A Precision Decay at Rest $\nu$ Oscillation Expt: OscSNS

- Short-Baseline Neutrino Anomalies
- 3+N Neutrino Oscillation Models
- Next Step: Observe Oscillations in the Detector
- OscSNS: Decay at Rest Neutrino Experiment
Short-Baseline Neutrino Anomalies

More precise information will come from the Planck satellite.
Sterile Neutrinos

- 3+N models

- $N>1$ allows CP violation for short baseline experiments
  - $\nu_\mu \rightarrow \nu_e \neq \overline{\nu}_\mu \rightarrow \overline{\nu}_e$
Global 3+N Fits

3+1

Table 2: The χ² values, degrees of freedom (dof) and probabilities associated with the best-fit and null hypothesis in each scenario. Also shown are the results from the Parameter Goodness-of-fit tests. Pbest refers to the χ²-probability at the best fit point and Pnull refers to the χ²-probability at null.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Δm² (eV²)</th>
<th>DoF</th>
<th>χ²</th>
<th>Pbest</th>
<th>Pnull</th>
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<tr>
<td>All</td>
<td>3+1</td>
<td>59</td>
<td>53.5</td>
<td>0.981</td>
<td>0.142</td>
</tr>
<tr>
<td>App</td>
<td>3+1</td>
<td>59</td>
<td>53.5</td>
<td>0.981</td>
<td>0.142</td>
</tr>
<tr>
<td>Dis</td>
<td>3+1</td>
<td>59</td>
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3+2

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<th>χ²</th>
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<th>Pnull</th>
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<td>All</td>
<td>3+2</td>
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<td>0.981</td>
<td>0.142</td>
</tr>
<tr>
<td>App</td>
<td>3+2</td>
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3+3

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<th>Pnull</th>
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<tr>
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<tr>
<td>Dis</td>
<td>3+3</td>
<td>59</td>
<td>53.5</td>
<td>0.981</td>
<td>0.142</td>
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</table>

Table 3: The oscillation parameter best-fit points in each scenario considered. The values of Δm² shown are in units of eV².

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Δm² (eV²)</th>
<th>u</th>
<th>v</th>
<th>φ</th>
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<tbody>
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<td>All</td>
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<td>0.12</td>
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<td>17</td>
<td>0.13</td>
<td>0.12</td>
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<td>η</td>
<td>3+1</td>
<td>17</td>
<td>0.13</td>
<td>0.12</td>
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<tr>
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<th>Δm² (eV²)</th>
<th>u</th>
<th>v</th>
<th>φ</th>
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<tbody>
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<td>0.11</td>
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<td>App</td>
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<td>0.11</td>
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<tr>
<td>Dis</td>
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<td>22</td>
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<tr>
<td>η</td>
<td>3+2</td>
<td>22</td>
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<td>0.11</td>
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<table>
<thead>
<tr>
<th>Scenario</th>
<th>Δm² (eV²)</th>
<th>u</th>
<th>v</th>
<th>φ</th>
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<tbody>
<tr>
<td>All</td>
<td>3+3</td>
<td>26</td>
<td>0.16</td>
<td>0.10</td>
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<tr>
<td>App</td>
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<td>0.16</td>
<td>0.10</td>
</tr>
<tr>
<td>Dis</td>
<td>3+3</td>
<td>26</td>
<td>0.16</td>
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</tr>
<tr>
<td>η</td>
<td>3+3</td>
<td>26</td>
<td>0.16</td>
<td>0.10</td>
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</tbody>
</table>
OscSNS

- Spallation neutron source at ORNL
- ~1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos
## SNS Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Linac Length</td>
<td>493 m</td>
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<tr>
<td>Accumulator Ring Circumference</td>
<td>221 m</td>
</tr>
<tr>
<td>Beam Power on Target</td>
<td>1.4 MW</td>
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<tr>
<td>Beam Energy on Target</td>
<td>1.3 GeV</td>
</tr>
<tr>
<td>Average Beam Current</td>
<td>1.1 mA</td>
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<tr>
<td>Repetition Rate</td>
<td>60 Hz</td>
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<tr>
<td>Ion Type, Source-Linac</td>
<td>H⁻</td>
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<tr>
<td>LINAC-Beam Duty Factor</td>
<td>6.2%</td>
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<tr>
<td>Number of Injected Turns</td>
<td>1225</td>
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<tr>
<td>Particles Stored in Ring</td>
<td>1.5 x 10^{14}</td>
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<tr>
<td>Extracted Pulse Length</td>
<td>695 ns</td>
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<td>Peak Current on Target</td>
<td>45 A</td>
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<tr>
<td>Target</td>
<td>Mercury</td>
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<tr>
<td>Beam Spot on Target</td>
<td>7 x 20 cm</td>
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<td>Moderators Ambient</td>
<td>2 (Water)</td>
</tr>
<tr>
<td>Moderators Cryogenic</td>
<td>2 (LH₂)</td>
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<tr>
<td>Neutron Beam Ports</td>
<td>18</td>
</tr>
<tr>
<td>Protons Accelerated per Year</td>
<td>2x10^{23} (~0.3 g)</td>
</tr>
</tbody>
</table>
OscSNS

\[
\begin{align*}
\bar{\nu}_\mu &\rightarrow \bar{\nu}_e \ \Delta(L/E) \approx 3\% \ , \ \bar{\nu}_e \ p \rightarrow e^+ n \\
\nu_e &\rightarrow \nu_s \ \Delta(L/E) \approx 3\% \ , \ \nu_e \ C \rightarrow e^- \ N_{gs} \\
\nu_\mu &\rightarrow \nu_s \ \Delta(L/E) < 1\% \ ; \ \text{Monoenergetic} \ \nu_\mu \ ; \ \nu_\mu \ C \rightarrow \nu_\mu \ C^*(15.11) \\
\bar{\nu}_\mu &\rightarrow \bar{\nu}_s \ ; \ \bar{\nu}_\mu \ C \rightarrow \bar{\nu}_\mu \ C^*(15.11) 
\end{align*}
\]

OscSNS would be capable of making precision measurements of \( \nu_e \) appearance & \( \nu_\mu \) & \( \nu_e \) disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)).
Spallation Neutron Source at ORNL
Hamamatsu R5912 assumed 60 rows (6°) of 54 each PMTs located 14" (.356m) center to center. Tube center located 3.4m radially from detector tank center line (3240 tubes).
Particle Identification
(with 0.031 g/l of b-PBD)

Particle Identification depends on Cherenkov cone fit, position fit, and fraction of late light
2.2 MeV $\gamma$ Identification

- Correlated Distribution
- Uncorrelated Distribution

1. Probability/10 cm vs $\Delta r$ (cm)
2. Probability/10 usec vs $\Delta t$ (usec)
3. Probability/Hit vs $N_\gamma$ Hits

Graphs showing the probability distributions for correlated and uncorrelated distributions in various parameters.
OscSNS Advantages Over Other Neutrino Oscillation Experiments

• Well understood ν fluxes: νμ, νe, νμ̄
• Well understood ν cross sections
• Low duty factor
• Absence of nuclear effects
• Very low backgrounds (~0.1%)
• Beam comes for free from the SNS, which runs >1/2 the year
• Search for both appearance & disappearance oscillations
• Possibility of observing oscillations in the detector for Δm² > 1 eV²!
OscSNS $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Experiment vs LSND

(Assuming $\Delta m^2 < 1 \text{eV}^2$)

- More Detector Mass (x5)
- Higher Intensity Neutrino Source (x2)
- Lower Duty Factor (x1000) (less cosmic background)
- Separation of $\nu_\mu$ & $\nu_e/\bar{\nu}_\mu$ Fluxes
- Negligible DIF Background (backward direction)
- Lower Neutrino Background (x4) (60m vs 30m)
- For LSND parameters, expect $\sim 350 \nu_e$ oscillation events & $\sim 80$ background events per year!
Goals of the OscSNS Experiment

• Prove the existence of sterile neutrinos by comparing NC reactions in near and far detector and by observing oscillations in the detector of a NC reaction
• Short baseline $\nu_e$ and $\bar{\nu}_e$ appearance
• Short baseline $\nu_e$, $\nu_\mu$ and $\bar{\nu}_\mu$ disappearance
• The resolution of the current short-baseline anomalies
• Neutrino cross section measurements
OscSNS at ORNL

- $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance sensitivity for 1 & 3 years of running:

  $\bar{\nu}_e \ p \rightarrow \ e^+ \ n; \ n \ p \rightarrow \ d \ \gamma \ (2.2 \ MeV)$
$\bar{\nu}_e p \rightarrow e^+ n$

Assuming $\sin^2 2\theta = 0.005$
$\bar{\nu}_e \ p \rightarrow \ e^+ \ n$

Assuming 5y of data & $\sin^22\theta = 0.005$, $\Delta m^2=1 \ eV^2$
$\bar{\nu}_e \, p \rightarrow e^+ \, n$

Assuming 5y of data & $\sin^2 2\theta = 0.005$, $\Delta m^2 = 4 \, \text{eV}^2$
Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:
\[ \nu_\mu \ C \rightarrow \nu_\mu \ C^*(15.11) \]

KARMEN Measurement of $\nu_\mu$ C $\rightarrow$ $\nu_\mu$ C*(15.11)

$\sigma_{NC} = (3.2\pm0.5\pm0.4) \times 10^{-42}$ cm$^2$ (B. Armbruster et al., Phys. Lett. B423 (1998) 15)

$\sigma_{NC} \sim 2.8 \times 10^{-42}$ cm$^2$ (Kolbe, Langanke, & Vogel, Nucl. Phys. A652 (1999) 91)
Measurement of Oscillation Parameters with Two Detectors

$\nu_\mu$ disappearance

![Graph showing oscillation parameters]
\[ \nu_\mu \rightarrow \nu_\mu \ C^*(15.11) \]

Assuming \( \sin^2 2\theta = 0.15 \)
\[ \nu_\mu \ C \rightarrow \nu_\mu \ C^*(15.11) \]

Assuming 5y of data & \( \sin^22\theta = 0.15 \), \( \Delta m^2 = 1 \text{eV}^2 \)
$\nu_\mu \text{ C} \rightarrow \nu_\mu \text{ C}^*(15.11)$

Assuming 5y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 4 \text{ eV}^2$
\( \nu_e \text{ C} \rightarrow \text{e}^- \text{ N}_{gs} \)

Assuming \( \sin^2 2\theta = 0.15 \)
$\nu_e \ C \rightarrow \ e^- \ N_{gs}$

Assuming 5y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 1 \text{ eV}^2$
$\nu_e \text{ C} \rightarrow \text{e}^- \text{ N}_{gs}$

Assuming 5y of data & $\sin^2 2\theta = 0.15$, $\Delta m^2 = 4 \text{ eV}^2$
## OscSNS Event Rates at 60m

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events/year</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e , C \rightarrow e^- , N_{gs}$</td>
<td>4650</td>
</tr>
<tr>
<td>$\nu_e , C \rightarrow e^- , N^*$</td>
<td>2247</td>
</tr>
<tr>
<td>$\nu_\mu , C \rightarrow \nu_\mu , C^*(15.11)$</td>
<td>1463</td>
</tr>
<tr>
<td>$\nu , C \rightarrow \nu , C^*(15.11)$</td>
<td>6322</td>
</tr>
<tr>
<td>$\nu_e , e^- \rightarrow \nu_e , e^-$</td>
<td>1320</td>
</tr>
<tr>
<td>$\nu_\mu , e^- \rightarrow \nu_\mu , e^-$</td>
<td>450</td>
</tr>
<tr>
<td>100% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\bar{\nu}_e , p \rightarrow e^+ , n$</td>
<td>99,275</td>
</tr>
<tr>
<td>0.4% $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, $\bar{\nu}_e , p \rightarrow e^+ , n$</td>
<td>397</td>
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</tbody>
</table>
Conclusion

• There are anomalies in short baseline $\nu$ experiments that cannot be explained by the 3 $\nu$ paradigm and that suggest the existence of sterile $\nu$.
• Sterile $\nu$ would contribute to the dark matter of the universe and would have a big impact on astrophysics and cosmology.
• The world neutrino & antineutrino data can be fit fairly well to a 3+N oscillation model with large $\nu_\mu$ disappearance (>7%).
• The OscSNS experiment can measure neutrino oscillations with high significance (>5$\sigma$) and prove that sterile neutrinos exist!
• OscSNS can also make numerous cross section measurements, including precision measurements of $\nu_\ell e \rightarrow \nu_\ell e$ elastic scattering.
2. Questions & Answers

A. What major scientific discoveries have occurred in your research area since the 2007 LRP was drafted?

Since the 2007 LRP was drafted, there has been ever increasing evidence for the existence of sterile neutrinos. This evidence includes global fits to world data, the excess of $\bar{\nu}_e$ and $\nu_e$ events from MiniBooNE, the reactor neutrino anomaly, the radioactive source anomaly, and cosmological data, and has resulted in increased theoretical interest.

B. What compelling and unique science is to be done in the next 5 years?

A neutrino oscillation experiment at the SNS (e.g. OscSNS) could prove if sterile neutrinos explain the above anomalies. Such an experiment represents a unique opportunity for U.S. science because of the existence of the SNS. JPARC, while inferior as the ideal neutrino source, could provide competition.

C. What science would you expect to pursue in the program in 2020 and beyond?

The discovery of light, sterile neutrinos would open up a whole new area of neutrino physics research. In addition to being important for nuclear and particle physics, sterile neutrinos would have a large impact on astrophysics and cosmology. In particular, sterile neutrinos could play a role in dark matter.

D. What is the international context, and how does it affect your vision?

The SNS is unique in the world and provides the U.S. with the rare opportunity to do a significant experiment in neutrino physics. Studies with radioactive sources or reactors allow investigation of the disappearance of $\nu_e$ $\bar{\nu}_e$. A stopped pion and muon source uniquely allows the precise investigation of the disappearance of both $\nu_\mu$ and $\nu_e$ as well as $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations.
MiniBooNE Detector Tank
800 tons of mineral oil; add ~0.031 g/l of b-PBD

10% -> 25% Photocathode coverage with 8” Hamamatsu Phototubes: R1408, R5912

Charge Resolution:
1.4 PE, 0.5 PE

Time Resolution:
1.7 ns, 1.1 ns
MiniBooNE Event Excesses

Event Excess from 200-1250 MeV = 240.3+-34.5+-52.6 (3.8σ)
MiniBooNE Event Excesses

Event Excess from 200-1250 MeV = 240.3±34.5±52.6 (3.8σ)
Oscillation Probability

$P(E_\nu)$ vs. $E_\nu$ (GeV) for
- 3+2 best fit neutrino
- 3+2 best fit antineutrino
- 3+1 best fit

Logarithmic scale for probability and energy.
MiniBooNE Combined Neutrino + Antineutrino 3+1 Fit
MiniBooNE Allowed Regions

Neutrino

Antineutrino
3+N Global Fits to World $\nu$ Data

Giunti & Laveder, arXiv:1111.1069
(Some tension with $\nu_\mu$ disappearance)
$\chi^2 = 152.4/144$ DF (Prob = 30%)

Kopp, Maltoni, & Schwetz,
$\chi^2 = 110.1/130$ DF (Prob = 90%)
The OscSNS White Paper

April 30, 2012

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http://www.phys.ufl.edu/~hray/oscns/
MB Spatial Distributions

Neutrino

Antineutrino

Relative Normalization
MB Spatial Distributions

Neutrino

Antineutrino

Absolute Normalization
MB Spatial Distributions
(Statistical Errors Only)

<table>
<thead>
<tr>
<th></th>
<th>Neutrino</th>
<th>Antineutrino</th>
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<tr>
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<td>$&lt;X_{\text{Data}}&gt;-&lt;X_{\text{MC}}&gt;$</td>
<td>$&lt;X_{\text{Data}}&gt;-&lt;X_{\text{MC}}&gt;$</td>
</tr>
<tr>
<td></td>
<td>$= -0.2\pm 6.8$</td>
<td>$= -2.1\pm 8.7$</td>
</tr>
<tr>
<td></td>
<td>$&lt;Z_{\text{Data}}&gt;-&lt;Z_{\text{MC}}&gt;$</td>
<td>$&lt;Z_{\text{Data}}&gt;-&lt;Z_{\text{MC}}&gt;$</td>
</tr>
</tbody>
</table>

$\chi^2 = 6.2/6 \text{ DF (Prob = 40\%)}$
Backgrounds: Order \( (G^2\alpha\alpha_s) \), single \( \gamma \) FS?

Dominant process accounted for in MC!

Axial Anomaly

Radiative Delta Decay

Other PCAC

So far no one has found a NC process to account for the \( \nu \) low-energy excess. Work is in progress:

R. Hill, arXiv:0905.0291

Jenkins & Goldman, arXiv:0906.0984

Serot & Zhang, arXiv:1011.5913; 1206.3812
NC$\gamma$ Background Estimates

- $<E_\nu>$ $\sim$ 800 MeV for $\pi^0$ production in MB
- MB: $<\sigma_{\pi^0}>$ $\sim$ 5x10^{-40} cm$^2$/N
- MB: $<\sigma_{\gamma}>$ $\sim$ 5x10^{-42} cm$^2$/N
- Richard Hill: $<\sigma_{\gamma}>$ $\sim$ 6.7x10^{-42} cm$^2$/N ($\Delta$: 5.0; Compton: 0.9; $\omega$: 0.1; Coh: 0.7)
- Xilin Zhang: $<\sigma_{\gamma}>$ $\sim$ 3.7x10^{-42} cm$^2$/N (Incoh: 3.0; Coh: 0.7); Zhang believes that the background estimates from Hill are overestimated by a factor of $\sim$2 due to nuclear effects

- The NC $\gamma$ background estimates from Hill & Zhang are fairly consistent with the MB estimates
Corrections to the HARP-CDP Analysis of the LSND Neutrino Oscillation Backgrounds

G. T. Garvey, W. C. Louis, G. B. Mills, & D. H. White
Los Alamos National Laboratory; Los Alamos, NM 87545

(Dated: December 12, 2011)

Several mistakes have been found in recent papers that purport to reanalyze the backgrounds to the LSND neutrino oscillation signal. Once these mistakes are corrected, then it is determined that the background estimates in the papers are close to (if not lower than) the LSND background estimate.

The HARP-CDP group analyzed the pion production data taken by the HARP experiment at CERN with 1.5 GeV/c protons incident on a Be target and performed a reanalysis [1, 2] of the backgrounds to the LSND $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ oscillation signal [3]. LSND observed a beam-on minus beam-off excess of 117.9 ± 22.4 events. After subtracting a neutrino background of 30.0 ± 6.0 events, LSND determined the oscillation signal to be 87.9 ± 23.2 events [3]. The HARP-CDP group estimates a higher neutrino background of 46.7 ± 20.6 events, which leads to an oscillation signal of 71.2 ± 30.4 events [2]. However, the HARP-CDP group made several errors in making their background estimate. The most egregious errors are discussed below.

HARP-CDP multiplies the intrinsic $\bar{\nu}_e$ background by a factor of 1.6, which is the ratio of “All Enriched” “Best Estimate” $\bar{\nu}_e$ in Table 15 [1]. However, this neglects the fact that HARP-CDP overestimates the decay at rest (DAR) fluxes and does not normalize to the $\nu_e$ flux. Thus, HARP-CDP instead should use a factor of 1.21, which is the ratio of “Enriched” “Best Estimate” $\bar{\nu}_e$ to $\nu_e$ in Table 15. This increases the intrinsic $\bar{\nu}_e$ background by 4.1 events (from 19.5 to 23.6 total events) instead of by 1.7 events.

In Table 15 of the first HARP-CDP paper [1], the $\pi^-$ and $\pi^+$ decay in flight (DIF) fluxes are factors of 3.3 and 2.5 higher in the “Best Estimate” than in the fluxes used by LSND [3]. However, LSND has made high statistics measurements of $\nu_{\mu}$ and $\bar{\nu}_{\mu}$ scattering [4], and the HARP-CDP “Best Estimate” DIF fluxes are inconsistent with LSND measurements. For example, for $\nu_e p \rightarrow \mu^+ n$ scattering, LSND observes 214 ± 35 events, which is consistent with the flux estimate and a factor of 3.3 times lower than the HARP-CDP flux estimate. For $\nu_{\mu} p \rightarrow \mu^- N_{\mu}$ scattering, LSND observes 66.9 ± 9.1 events, which is consistent with the flux estimate and a factor of 2.5 times lower than the HARP-CDP flux estimate. Therefore, it is clear that HARP-CDP is overestimating the DIF flux and overestimating the number of DIF events observed in LSND by factors of 2.5-3.3. As the intrinsic $\bar{\nu}_e$ background all comes from DIF, this implies that the HARP-CDP intrinsic $\bar{\nu}_e$ background estimate should be reduced by a large factor (up to a factor of 3.3).

In Table 17, the first HARP-CDP paper [1] discusses the backgrounds from $\bar{\nu}_e p \rightarrow \mu^+ n$, where the $\mu^+$ is not observed if it is too low in energy ($T_{\mu} < 3$ MeV). However, the $T_{\mu} < 3$ MeV cut is not a hard cutoff. Rather, LSND still observes some muons down to 2 MeV or lower, especially because the energy lost by the recoil neutron is included. Also, LSND checked the background estimate by extrapolating the observed phototube (PMT) hit distribution down to zero. Therefore, the HARP-CDP background estimate of 13.8 events is overestimated, and HARP-CDP should use the LSND value of 10.5 events instead.

The second HARP-CDP paper [2] estimates a background of 2.5 events from $\nu_e e^- \rightarrow e^- N_{\mu}$ events, where the $N_{\mu}$ beta decays mimic a 2.2 MeV $\gamma$ from neutron capture. However, this background is overestimated, partly because a 2.2 MeV positron produces more PMT hits than a 2.2 MeV $\gamma$. A 2.2 MeV $\gamma$ produces the same number of PMT hits as an $\sim 1$ – 1.5 MeV positron, including the energy from positron-electron annihilation. In the LSND analysis, these $N_{\mu}$ beta decays that mimic 2.2 MeV $\gamma$s are determined to be very small (~0.2 events just to pass the minimal cuts). Indeed, LSND determined that the R distribution of $N_{\mu}$ events looks indistinguishable from the R distribution of N inclusive events without a beta.

In summary, using the corrected estimate of the intrinsic $\bar{\nu}_e$ background of 23.6 events, the HARP-CDP excess should be 83.7 events, which agrees reasonably well with the LSND estimate of 87.9 ± 23.2 events. However, this ignores the problem with the HARP-CDP DIF fluxes, which overestimate the intrinsic $\bar{\nu}_e$ background. For example, if the HARP-CDP intrinsic $\bar{\nu}_e$ flux is reduced by a factor of 3.3 to make the DIF estimates agree with LSND data, then the HARP-CDP $\bar{\nu}_e$ background decreases to 7.1 events and the excess increases to 102.2 ± 23.2 events.

## LSND vs HARP-CDP: Number of DIF $\nu$ Events

<table>
<thead>
<tr>
<th>Process</th>
<th>LSND Data</th>
<th>LSND Flux Estimate</th>
<th>HARP-CDP Flux Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu$ C $\rightarrow$ $\mu^- N_{gs}$</td>
<td>77.8+-8.9</td>
<td>78+-8</td>
<td>184+-18</td>
</tr>
<tr>
<td>$\nu_\mu$ C $\rightarrow$ $\mu^- X$</td>
<td>2464+-50</td>
<td>3208+-642</td>
<td>6382+-1276</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ p $\rightarrow$ $\mu^+ n$</td>
<td>286+-27</td>
<td>389+-78</td>
<td>1176+-235</td>
</tr>
</tbody>
</table>

Therefore, the LSND DIF flux estimate agrees well with LSND data; however, HARP-CDP has overestimated the DIF flux by a factor of ~2-3.

- Relative neutrino fluxes from Table 15 of arXiv:1110.4265 [hep-ex]; (HARP-CDP neutrino flux is 2.50 times larger than LSND neutrino flux & HARP-CDP antineutrino flux is 3.27 times larger than LSND antineutrino flux)
- C cross sections from Hayes & Towner, Phys. Rev. C61, 044603 (2000); 10% systematic error for exclusive reactions & 20% systematic error for inclusive reactions
\( \nu_\mu \ C \rightarrow \nu_\mu \ C^*(15.11) \)

Assuming 5y of data & \( \sin^22\theta = 0.15 \), \( \Delta m^2 = 0.9 \) eV\(^2\) & 40 m long detector
OscSNS Design Considerations

- Add Gd to oil?
- Size of detector
- Cylindrical or spherical detector
- b-PBD concentration
- PMT coverage
- Add near detector?
Typical Michel Electron Event Display
Typical Michel Electron Event Display
Typical Michel Electron Event Display
3+N Models Require Large $\nu_\mu$ Disappearance!

In general, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

Reactor Experiments: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) \sim 15\%$

LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

Therefore: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 7\%$

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.
SciBooNE/MiniBooNE Neutrino Disappearance Limits

arXiv:1106.5685
Combined disappearance result

- Joint analysis:
- BF point $\Delta m^2 = 5.9 \text{ eV}^2$, $\sin^2 2\theta = 0.086$
- $\chi^2 = 40.0$ (probability 47.1%) at the best fit point
- $\chi^2 = 43.5$ (probability 41.2%) for the null hypothesis
- With $\Delta \chi^2 = 3.5$, null is excluded at 81.9% CL

- Probabilities are based on fake data studies

G. Cheng, W. Huelsnitz