Complementarity of Short-Baseline Neutrino Oscillation Searches with CEvNS

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with Dutta, Gao, Kubik, Mahapatra, Mirabolfathi, Strigari - Phys. Rev. D 94, 093002
+ Dutta, Dent to appear
& Representing the MiνER Collaboration

Please see the excellent review 1803.10661 by
Dentler, Hernandez-Cabezudo, Kopp, Machado, Maltoni, Martinez-Soler, Schwetz

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Outline

• **Summary of Status of Anomalies:**
  There are SEVERAL, generally consistent within “types”, but not obviously consistent with each other globally. See talk by Danny Marfatia for one possible approach – a sterile sector WITH Non-Standard Interactions

• **Review of Physics and Analysis:**
  Pros and Cons of various experimental approaches to characterizing short-baseline steriles with CEvNS

• **Projection of Sensitivity with CEvNS:**
  Complementarity of beam and reactor searches
Formalism

• At the matrix element level: Sum over intermediate states and square the amplitude

\[ P_{\alpha\beta} = \sum_{j,k=1}^{4} U_{\alpha j}^* U_{\beta j} U_{\alpha k} U_{\beta k}^* \exp \left( -i \frac{\Delta m_{jk}^2 L}{2E} \right) \]

• Transition to self and transition to alternate flavor

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

\[ P_{\alpha\beta} = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right) \]
REACTOR and GALLIUM ANOMALIES

• Nuclear reactors produce $\bar{\nu}_e$ flavor states; effect of steriles is *disappearance*

• The “REACTOR ANOMALY”: There is a global $\sim 3\sigma$ flux deficit relative to the theoretical expectation. This is amplified by recent reevaluation of the theory (Huber / Mueller et. al 1101.2663 & 1106.0687). Observed/Expected is $\sim 94%$

• Radiactive source experiments with Gallium (GALLEX and SAGE – 0711.4222 & 1006.3244) likewise show a flux deficit.

• There is an observed “bump” in the reactor spectrum near 5 MeV (1610.04326)

• Daya Bay (1704.02276) has used time evolution of the fuel composition to break down flux contributions. There is a suggestion that the anomaly is associated with $^{235}\text{U}$, while $^{239}\text{Pu}$ is consistent. This would disfavor a sterile interpretation. However, there is some disagreement on methodolgy (1510.08948)

• Dentler et. al (1709.04294) find goodness of fit 73% with free flux normalizations vs. 18% with fixed flux plus sterile $\Delta m^2 \sim \text{eV}^2$.

• However, DANSS and NEOS prefer sterile to flux rescaling. This weakens the global preference. Including time-dependence of decay chains and neutron capture on fission products reduces Daya Bay’s preference below $2\sigma$ – P. Huber
Without reactors, a larger $|U_{e4}|^2 \sim 5 - 6 \times 10^{-2}$ is ok

From Dutta
Daya Bay DANSS and NEOS

- Newer (1607.01174, 1610.0534, 1606.02896) reactor analyses take RATIOS of observations at different baselines in order to REMOVE dependence upon the flux normalization and intrinsic spectral shape.

- Inclusion of a sterile improves the fit at the level of $3\sigma$ (1803.10661)
LSND and MiniBooNE

• At MiniBooNE, 8 GeV protons from FNAL Booster strike a Be target. Magnetically focused charged pions produce $\nu_\mu$ or $\bar{\nu}_\mu$ beams. Detector is 818 tons of mineral oil at $\sim 540$ m baseline. Detection is flavor-sensitive CCQE off electrons. Neutrino energies are around 500 MeV. (1805.12028)

• Around $10^{21}$ protons on target

• There is $4.8\sigma$ evidence of an excess of electron neutrino appearance.

• Two neutrino mu to e oscillation has goodness of fit 20.1%. Background only hypothesis is $5 \times 10^{-7}$ relative to best fit with $L/E_\nu \approx 1$[m/MeV].

• This is MUCH too short for standard neutrino oscillation to be responsible. BUT – the transition could occur *through* a sterile.

• In combination with results form the prior similar LSND experiments at Los Alamos (which is compatible) the significance is $6.1\sigma$
MiniBooNE Results

- 1805.12028 Left: Neutrino Mode and Right: Combined with Anti-Neutrino
- Best fit “dot” should not be strongly preferred over regions in contours
Neutrino 4

• Hosted at a megawatt research reactor in Russia. 95% $^{235}\text{U}$. 480 live days.

• Baseline is 6-12 meters. Core is compact and detector is segmented.

• Gadolineum-doped liquid scintillator with 1.8 m$^3$ detects neutrinos via inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$).

• Analysis uses RATIOS of events and plots in $L/E_\nu$ to extract oscillation without dependence upon normalization of flux.

• Claim $3\sigma$ preference for oscillation. NOTE: this is a DELTA $\chi^2$. The no-oscillation hypothesis is a reasonably good fit. This is NOT a $3\sigma$ exclusion of the SM.

• The IBD detection FULLY RECONSTRUCTS the neutrino energy – this allows for “coherency” of the oscillation over many cycles, with deep cuts as a function of $\Delta m^2$. It is also flavor sensitive.

• But, the cross-section is very low compared to coherent scattering
Neutrino 4

Best fit $\Delta m^2 = 7.22 \text{eV}^2$, $\sin^2(2\theta) = 0.35$

Observed, 24p, 500keV

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

$\chi^2$/DoF 18.84/25  GoF 0.80

Unity $\chi^2$/DoF 30.15/27  GoF 0.31
Neutrino 4

- Yellow, Green, and Blue are increasingly favored
$$|U_{\mu 4}|^2 \leq 0.01$$

Dentler, Harnadex-Cabezudo, Kopp, Machado, Maltoni, Schwetz, ’18

<table>
<thead>
<tr>
<th>Experiment</th>
<th>References</th>
<th>Comments</th>
<th>Data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>IceCube (IC)</td>
<td>[52-54]</td>
<td>MSW resonance in high-E atmospheric $\nu_\mu$</td>
<td>189</td>
</tr>
<tr>
<td>CDHS</td>
<td>[101]</td>
<td>accelerator $\nu_\mu$</td>
<td>15</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>[102, 103, 107]</td>
<td>accelerator $\nu_\mu$ and $\nu_\nu$</td>
<td>15 + 42</td>
</tr>
<tr>
<td>Super-Kamiokande (SK)</td>
<td>[48, 104]</td>
<td>low-E atmospheric neutrinos</td>
<td>70</td>
</tr>
<tr>
<td>DeepCore (DC)</td>
<td>[49, 50]</td>
<td>low-E atmospheric neutrinos</td>
<td>64</td>
</tr>
<tr>
<td>NOvA</td>
<td>[44]</td>
<td>NC data</td>
<td>1</td>
</tr>
<tr>
<td>MINOS/MINOS+</td>
<td>[43]</td>
<td>accelerator $\nu_\mu$, CC &amp; NC event spectra</td>
<td>108</td>
</tr>
</tbody>
</table>
Searching for New Physics with CEvNS

• Large statistics allow precision discrimination
• Can search for new neutral currents, e.g. $Z'$, NSI – this creates a modification to the RATE only
• Sensitivity is BEST to models that impact also the expected event distribution SHAPE:
• Light mediators, magnetic moment, sterile
• Huge event rates of ~ 1/kg/hour are possible in the SM
• The signal region stands out b/c of narrow bandwidth and coherency enhancement
• For BSM physics look to distinguish rate, shape, and Si Vs. Ge
Oscillation to Sterile 4\textsuperscript{th} Flavor Neutrino

\[ P_{(\alpha \rightarrow \beta)} = \sin^2 [2\theta] \times \sin^2 \left[ \frac{\Delta m^2 L}{4E_\nu} \right] \]

\[ \lambda = 4.97 \text{ [m]} \times \left\{ \frac{E_\nu}{1 \text{ [MeV]}} \right\} \times \left\{ \frac{1 \text{ eV}^2}{\Delta m^2} \right\} \]

\[ \gamma_i(\Delta m_{14}^2 L) \equiv \frac{1 - (N_{\text{Osc}}^i/N_{\text{Exp}}^i)}{\sin^2 2\theta_{14}} \]

\[ \gamma_i(\Delta m_{14}^2 L) = \left\langle \sin^2 \left[ \frac{\Delta m_{14}^2 L}{4E_\nu} \right] \right\rangle_{E_\nu} \equiv \iint dE_\nu \, d\sigma \, \lambda \times \sin^2 \left[ \frac{\Delta m_{14}^2 L}{4E_\nu} \right] \div \iint dE_\nu \, d\sigma \, \lambda \]

- Probability for oscillation depends on mixing (amplitude) and mass gap (phase)
- For the region of interest, an experimental baseline on the order of meters is relevant
- Dimensionless scale-invariant basis functions encapsulate all aspects of theory
Depletion via Oscillation

Sterile Neutrino Oscillation in Reactor CEνNS with $^{72}$Ge

Larger values in the vertical correspond to greater depletion via oscillation

Universal curve bases are rescaled (vert.) by mixing amplitude and (horiz.) mass gap

Bins are selected for approximately equivalent population event rates

Even with a fixed length scale, multiple energy samples give sensitivity to oscillation

Oscillation decoheres over multiple cycles & with mixing in the neutrino energy
COHERENT at the SNS

- Stopped Positive Pion produces isotropic muon neutrino $\nu_{\mu}$ of fixed energy $\sim 30$ MeV

- This is $\sim 20X$ the mean energy of a reactor neutrino

- Subsequently the delayed decay of the $\mu^+$ to $e^+\nu_e\bar{\nu}_{\mu}$ yields calculable SPECTRA with endpoint energy $m_{\mu}$ (1804.09459). The $\nu_{\mu} : \nu_e : \bar{\nu}_{\mu}$ flavors are produced in equal proportion. BUT, for a NR threshold $\sim 5$ keV, the coherent scattering rates are around $0.2 : 0.3 : 0.5$ due to rate enhancement at higher energy.

- INTEGRATED cross section is $20^2 = 400X$ larger and recoils are similarly more energetic – this is why low threshold is less critical for COHERENT. In principle, it also allows for much more massive detectors.

- Timing information helps with background suppression.

- BUT flux is $\sim 10^5$ times lower than a reactor.
Coherent Scattering at a Reactor

- Flux is high, \((10^{12} - 10^{13} \text{ per cm}^2 \text{ per second})\) and backgrounds are challenging.

- The reactor spectrum is (reasonably) well known.

- Because of the neutral current coherent, scattering detection never resolves flavor.

- Because of the differential cross-section, a given neutrino can produce many different recoils, and the map is NOT INVERTABLE. BUT harder neutrinos will tend to produce harder recoils, so binning in energy is essential.

- On an event-by-event basis one never knows what the neutrino energy was (directional detection would resolve this).
Reactor Anti-Neutrino Source

- $^{235}$U yields a thermal energy of 202 MeV per fission
- Neutrino yield in cascade is 6.14 with 1.5 MeV mean energy
- If reactor power is known, then the neutrino flux is known
- Spectrum is experimental (Schreckenbach et al.) above 2 MeV
- Below inverse $\beta$ threshold, spectrum is theoretical (Kopeiken)
- Coherency of scattering is naturally well-maintained
- MW reactor delivers flux of $1.5 \times 10^{12}/\text{cm}^2/\text{sec} @ 1 \text{ m}$ (vs. Solar $\sim 5 \times 10^6/\text{cm}^2/\text{sec}$)
Integrated Event Rate

\[ N_{\text{Exp}}^{i,n} = \phi_0 \times T_n \times \frac{L_0^2}{L_n^2} \times \frac{M_{\text{Det}}}{M} \times \int_{E_{\nu}^{\text{min}}(E_R^{i\|})}^{\infty} dE_{\nu} \lambda(E_{\nu}) \int_{E_R^{i\|}}^{\min\{E_R^{i\|},E_R^{\text{max}}(E_{\nu})\}} dE_R \frac{d\sigma}{dE_R}(E_{\nu}, E_R) \]

- Integrate in the physical region over recoils and over the normalized \( E_\nu \) spectrum
- Result is proportional to flux, time, and mass, and inversely so to distance-square
- Form factor \( F^2(q^2) \) is suppressed (assumed equal to unity)
- For MeV order neutrinos, an ultra-low detection threshold is vital
- Note “area” is from the interaction cross section – NOT the physical detector dimension
Formalism

• CEvNS Neutral current touches all flavors – use unitarity at reactors

\[
P_{\bar{\nu}_e \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_e \rightarrow \bar{\nu}_\mu} + P_{\bar{\nu}_e \rightarrow \bar{\nu}_\tau} = 1 - 4|U_{e4}|^2 \left( 1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2 \right) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)
\]

• And at the SNS beamline. If we idealize prompt and delayed as separate experiments we can solve the system.

\[
P_{\nu_{\mu} \rightarrow \nu_{\mu}} + P_{\nu_{\mu} \rightarrow \nu_e} + P_{\nu_{\mu} \rightarrow \nu_\tau} = 1 - 4|U_{\mu4}|^2 \left( 1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2 \right) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)
\]

\[
P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_{\mu}} + P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_e} + P_{\bar{\nu}_{\mu} \rightarrow \bar{\nu}_\tau} = 1 - 4|U_{\mu4}|^2 \left( 1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2 \right) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)
\]

\[
P_{\nu_e \rightarrow \nu_e} + P_{\nu_e \rightarrow \nu_\mu} + P_{\nu_e \rightarrow \nu_\tau} = 1 - 4|U_{e4}|^2 \left( 1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2 \right) \sin^2 \left( \frac{\Delta m_{41}^2 L}{4E} \right)
\]

\[
|U_{e4}|^2 ; |U_{\mu4}|^2 ; 1 - |U_{e4}|^2 - |U_{\mu4}|^2 - |U_{\tau4}|^2
\]
SNS Delayed

Sterile Neutrino Oscillation in Reactor CEνNS with CsI

\[ \gamma \equiv \left( 1 - \frac{N_{\text{Osc}}}{N_{\text{Exp}}} \right) \div \sin^2 2\theta_{14} \]

\[ \Delta m^2_{14} \text{[eV]}^2 \times \text{L [m]} \]
Sterile Neutrino Oscillation in Reactor CEνNS with CsI

\[ \gamma^j \equiv \frac{1 - N_{\text{Osc}}/N_{\text{Exp}}}{\sin^2 2\theta_{14}} \]

\[ \Delta m_{14}^2 \ [\text{eV}^2] \times L \ [\text{m}] \]
Sterile Neutrino Oscillation in Reactor CEvNS with Ge

\[ \gamma^j \equiv (1 - N_{\text{obs}}/N_{\text{exp}}) \div \sin^2 2\theta_{14} \]

\[ \Delta m^2_{14} \text{[eV]}^2 \times L \text{[m]} \]
SNS Delayed CsI, 100 [kg·d/m²], 20 [m], $E_R > 5$ [keV], 0 BG, 1% Sys

$\sin^2 2\theta_{xx}$

$\Delta m^2_{14}$ [eV²]

$\sqrt{q^A_0}$
SNS Prompt CsI, 100 [kg·d/m²], 20 [m], \( E_R > 5 \) [keV], 0 BG, 1% Sys

\( \sqrt{q_0^d} \)
Reactor

Ge $\chi^2$ Significance, $10 [GW \cdot kg \cdot d/m^2]$, $E_R > 100 [eV]$, 1 dru, 1% Sys

$\sqrt{q_0^4}$

$\Delta m_{14} [eV]^2$

$\sin^2 2\theta_{14}$
Reactor

$$\sqrt{q_0^4} = 3, \text{ Ge 10 [GW\cdot kg\cdot d/m^2]}, E_R > 40 \text{ [eV]}, 1 \text{ dru, 1\% Sys}$$
$\sqrt{q_0^4} = 3$, SNS Delayed CsI, 100 [kg·d/m²], $E_R > 5$ [keV], 0 BG, 1% Sys
Reactor Threshold

- Low threshold is essential for additional channels

*PRELIMINARY* Sterile Oscillation, 1 DRU, $\sin^2 2\theta = 0.1$, $\Delta m^2 = 1 \text{ eV}^2$, 10,000 kg–Days, MINER 3 [m]
Reactor Binning

- One must bin in order to separate correlated effects

*PRELIMINARY* Sterile Oscillation at Reactor, $\sin^2 2\theta = 0.1$, 1 DRU, 5% Systematics
Reactor Systematics

• Large systematics require low thresholds

*PRELIMINARY* Sterile Oscillation at Reactor, $\sin^2 2\theta = 0.1$, 1 DRU