Hunt for Steriles: Decay at Rest (DAR) Experiments

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Contents of this talk

* Sterile neutrino?
* Positive indications
* the LSND DAR experiment
* DAR neutrinos and their oscillations
* Proposed projects
  - JSNS$^2$
  - K-Pipe
  - OscSNS
* Summary
The interactions have a nesting structure like a Matryoshka doll.

All the fermions which feel strong interaction feel EM and all the fermions which feel EM interaction feel Weak interaction.

For example, there is no neutral quark.
There is one more layer of the interactions; "Gravity"
We now know $\nu$'s have mass and all the fermions feel the Gravity as well.

Sterile Neutrino?
An example
If the nesting pattern continues, there shall be fermion $\nu_s$, which feels only the Gravity.

We can not observe the $\nu_s$ by experiments even if it exists, since it does not feel the 3 interactions.
However, if something \((X)\) transforms \(\nu_s\) to our \(\nu_\alpha\) (like \(\nu_\mu\) to \(\nu_e\)), we have chance to observe the existence of the \(\nu_s\) through OUR neutrino oscillation.

\[ \nu_s \xrightarrow{X?} \nu_\alpha \]

⇒ Sterile Neutrino?
### Some Indications

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \nu ) source</th>
<th>Mode</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>Decay-At-Rest</td>
<td>( \bar{\nu}_\mu \rightarrow \bar{\nu}_e )</td>
<td>3.8( \sigma )</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>Decay-In-Flight</td>
<td>( \nu_\mu \rightarrow \nu_e )</td>
<td>3.4( \sigma )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>( \bar{\nu}_\mu \rightarrow \bar{\nu}_e )</td>
<td>2.8( \sigma )</td>
</tr>
<tr>
<td>Ga-Solar</td>
<td>e capture</td>
<td>( \nu_e \rightarrow \nu_x )</td>
<td>2.7( \sigma )</td>
</tr>
<tr>
<td>Reactor</td>
<td>( \beta )-decay</td>
<td>( \bar{\nu}_e \rightarrow \nu_x )</td>
<td>3.0( \sigma )</td>
</tr>
</tbody>
</table>

#### \( \nu_e \) Appearance

![\( \nu_e \) Appearance](image1)

#### \( \nu_e \) Disappearance

![\( \nu_e \) Disappearance](image2)
Some Indications

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

3+1 cadre

\( \nu_e \) Appearance

\[ P_{\nu_\mu \rightarrow \nu_e} \sim 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2 \left( \frac{m^2_4 L}{4E_{\nu_\mu}} \right) \]

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

\( \nu_e \) Disappearance

\[ P_{\nu_e \rightarrow \nu_e} \sim 1 - 4|U_{s4}|^2|U_{e4}|^2 \sin^2 \left( \frac{m^2_4 L}{4E_{\nu_e}} \right) \]

\[ |U_{s4}|^2 \sim 0.9, \quad |U_{e4}|^2 \sim 0.1, \quad |U_{\mu 4}|^2 \sim 0.01 \]

\( m_4 > 1 \text{eV} \)
<table>
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<tr>
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<th>ν source</th>
<th>Mode</th>
<th>Significance</th>
</tr>
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<tbody>
<tr>
<td>LSND</td>
<td>Decay-At-Rest</td>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>3.8σ</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>Decay-In-Flight</td>
<td>$\nu_\mu \rightarrow \nu_e$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$</td>
<td>3.4σ $2.8σ$</td>
</tr>
<tr>
<td>Ga</td>
<td>e capture</td>
<td>$\nu_e \rightarrow \nu_x$</td>
<td>2.7σ</td>
</tr>
<tr>
<td>Reactor</td>
<td>β-decay</td>
<td>$\bar{\nu}_e \rightarrow \nu_x$</td>
<td>3.0σ</td>
</tr>
</tbody>
</table>

LSND shows the most significant results.

⇒ It is necessary to check the results using the same neutrino (DAR) and the same detection principle (Inverse Beta Decay), yet much better sensitivity.

-- Otherwise, the ghost of LSND remains forever....
Sterile Neutrino has become very hot subject now.
LSND experiment ($\bar{\nu}_e$ appearance)

\[ \pi^+(\text{stop}) \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+(\text{stop}) \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

800MeV p

DAR

Liquid Scintillator

IBD

$\bar{\nu}_e + p \rightarrow e^+ (<53\text{ MeV}) + n$

$n + p \rightarrow d + \gamma(2.2\text{ MeV})$. 
LSND (LAMPF) Beam


- 1 mA, 798 MeV proton beam with 6% DF
- 30 cm water target from 1993-1995
- High Z target from 1996-1998
- 28,896 C (0.3 g) of protons on target from 1993-1998
- Neutrinos from $\pi^+/\mu^+$ DAR: $\pi^+ \rightarrow \mu^+ \nu_\mu$, $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- $\pi^-/\mu^-$ DAR are highly suppressed
- $\mu^-/\mu^+ \sim 8 \times 10^{-4}$
- Few % of $\pi^+$ DIF

![Diagram of LSND (LAMPF) Beam setup](image)
LSND Detector


- 8.3 m long x 5.7 m diameter cylindrical tank
- Tank covered by 1220 8” PMTs (25% coverage)
- Tank filled with 167 tons of mineral oil + 0.031 g/l of b-PBD
- 45 MeV electron: ~1500 pes with ~280 pes in Cherenkov cone
- δr ~ 14 cm; δθ ~ 12°; δE/E ~ 7%
- Separate veto shield had inefficiency of < 10⁻⁵ for cosmic muons
- Electron PID from fit to Cherenkov cone & time distribution
- Neutron PID from 2.2 MeV γ (np -> dγ)
Detection Principle: IBD

\[ E_p \sim E_\nu - 0.8 \text{MeV} \]

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

\[ n + p \rightarrow d + \gamma : (E_D = 2.2 \text{MeV}) \]

Delayed Coincidence
\[ \Delta t \sim 200 \mu s \]

---

**ν̄e Excess**

**Oscillation Parameter**
Future DAR Experiments

@ J-PARC
Material Life science Facility
- JSNS²
- K-Pipe

@ Oak Ridge
Spallation Neutron Source
-OscSNS
(1) High energy (~GeV) protons hit a dense target material and produce $\pi^+$. 
(2) $\pi^+$ stops in the material and decays producing $\nu_\mu$ and $\mu^+$. 
(3) $\mu^+$ stops in the material and decays producing $\nu_e$ and $\bar{\nu}_\mu$. 
(4) $\nu$'s from $\pi^-$ and $\mu^-$ are highly suppressed.
Neutrino Spectrum from DAR+Decay in Flight

\[ \pi^+ \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]

\[ \mu^- + Z^+ \rightarrow \nu_\mu + Z^- \]
\[ \pi^- \rightarrow \mu^- + \bar{\nu}_\mu \]

\[ K^+ \rightarrow \mu^+ + \nu_\mu \]

\[ K^+ \rightarrow \pi^0 + e^+ + \nu_e \]
\[ K_L \rightarrow \pi^- + e^+ + \nu_e \]

\[ \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \]
Pulsed beam can separate $\nu$'s from $\mu^+$ and hadrons

JSNS$^2$ case

beam structure

$\nu$ from $\pi$ & $K$ decays
(monochromatic)

$\nu$ from $\mu$ decay.
Since the parent $\mu^+$ has no momentum, the neutrino energy spectra are well known.
Cosmic-ray BKG can also be suppressed strongly by the pulsed beam

Open 9µs event gate for every 40ms of beam pulse

⇒ Cosmic-ray BKG is suppressed to 1/4,400x1/2 (by analysis)
( ~500m underground equivalent)
Why DAR?

* The energy spectra of the neutrinos are perfectly known.
* The neutrino–nucleus cross section is known to a few%.
* The time structure of the neutrino is perfectly known.
* $\mu^+$-origin and hadron-origin $\nu$ can be separately obtained.
* Monochromatic $\nu_{\mu}$ can be obtained.
* Neutrinos are free. Can perform experiments as parasite.
* ....
## Oscillation Modes of the Future Projects

<table>
<thead>
<tr>
<th>Name</th>
<th>Site</th>
<th>Target Oscillation Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>JSNS²</td>
<td>J-PARC MLF</td>
<td>$\mu^+ \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$ [appearance]</td>
</tr>
<tr>
<td>K-Pipe</td>
<td>J-PARC MLF</td>
<td>$K^+ \rightarrow \nu_\mu \rightarrow \nu_\mu$ [disapp., $L$ dependence]</td>
</tr>
</tbody>
</table>
| OscSNS   | OscSNS    | $\mu^+ \rightarrow \bar{\nu}_\mu \rightarrow \bar{\nu}_e$, [appearance]  
|          |           | $\nu_x \rightarrow \nu_x$ [disapp., $L$ dependence]  
|          |           | $(\pi^+ \rightarrow \nu_\mu \rightarrow \nu_e$, [appearance]) |
JSNS$^2$

(J-PARC Sterile Neutrino Search at J-PARC Spallation Neutron Source)

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Accelerator: J-PARC MLF

1MW, 3GeV $p$
Neutrino source: Hg target in MLF

- World-class high intensity neutron source driven by high power proton beam
  - beam energy: 3GeV
  - design beam power: 1MW

\[ p + Hg \rightarrow \pi^\pm + X \]
\[ \pi^\pm (stop) \rightarrow \mu^+ + \nu_\mu \]
\[ \mu^+ (stop) \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \]
MLF mercury target and Intrinsic $\bar{\nu}_e$ BKG estimation

$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e (\sim 20\%)$

<table>
<thead>
<tr>
<th>Material</th>
<th>Lifetime, ns (experiment)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be</td>
<td>2162.1 ± 2.0</td>
</tr>
<tr>
<td>Fe</td>
<td>206.0 ± 1.0</td>
</tr>
<tr>
<td>Hg</td>
<td>76.2 ± 1.5</td>
</tr>
</tbody>
</table>

T. Suzuki et al.
PRC35,2212(1987)

Target $\pi^-$ absorb $\mu^-$ capture suppression $\times \pi^-/\pi^+$

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>H2O</td>
<td>96%</td>
<td>88%</td>
<td>$5 \times 10^{-3}$ $\times$ 0.13 $= 6.5 \times 10^{-4}$</td>
</tr>
<tr>
<td>J-PARC</td>
<td>Hg(+Fe+Be)</td>
<td>99%</td>
<td>$\sim 80%$</td>
<td>$1.7 \times 10^{-3}$ $\times$ 1. $= 1.7 \times 10^{-3}$</td>
</tr>
</tbody>
</table>
Suppression of $\mu^- \rightarrow \bar{\nu}_e$ Background

Can be separated by the spectrum analysis

$\Delta m^2 = 0.5 \text{ eV}^2$

$\Delta m^2 = 2.5 \text{ eV}^2$

$\Delta m^2 = 3.5 \text{ eV}^2$

$\Delta m^2 = 5.5 \text{ eV}^2$

$\bar{\nu}_e / \bar{\nu}_\mu \sim 1.7 \times 10^{-3}$
* Gd-LS mass = 25 ton×2
* 150 10inch PMT.
* Movable
Inverse $\beta$-decay

$\bar{\nu}_\mu \Rightarrow \bar{\nu}_e + p \rightarrow e^+ + n$

oscillation

$n+\text{Gd} \rightarrow \text{Gd}'+\gamma_s \ (\Sigma E_\gamma=8\text{MeV})$

~30$\mu$s average

Delayed Signal ($n+\text{Gd}$)
(8MeV)

Prompt Signal ($e^+$)
(20~60MeV)

Free from environmental $\gamma$ BKG
(\(E_\gamma<2.8\text{MeV}\))
Signal extraction and the sensitivity

- Signal events can be distinguished from the dominant background (from another neutrino process) by using the difference of energy distributions.
- Most of the parameter region indicated by LSND exp. can be explored with more than $5\sigma$ significance in 5 years with 1MW beam power.
History and status of JSNS2

The group is actively moving forward
On site Background Measurement (2014)

- main scintillators
  - 24 pieces, 500kg
- 2 layers of veto scintillators
  - inner and outer veto
  - efficiency > 99.9%

MLF 3rd floor (maintenance area)

Mercury Target
(neutron & neutrino source)

3 GeV proton beam

side view

front view
Beam related accidental BKG will not be problem.
• If we see the positive signal, the phase-II experiment will be performed with longer baseline and larger detector as far detector.

(e.g.: L~60m, M ~1000 ton, outside the MLF building)
A Decisive Disappearance Search at High-\(\Delta m^2\) with Monoenergetic Muon Neutrinos

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arXive:1506.0581v1

\(L\) dependence of monochromatic \(\nu_\mu\) disappearance

120m long liquid scintillator tank (pipe) (684 tons)
K-Pipe

ν from K⁺:
Possible only at J-PARC MLF

ν_{μ} \rightarrow ν_S (Deficit)

ν detection principle
ν_{μ} + ^{12}C \rightarrow \mu^- + X

Sensitivity (3years)
The OscSNS White Paper

October 8, 2013

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Contact Persons: H. Ray and W. C. Louis
Oak Ridge  Spallation Neutron Source

Figure 4.2: A photograph of the completed SNS facility.

Table 4.1: SNS design parameters.
ν selection with pulsed beam

ν:\ t<0.6\mu s \rightarrow BKG\ reduction = 1/28,000

\bar{\nu}_\mu, \nu_e:\ If\ \Delta t=9\mu s, \rightarrow BKG\ reduction = 1/1,900 \times 1/2(\text{analysis})
Figure 5.1: A cut-away schematic drawing of the OscSNS cylindrical detector tank.
Several Detection Modes Using $L$ dependence

(1) $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ appearance

$$\bar{\nu}_e (E < 53 MeV) + p \rightarrow e^+ + n \rightarrow n + p \rightarrow D + \gamma (2.2 MeV; \Delta t = 200 \mu s)$$

(2) $\bar{\nu}_\mu, \nu_e, \nu_\mu \rightarrow \nu_S$ Neutral Current Disappearance

$$\nu_x + ^{12} C \rightarrow \nu_x + ^{12} C^* \rightarrow ^{12} C + \gamma (15.1 MeV)$$

(3) $\nu_\mu \rightarrow \nu_e$ appearance

$$\nu_e (30 MeV) + ^{12} C \rightarrow e^- (12.5 MeV) + ^{12} N_{gs} \rightarrow ^{12} N_{gs} \rightarrow e^+ (<17 MeV; \Delta t = 11 ms) + \nu + C$$
### Expected # of events and BKG per calendar year

**Disappearance Search**

<table>
<thead>
<tr>
<th>Channel</th>
<th>Background</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_\mu \ ^{12}C \rightarrow \nu_\mu \ ^{12}C^*$</td>
<td>1060 ± 36</td>
<td>3535 ± 182</td>
</tr>
<tr>
<td>$\nu_e \ ^{12}C \rightarrow \nu_e \ ^{12}C^*$</td>
<td>224 ± 75</td>
<td>745 ± 42</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \ ^{12}C \rightarrow \bar{\nu}</em>\mu \ ^{12}C^*$</td>
<td>24 ± 13</td>
<td>2353 ± 123</td>
</tr>
</tbody>
</table>

**Appearance Search** ($P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 0.26\%$)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Background</th>
<th>Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: $\bar{\nu}_e \ ^{12}C \rightarrow e^+ \ ^{11}B \ n$</td>
<td>42 ± 5</td>
<td>120 ± 10</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: $\bar{\nu}_e \ p \rightarrow e^+ \ n$</td>
<td>12 ± 3</td>
<td>3.5 ± 1.5</td>
</tr>
<tr>
<td>$\nu_\mu \rightarrow \nu_e$: $\nu_e \ ^{12}C \rightarrow e^- \ ^{12}N_{gs}$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
L/E distributions (5 net years)

\[ \bar{\nu}_e + p \rightarrow e^+ + n \quad \nu_\mu + C \rightarrow \nu_\mu + C^*(15.1 \text{MeV}) \quad \nu_e + C \rightarrow e^- + N_{gs} \]

\[ \sin^2 2\theta = 0.005 \]

\[ \Delta m^2 = 1 eV^2 \]

\[ \sin^2 2\theta = 0.15 \]

\[ \Delta m^2 = 4 eV^2 \]
OscSNS

\[ \bar{\nu}_\mu \rightarrow \bar{\nu}_e \]

\[ \nu_\mu \rightarrow \nu_\mu \]

→ Completely cover LSND
### JSNS$^2$ vs OscSNS vs LSND

<table>
<thead>
<tr>
<th></th>
<th>JSNS$^2$</th>
<th>OscSNS</th>
<th>LSND</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Target Mass.</strong></td>
<td>50t</td>
<td>450t</td>
<td>167t</td>
</tr>
<tr>
<td><strong>baseline</strong></td>
<td>24m</td>
<td>60m</td>
<td>30m</td>
</tr>
<tr>
<td><strong>beam energy</strong></td>
<td>3GeV</td>
<td>1GeV</td>
<td>0.8GeV</td>
</tr>
<tr>
<td><strong>beam power</strong></td>
<td>1MW</td>
<td>1.4MW</td>
<td>--</td>
</tr>
<tr>
<td><strong>Duty Factor</strong> for $\bar{\nu}_\mu$ &amp; $\nu_e$</td>
<td>1/8,800</td>
<td>1/3,800</td>
<td>1/14</td>
</tr>
<tr>
<td></td>
<td>1/40,000</td>
<td>1/28,000</td>
<td></td>
</tr>
<tr>
<td><strong>Stopping $\mu-$/$\mu+$</strong></td>
<td>1.7x10^{-3}</td>
<td>~10^{-3}</td>
<td>6.5x10^{-4}</td>
</tr>
<tr>
<td><strong>delayed signal</strong></td>
<td>8MeV, $\Delta t$=30µs</td>
<td>2.2MeV, $\Delta t$=200µs</td>
<td>2.2MeV, $\Delta t$=200µs</td>
</tr>
<tr>
<td><strong>Liquid Scintillator</strong></td>
<td>Gd Loaded (Cherenkov)</td>
<td>Cherenkov + Low Scinti.</td>
<td>Cherenkov + Low Scinti.</td>
</tr>
<tr>
<td><strong>Cosmic fast n rejection</strong></td>
<td>Pulse Shape Discri. (Cherenkov)</td>
<td>Cherenkov</td>
<td>Cherenkov</td>
</tr>
<tr>
<td><strong># of $\nu_e$ signal (BKG) events</strong></td>
<td>500(300)/5year (sin$^2$2$\theta$=0.003)</td>
<td>600(200)/5year (P=0.26%)</td>
<td>88/6year</td>
</tr>
<tr>
<td><strong>$\Delta E/E$</strong></td>
<td>3% @35MeV</td>
<td>--</td>
<td>7% @45MeV</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td>$4M$</td>
<td>$22M$</td>
<td>--</td>
</tr>
</tbody>
</table>
Summary

* Direct tests of the LSND positive result is very important.
* There are two such proposals; JSNS$^2$ and OscSNS, both highly improve the $\nu_s$ sensitivity over the LSND.
* Tests of other oscillation modes are possible, like K-Pipe
* Support from the neutrino community is important to realize them.