Very Short Baseline Neutrino Oscillation Experiments using Cyclotron Decay-at-Rest Sources

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Short-baseline $\nu$ oscillation

- Recent results from short-baseline neutrino experiments hint towards high $\Delta m^2 \sim 0.1-10$ eV$^2$ oscillation.
- Are they pointing towards Sterile $\nu$s or something else?
- Short-baseline means: $L/E \sim 1$ (m/MeV or km/GeV)

**LSND**: $L = 30$ m, $<E_{\bar{\nu}_\mu}> = 40$ MeV

- 3.8 $\sigma$ excess of $\bar{\nu}_e$ events in a beam of $\bar{\nu}_\mu$

**MiniBooNE**: $L = 541$ m, $<E_{\nu_\mu,\bar{\nu}_\mu}> = 700$ MeV

- A 2.8 $\sigma$ excess of $\bar{\nu}_e$ events in the anti-neutrino mode above 475 MeV, consistent with LSND.
No oscillation in the $\nu$-mode for energies above 475 MeV

An unexplained 3 $\sigma$ excess of $\nu_e$ events in the $\nu$-mode of MiniBooNE below 475 MeV

No hint of steriles in MiniBooNE $\nu_\mu/\bar{\nu}_\mu$ disappearance

Recent Reactor Anomaly

Reanalysis of reactor fluxes in Mueller et al., (arXiv:1101.2663) shows 2.5% upward shift in flux

Overall reduction in predicted flux compared to existing data can be interpreted as oscillations at baselines of order 10–100 m (arXiv:1101.2755)

Gallex-Sage reduced calibration source rate also suggesting possible $\nu_e$ disappearance
What do we need?

- We have both positive and negative hints for sterile high $\Delta m^2$ oscillation. Nothing is conclusive!!
- We need powerful new experiments to have appearance and disappearance searches at high significance involving both neutrinos and anti-neutrinos

Combine powerful new multi-kiloton liquid scintillator, argon or water detectors with a modest power decay-at-rest neutrino source at short-baseline

Observe the $L/E$ dependence of the oscillation wave across the length scales of these detectors

SKA, Patrick Huber, arXiv:1007.3228


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Stopped Pion Source

- 800 MeV protons from cyclotrons interact in a low-A target (C, H₂O) producing $\pi^+$ and, at a low level, $\pi^-$

$$p + X \rightarrow \pi^\pm + X'$$

- Low-A target is embedded in a high-A, dense material where pions are brought to rest
- $\pi^-$ & daughter $\mu^-$ captured before DIF, minimizing $\bar{\nu}_e$
- $\pi^+$ decay produces mono-energetic 29.8 MeV $\nu_\mu$ & $\mu^+$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

- $\mu^+$ decays at rest, providing Michel spectrum

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$
Decay At Rest (DAR) Source

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

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

Provides an equal, high-intensity, isotropic, DAR \( \nu_\mu, \nu_e \) and \( \bar{\nu}_\mu \) beam with tiny \( \bar{\nu}_e \) contamination \((4 \times 10^{-4})\)
Cyclotrons: ideal low-cost source for low energy protons

Bunch spacing \(\sim\) few tens of ns, continuous source

Average beam power, 10 - 100 kW, prototypes for DAE\(\delta\)ALUS

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Neutrino Source Details

$4 \times 10^{21}$ per year, per flavor ($\nu_\mu$, $\bar{\nu}_\mu$ and $\nu_e$),

$1.6 \times 10^{18}$ per year of $\bar{\nu}_e$ ($4 \times 10^{-4}$ compared to other flavors);

Delivered as 100 kW average power, with 200 kW instantaneous power,

(50% duty factor allowing equal beam-on and beam-off data sets);

800 MeV protons on target;

$\pm 25$ cm smearing (assumed flat) on neutrino production point;

20 m distance from average production point to face of detector fiducial region.

- p/$\pi$ ratio uncertain: conservative 10% correlated normalization error on all flavors
- 20% normalization error on the $\pi^-$ DIF background
- No uncertainty in the shape of the energy spectrum
DAR beam interactions

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

\[ \bar{\nu}_e + p \rightarrow e^+ + n \text{ (IBD)} \]

Free protons: Liquid scintillator oil, H\(_2\)O

Low kinematic threshold: 1.81 MeV

Coincidence tag between prompt positron and the delayed neutron capture by a proton

n + p \rightarrow d + \gamma (2.2 MeV) after \(\sim 250 \mu s\)

\[ \nu_e \rightarrow \nu_e \text{ Disappearance} \]

\(\nu_e + ^{12}C \rightarrow e^- + ^{12}N \text{ g.s.}\). Threshold 17.33 MeV, well measured, \(\sim 5\) to 10% uncertainty prompt \(e^-,\) followed within a 60 ms window by \(e^+\) from \(\beta\)-decay of the \(^{12}N \text{ g.s.}\), mean \(\tau\) 15.9 ms

\(\nu_e + ^{40}Ar \rightarrow e^- + ^{40}K^*\) Threshold 4.24 to 5.89 MeV depending on which \(^{40}K^*\)

It has the highest cross-section in the energy range of interest, excellent for Disappearance studies

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Add one sterile $\nu$ with three active ones at the eV scale

SBL approximation: $\Delta m_{21}^2 \approx \Delta m_{31}^2 \approx 0$ and $x_{ij} \equiv \Delta m_{ij}^2 L/4E$

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 x_{41} \equiv \sin^2 2\theta_{\mu e} \sin^2 x_{41}$$

Example Fit: $\Delta m_{41}^2 = 0.57$ eV$^2$ and $\sin^2 2\theta_{\mu e} = 0.0097$ using LSND, MB-$\bar{\nu}$, KARMEN (Karagiorgi et al., arXiv:0906.1997)

$$P(\nu_e \rightarrow \nu_e) = 1 - 4|U_{e4}|^2(1 - |U_{e4}|^2) \sin^2 x_{41} \equiv 1 - \sin^2 2\theta_{ee} \sin^2 x_{41}$$

Example Fit: $\Delta m_{41}^2 = 1.78$ eV$^2$ and $\sin^2 2\theta_{ee} = 0.089$ using all reactor data with new fluxes (J. Kopp et al., arXiv:1103.4570)

No CPV: can’t reconcile $\bar{\nu}$ (LSND, MB) and $\nu$ (MB) data
Add two sterile neutrinos with three active ones at the eV scale

**SBL approximation:** \( \Delta m_{21}^2 \approx \Delta m_{31}^2 \approx 0 \) and \( x_{ij} \equiv \frac{\Delta m_{ij}^2 L}{4E} \)

\[
P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = 4|U_{e4}|^2|U_{\mu4}|^2 \sin^2 x_{41} + 4|U_{e5}|^2|U_{\mu5}|^2 \sin^2 x_{51}
+ 8|U_{e4}U_{\mu4}U_{e5}U_{\mu5}| \sin x_{41} \sin x_{51} \cos(x_{54} + \delta)
\]

\( \delta \equiv \arg(U_{e4}^*U_{\mu4}U_{e5}U_{\mu5}^*) \) is the CP-phase

\[
P(\nu_e \rightarrow \nu_e) = 1 - 4(1 - |U_{e4}|^2 - |U_{e5}|^2)(|U_{e4}|^2 \sin^2 x_{41} + |U_{e5}|^2 \sin^2 x_{51})
- 4|U_{e4}|^2|U_{e5}|^2 \sin^2 x_{54}
\]

|       | \( \Delta m_{41}^2 \) | \( |U_{e4}| \) | \( |U_{\mu4}| \) | \( \Delta m_{51}^2 \) | \( |U_{e5}| \) | \( |U_{\mu5}| \) | \( \delta / \pi \) |
|-------|----------------------|------------------|------------------|----------------------|------------------|------------------|------------------|
| A : arXiv:1103.4570 | 0.47 | 0.128 | 0.165 | 0.87 | 0.138 | 0.148 | 1.64 |
| B : arXiv:0906.1997 | 0.39 | 0.40 | 0.20 | 1.10 | 0.21 | 0.14 | 1.1 |

Global best-fit points for (3+2) model. Mass splittings are shown in eV^2

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LENA Scintillation Detector

50 kt Fiducial (Unsegmented)

100 m tall by 30 m diameter

Source-to-detector-face = 20 m

Low detection threshold

Excellent Vertex and Energy Resolution

Clear coincidence signal for $\bar{\nu}_e$ IBD events

Deep underground location (4000 mwe)

Negligible cosmic muon backgrounds

**Neutrino Energy threshold**

For appearance : $E_\nu > 20 \text{ MeV}$

For disappearance : $E_\nu > 33 \text{ MeV}$
Appearance wave in LENA

50 kt LENA (Appearance mode)

Bin and fit IBD data with reconstructed $L/E$

(3+1) fit : Karagiorgi et al., arXiv:0906.1997

$\Delta m^2_{41} = 0.57 \text{ eV}^2$ & $\sin^2 2\theta_{\mu e} = 0.0097$

(3+2) fit : J. Kopp et al., arXiv:1103.4570

Accessible L range : 20–120 m

DAR energy range : 20–52.8 MeV

Oscillation wave is dramatic in the long LENA detector and can provide a powerful handle to discriminate between (3+1) and (3+2) schemes

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## Appearance Event Rates

|            | $\Delta m^2_{41}$ | $|U_{e4}|$ | $|U_{\mu4}|$ | $\Delta m^2_{51}$ | $|U_{e5}|$ | $|U_{\mu5}|$ | $\delta/\pi$ |
|------------|-------------------|-----------|---------------|-------------------|-----------|-----------|-------------|
| A : arXiv:1103.4570 | 0.47 | 0.128 | 0.165 | 0.87 | 0.138 | 0.148 | 1.64 |
| B : arXiv:0906.1997 | 0.39 | 0.40 | 0.20 | 1.10 | 0.21 | 0.14 | 1.1 |

<table>
<thead>
<tr>
<th>Fiducial Mass</th>
<th>Radius</th>
<th>Length</th>
<th>Signal (A : 1103.4570)</th>
<th>Signal (B : 0906.1997)</th>
<th>Intrinsic $\bar{\nu}_e$ Background</th>
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<tbody>
<tr>
<td>50 kt</td>
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</table>

- Signal and beam background events in 5 to 50 kt LENA
- Total $4 \times 10^{21} \bar{\nu}_\mu$ (100 kW source), efficiency 90%
- The intrinsic $\bar{\nu}_e$ beam contamination is $4 \times 10^{-4}$

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5 kt LENA combined with a small 10 kW DAR source can test the LSND/MiniBooNE anti-neutrino signal at 5σ CL in 3+1 model in 1 yr
Bin and fit $\nu_e$ scattering data with $L/E$

(3+1) fit : J. Kopp et al., arXiv:1103.4570

$\Delta m^2_{41} = 1.78 \text{ eV}^2$ and $\sin^2 2\theta_{ee} = 0.089$

(3+2) fit : J. Kopp et al., arXiv:1103.4570

Accessible L range : 20–120 m

DAR energy range : 33–52.8 MeV

Different shape for (3+1) and (3+2) waves.
Comparison between the amplitudes of the wave in various $L/E$ bins cancels flux uncertainties
### Disappearance Event Rates

|          | $\Delta m_{41}^2$ | $|U_{e4}|$ | $|U_{\mu4}|$ | $\Delta m_{51}^2$ | $|U_{e5}|$ | $|U_{\mu5}|$ | $\delta/\pi$ |
|----------|-------------------|-----------|-------------|-------------------|-----------|-------------|-------------|
| A : arXiv:1103.4570 | 0.47 | 0.128 | 0.165 | 0.87 | 0.138 | 0.148 | 1.64 |
| B : arXiv:0906.1997 | 0.39 | 0.40 | 0.20 | 1.10 | 0.21 | 0.14 | 1.1 |

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<th>Length</th>
<th>Evts w/ Osc (A : 1103.4570)</th>
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<th>Evts, No Osc</th>
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<tr>
<td>50 kt</td>
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<td>5 kt</td>
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<td>30874</td>
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</tr>
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- **CC $\nu_e$ scattering events on $^{12}$C in 5 to 50 kt LENA**
- **Total $4 \times 10^{21} \nu_e$ (100 kW source), efficiency 80%**
- **$E_\nu$ threshold of 33 MeV and resolution $10\%/\sqrt{E_e/\text{MeV}}$**

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DAR-LENA $\nu_e \rightarrow \nu_e$ Sensitivity

100 kW source ($4 \times 10^{21} \nu_e$), 5 - 50 kt fiducial

(3+1) model with simple 2-$\nu$ approximation

Triangle & Bullet: (3+1) best-fit values for all reactor data with old & new fluxes

Dashed green curve: 99% CL (2 dof) limit from reactor data with new reactor fluxes

10 kt LENA with a flux of $4 \times 10^{21} \nu_e$ can provide stringent test of the recent reactor anomaly at 3 $\sigma$ CL (2 dof)

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NO$\nu$A : Coming Soon

Segmented Scintillator Detector

- Detector mass 14 kt
- CH$_2$ Scintillator Target, 30% PVC
- Dimensions : $15.7 \m m \times 15.7 \m m \times 67 \m m$
- NO$\nu$A not made for low energy signal
- It can only perform $\nu_e$ disappearance
- Cannot see the 2.2 MeV $\gamma$ from n capture
- Very little shielding – 3 m of Earth

Largest background : $10^{10}$ Michel electrons/year produced by stopped cosmic muon decay

Michel electron events identified and vetoed by tracking the parent muon

For this study, we consider 10,000 to 50,000 un-vetoed Michel background events

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### NOνA Event Rates

|                      | $\Delta m^2_{41}$ | $|U_{e4}|$ | $|U_{\mu4}|$ | $\Delta m^2_{51}$ | $|U_{e5}|$ | $|U_{\mu5}|$ | $\delta/\pi$ |
|----------------------|-------------------|------------|-------------|-------------------|----------|------------|-------------|
| A : arXiv:1103.4570  | 0.47              | 0.128      | 0.165       | 0.87              | 0.138    | 0.148      | 1.64        |
| B : arXiv:0906.1997  | 0.39              | 0.40       | 0.20        | 1.10              | 0.21     | 0.14       | 1.1         |

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<tbody>
<tr>
<td>14 kt</td>
<td>67 m</td>
<td>15.7 m</td>
<td>15.7 m</td>
<td>32388</td>
<td>27407</td>
<td>34415</td>
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</table>

- **CC $\nu_e$ scattering events on $^{12}$C in 14 kt NOνA far detector**
- **Total** $4 \times 10^{21} \nu_e$ (100 kW source), efficiency **50%**
- **$\nu$ energy threshold** of 38 MeV and resolution $100%/\sqrt{E_e/\text{MeV}}$
**DAR-NOνA ν_e → ν_e Sensitivity**

100 kW & 1 MW average source power

25k & 50k effective Michel e^- Backgrounds

(3+1) model with simple 2-ν approximation

Triangle & Bullet : (3+1) best-fit values for all reactor data with old & new fluxes

Dashed green curve : 99% CL (2 dof) limit from reactor data with new reactor fluxes


100 kW machine is marginal in covering the test points and a higher-power, full DAEδALUS type machine, is needed

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Possible detector for $\nu_e$ disappearance search with DAR beam

|                | $\Delta m^2_{41}$ | $|U_{e4}|$ | $|U_{\mu 4}|$ | $\Delta m^2_{51}$ | $|U_{e5}|$ | $|U_{\mu 5}|$ | $\delta/\pi$ |
|----------------|------------------|----------|--------------|------------------|----------|----------|-------------|
| A: arXiv:1103.4570 | 0.47             | 0.128    | 0.165        | 0.87             | 0.138    | 0.148    | 1.64        |
| B: arXiv:0906.1997 | 0.39             | 0.40     | 0.20         | 1.10             | 0.21     | 0.14     | 1.1         |

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<td>5 kt</td>
<td>50 m</td>
<td>10 m</td>
<td>7 m</td>
<td>345601</td>
<td>288061</td>
<td>368812</td>
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<tr>
<td>3 kt</td>
<td>30 m</td>
<td>10 m</td>
<td>7 m</td>
<td>292671</td>
<td>250392</td>
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<tr>
<td>1.5 kt</td>
<td>15 m</td>
<td>10 m</td>
<td>7 m</td>
<td>211445</td>
<td>186585</td>
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</table>

- CC $\nu_e$ scattering events on $^{40}$Ar in 1.5 to 5 kt LAr detector
- Total $4 \times 10^{21}$ $\nu_e$ (100 kW source), efficiency 90%
- $\nu$ energy threshold of 20 MeV and resolution $11%/\sqrt{E_e}+2.5\%$

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DAR-LAr $\nu_e \rightarrow \nu_e$ Sensitivity

- 100 kW average source power
- Negligible background from cosmic muons (under 4000 mwe of shielding)
- (3+1) model with simple 2-$\nu$ approximation
- Triangle & Bullet: (3+1) best-fit values for all reactor data with old & new fluxes
- Dashed green curve: 99% CL (2 dof) limit from reactor data with new reactor fluxes

1.5 kt LAr detector and 100 kW source is enough to test the reactor anomaly at high significance

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Can we use DAR beam with ICARUS or LarLAr?

- Use photo detectors to determine the $t_0$ for the $\nu_e$ events
- Determining $t_0$ is compromised if a muon comes through within 5 $\mu$s before the event
- Assume 20 kHz muon rate through the detector. One puts a 99.9% scintillator veto on top of the detector and vetos any events with a muon within 5 $\mu$s of the event. This produces a deadtime of $20,000\text{Hz} \times 5\text{ $\mu$s} = 10\%$
- 0.1% of the through-going muons will not be vetoed at a rate of 20 Hz. The random coincidence of these with a real $\nu_e$ event within 5 $\mu$s will be $10^{-4}$ fraction of the real events which is negligible
- Use LAr detector itself to veto muons with light detectors
Large neutrino detectors using liquid scintillator and liquid argon will come on-line within the next decade

These detectors combined with high intensity 10–100 kW cyclotron DAR neutrino sources would have unprecedented sensitivity to sterile $\nu$ oscillations in the high $\Delta m^2 \sim 0.5\text{–}10 \text{ eV}^2$ region

These experiments are an important option as a next major step to search for sterile neutrino oscillations

Thank you