate as a pure function of $L$, and are detected by electron elastic scattering.
New Reactor experiments

from Antonin Vacheret
## Comparison of Reactor Experiments

<table>
<thead>
<tr>
<th>Power Core Size</th>
<th>Mass</th>
<th>n Tag</th>
<th>L min</th>
<th>L max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stereo 58 MW</td>
<td>Compact</td>
<td>1.75 tons</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DANSS 3 GW</td>
<td>3.5 m</td>
<td>1 ton</td>
<td>9.7 m</td>
<td>12 m</td>
</tr>
<tr>
<td>POSEIDON 100 MW</td>
<td>40 cm</td>
<td>6 tons</td>
<td>25 cm</td>
<td>15 m</td>
</tr>
<tr>
<td>Neutrino-4 30 MW</td>
<td>Compact</td>
<td></td>
<td>6 m</td>
<td>15 m</td>
</tr>
<tr>
<td>SBL-Korea 2.8 GW</td>
<td>Compact</td>
<td></td>
<td>6 m</td>
<td>27 m</td>
</tr>
<tr>
<td>Prospect 85 MW</td>
<td>50 cm</td>
<td>2.5 tons</td>
<td>7 m</td>
<td>11 m</td>
</tr>
<tr>
<td>SoLi60 60 MW</td>
<td>50 cm</td>
<td>3 tons</td>
<td>5.5 m</td>
<td>11 m</td>
</tr>
<tr>
<td>NuLat</td>
<td>Compact</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Unlike the reactor $\theta_{13}$ experiments, short-baseline reactor experiments are done

- on the surface
- with small detectors
- without space for massive clean shielding
- and gamma catcher

Random coincidence backgrounds are one of the significant challenges.

How can we deal with Random Coincidence Backgrounds?

1. Neutron and gamma shielding
2. Unbiased spatial resolution ➔ Segmentation
3. High neutron capture efficiency and purity ➔ Gd and $^6$Li
Daya Bay, RENO and Double Chooz tag neutrons with Gd capture, in conjunction with a large gamma catcher to contain the gammas.

This may not work as well in the small short-baseline detectors.

Neutron Capture on Gadolinium

E = 8 MeV

Poorly contained in small detectors
Neutron Capture Options

Daya Bay, RENO and Double Chooz tag neutrons with Gd capture, in conjunction with a large gamma catcher to contain the gammas.

This may not work well in the small short-baseline detectors.

Neutron Capture on Gadolinium

$$n + Gd \rightarrow \gamma \gamma \gamma$$

E = 8 MeV

Poorly contained in small detectors

Neutron Capture on Lithium-6

$$n + ^6Li \rightarrow ^3H ^4He$$

E = 4.78 MeV

Contained in a few microns
Neutron Capture Options

Daya Bay, RENO and Double Chooz tag neutrons with Gd capture, in conjunction with a large gamma catcher to contain the gammas.

This may not work well in the small short-baseline detectors.

Neutron Capture on Gadolinium

\[ n + \text{Gd} \rightarrow \gamma + \gamma + \gamma \]

E = 8 MeV

Poorly contained in small detectors

Neutron Capture on Lithium-6

\[ n + \text{Li}^6 \rightarrow \text{He}^4 + \text{H}^3 \]

E = 4.78 MeV

Electron Equivalent ~0.5 MeV

Contained in a few microns
SoLi$\partial$: Tagging with $^6$Li in ZnS:Ag Sheets

The SoLi$\partial$ detector tags neutrons in thin sheets of $^6$Li-loaded Zinc Sulfide scintillator (ZnS:Ag).

ZnS:Ag releases light with a 200 ns mean emission time which forms a very pure, high efficiency neutron tag.

SoLi$\partial$ achieves unprecedented spatial resolution by segmenting its scintillator in cubes which are readout in two dimensions by wavelength shifting fibers.

See SoLi$\partial$ talk by Yermia

Neutron tag in the SoLi$\partial$ inspired CHANDLER detector, which is readout by total internal reflection.
Other things to look for:

1. A compact core
   (~50 cm)
2. A close detector site
   (5 to 7 m)
3. Good energy resolution
   (<7% @ 1 MeV)

These things are needed to probe \( \Delta m^2 \) in the range of 2 to 10 eV\(^2\).

Conclusions

• We have hints for a sterile neutrino coming from at least 5 different types of terrestrial measurements,

• And in two distinct channels: $\nu_\mu \rightarrow \nu_e$ appearance and $\nu_e$ disappearance.

• The Fermilab short-baseline program will soon start taking data to search for $\nu_e$ appearance and $\nu_\mu$ disappearance.

• SOX, the Borexino source experiment, will start taking $\nu_e$ disappearance data by the end of 2016.

• Multiple reactor experiments are expected to ramp up on a similar time scale and will attempt to compete in the search for $\nu_e$ disappearance.

We may have interesting new results for TAUP 2017!
Caution on Proposal Sensitivities


$$(5.58 \pm 0.12) \times 10^{20}$$ protons on target

541 m