Sterile Neutrinos
&
Neutral Current Scattering

Coherent Scattering Workshop
Dec 6th, 2012

J.A. Formaggio
MIT
Motivation for Measurement

Technique

Sources and Detectors

Projected Sensitivity
Motivation for Measurement

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Sources and Detectors

Projected Sensitivity
The Case for Sterile Neutrinos

- A number of recent (and not so recent) results seem to indicate the possibility of sterile neutrinos.

- Evidence stems from a variety of sectors:
  - Cosmology
  - Short-baseline (LSND/MiniBooNE)
  - Reactor anomaly
  - Gallex / SAGE Calibration source

- All suggestive, but no “smoking gun” accepted by the community at the moment.
The Case for Sterile Neutrinos

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- All suggestive, but no “smoking gun” accepted by the community at the moment.
A Smoking Gun, yes, but how?

• Such anomalous observations warrant further experimental verification, and to a certain degree that occurs and continues to occur.

• Example. LSND → MiniBooNE.

• Similar follow-up experiments also planned for the reactor anomaly.

• What do we want from a “smoking gun”?
  
  • Evidence that it is sterile.
  
  • Evidence that is it oscillations (length/energy dependence).

\[
\mathcal{P}(\nu_a \to \nu_s) = 1 - \sin^2(2\theta_s) \sin^2(1.27\Delta m_{S}^2 \frac{L}{E_{\nu}})
\]
The Argument for Coherent Scattering

- Coherent scattering allows to probe neutrinos using a *neutral current* channel; oscillation signature would be clear sign of active $\rightarrow$ sterile mixing.

- Previous evidence mainly in energy. Uses distance (oscillometry) instead, same detector:
  - For $\Delta m^2 \sim 1\ eV$
  - $L \sim O(1\ meter);\ E_\nu \sim O(1\ MeV)$
  - Simpler if just source is monochromatic.
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Look for Radioactive Source & Coherent Scattering detector
Oscillometry

Manifestation of oscillations over distance (L) within same experiment very powerful smoking gun. Effect difficult to mimic.

Proposed in conjunction with sterile neutrino searches numerous times in literature.

For 1 MeV neutrinos at 1 eV, implies 1 meter scale.
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Search for $1/r^2$ deviation
One big obstacle...

- For neutral current coherent scattering on a silicon target, the maximum kinetic energy is 50 eV. So a threshold of ~10 eV is necessary.

- Methods involving e-h pair detection have very low (or zero) quenching factors at these energies.

- Likewise, energies of at least few eV required to produce scintillation photons. Would yield poor statistics.

- Only remaining option is pure phonon detection.

\[ T_{\text{max}} \leq \frac{E_\nu}{1 + \frac{M_A}{2E_\nu}} \]

\[ T_{\text{max}} \leq 50 \text{ eV for Si at 0.8 MeV} \]
Oscillometry Techniques
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Neutrino-Electron Scattering, MegaCurie Sources

Allows for much higher thresholds. Sensitive to neutrino magnetic moment.

Henning, arXiv:1011.3811v1; BOREXINO, etc.
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**Charged Current Scattering, MegaCurie Sources**

Uses $^{115}\text{In}$ with low threshold (114 keV) to search for sterile component

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Uses $^{115}$In with low threshold (114 keV) to search for sterile component


Neutral Current Coherent Scattering, MegaCurie Sources

Uses bolometry to probe down to the eV recoil spectrum.

# Neutrino Sources

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<tr>
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<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td>Electron Capture</td>
<td>Mono-energetic, can place detector &lt; 1m from source, ideal for sterile neutrino search</td>
<td>&lt; 1 MeV energies require very low (~10 eVnr) thresholds, 30 day half-life, costly</td>
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<tr>
<td>Nuclear Reactor</td>
<td>Free, highest flux</td>
<td>Spectrum not well known below 1.8 MeV, site access can be difficult, potential neutron background at research reactors, reactor rarely off for GW power plants</td>
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<td>SNS funding travails, ESS and Daedalus don’t exist, ISODAR will have a low flux requiring large detectors</td>
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The Source

- Ideal mono-energetic sources have been constructed for experiments previously (SAGE, GALLEX), of order 1 MCi activity.

- A compact $^{37}$Ar is particularly attractive, since only inner brems photons produced. However, difficult to produce.

- $^{51}$Cr less ideal (but easier to produce) source. Allows for “recharging” for greater yield.

### Table: Source Properties

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<tr>
<th>Source</th>
<th>Half-Life</th>
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<th>Production</th>
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<tr>
<td>$^{37}$Ar</td>
<td>35.04 days</td>
<td>$^{37}$Cl</td>
<td>$^{40}$Ca(n,α)$^{37}$Ar capture on $^{50}$Cr</td>
<td>811 keV (90.2%), 813 keV (9.8%)</td>
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<tr>
<td>$^{51}$Cr</td>
<td>27.70 days</td>
<td>$^{51}$V</td>
<td>n capture on $^{50}$Cr</td>
<td>747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)</td>
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<tr>
<td>$^{65}$Zn</td>
<td>244 days</td>
<td>$^{65}$Cu</td>
<td>n capture on $^{64}$Zn</td>
<td>1343 keV (49.3%), 227 keV (50.7%)</td>
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**SAGE**

$^{71}$Ga + $\nu_e$ --> $^{71}$Ge + e$^-$

Use of $^{37}$Ar and $^{51}$Cr

**Gallex/GNO**

$^{71}$Ga + $\nu_e$ --> $^{71}$Ge + e$^-$

Use of $^{51}$Cr
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The Detector

- Given historical precedent, we focus on Transition Edge Sensors (TES) as the technology to push down to the 10 eV scale.

- Energy resolution dominated by the total heat capacitance of system ($C_{tot}$).

- At 15 mK, a 10 eV threshold could be achieved with a system capacitance of $C_{tot} < 300 \text{ pJ/K}$.

- Model must include noise sources from other internal decouplings.

\[
\sigma_E \approx \sqrt{\frac{4k_B T^2 C_{tot}}{\alpha} \sqrt{\frac{\beta + 1}{2}}}
\]
Detector Optimization

• System's mass optimized to reach 10 eV threshold assuming 15 mK temperature.

• Yields 50 g Si (20 g Ge) cube.

• Signal pulses show remarkable linearity.
Precedent

- Knaack and Meibner have achieved low enough impurities ($O(10^{12})$) where Debye heat capacity dominates.

- Using Mo-Au TES, 2 eV resolutions (FWHM) have been achieved, hence used here as well.

- Some existing experiments use similar technology, but are optimized for different parameters, such as mass, resolution, and timing. But no new technology is postulated.
The Array

- Array of 10,000 elements with Ar/Cr source just outside shield (10 cm closest distance). System would be a merger of CUORE-like cryogenic design and SCUBA-II like readout.

- Yields 500 kg Si / 200 kg Ge array.

- Source insertion outside system. Moved for in-situ calibration.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Detector Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Material</td>
<td>Si  Ge</td>
</tr>
<tr>
<td>Atomic Number</td>
<td>28  72.6</td>
</tr>
<tr>
<td>$\sigma_0(E_\nu)$ ($10^{-42}$ cm$^2$)</td>
<td>0.44  3.82</td>
</tr>
<tr>
<td>$T_{\text{max}}$</td>
<td>50.3 eV  19.4 eV</td>
</tr>
<tr>
<td>Threshold</td>
<td>10 eV</td>
</tr>
<tr>
<td>Efficiency ($f(E_\nu, T_0)$)</td>
<td>64.2%  23.6%</td>
</tr>
<tr>
<td>Detector cube size</td>
<td>28 mm  15.5 mm</td>
</tr>
<tr>
<td>Detector Mass</td>
<td>50 g  20 g</td>
</tr>
<tr>
<td>Number of Detectors</td>
<td>10,000</td>
</tr>
<tr>
<td>Total Mass</td>
<td>500 kg  200 kg</td>
</tr>
<tr>
<td>Yield at 10 cm ($\text{kg}^{-1}\text{day}^{-1}\text{MCi}^{-1}$)</td>
<td>15.28  19.0</td>
</tr>
<tr>
<td>Signal Rate at 10 cm</td>
<td>3.82 day$^{-1}$  1.90 day$^{-1}$</td>
</tr>
</tbody>
</table>
Backgrounds and Systematics

• Backgrounds stem from various sources:

  • Radiogenic impurities (U, Th, $^{60}$Co, and $^3$H). Most have signatures well above region of interest. Some, like $^3$H, have betas that have phase space in ROI.

  • Compton and photo-absorption.

  • Surface photons from atomic transitions.

  • Neutrons (< 0.1 eV/kg/yr in 10-100 keV, from CDMS measurements)

  • Neutrino-elastic scattering (not in energy range)

Estimates from CDMS place background at 40 events/kg/day/keV in the 1-10 keV region.

Leads to 1-2 events/kg/day in ROI
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<tr>
<td></td>
<td>Global</td>
</tr>
<tr>
<td>Source Strength</td>
<td>±1%</td>
</tr>
<tr>
<td>Cross-section</td>
<td>±1%</td>
</tr>
<tr>
<td>Detector Variation</td>
<td>±2%</td>
</tr>
<tr>
<td>Absolute Efficiency</td>
<td>±5%</td>
</tr>
<tr>
<td>Source-Induced Background</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Vertex Resolution</td>
<td>±2.8 cm</td>
</tr>
<tr>
<td>SourceExtent</td>
<td>±4 cm</td>
</tr>
<tr>
<td>Total Systematic</td>
<td>±5.5%</td>
</tr>
<tr>
<td>Statistical (Whole Array)</td>
<td></td>
</tr>
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</table>

Estimates from CDMS place background at 40 events/kg/day/keV in the 1-10 keV region.

Leads to 1-2 events/kg/day in ROI.
Wanted to determine what the potential sensitivity of such an experiment for a sterile neutrino at the 1 eV mass splitting scale.

• Array of 10,000 elements with Ar/Cr source just outside shield (10 cm closest distance).

• Measuring time of 300 days (for Ar, equivalent of 50 days signal, 250 days background).

• Background rate of 1 event/kg/day
Results

- Sensitivity study performed on 10,000 element array (500 kg Si, 200 kg Ge) (Ar or Cr source)

- Assumed 300 day measuring time with background rate of 1 event/kg/day.

- Analysis on shape + rate (bulk result from shape)

- Mock signal also tested.
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Alternate Measurements

coherent scattering measurement

\( \sin^2 \theta_W \) measurement

dark matter detection
A small scale demonstration (few kg) is beginning to be constructed.

Source acquisition may be difficult, would need to be warranted by the science.

Use of this technology appears promising, even at the ton scale.
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See Also...


Thank you for your attention
Backup Slides
He's a cop accused of murder.
And the only man who knows he's innocent
is the killer who framed him.

RICOCHET
This is one case that's going to be settled out of court.
New Hints

Mention et al. (hep-ex:1101.2755)
## Detector Properties

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{Si}$</td>
<td>43.2</td>
<td>pJ/K</td>
<td>Debye heat capacity</td>
</tr>
<tr>
<td>$C_{TES}$</td>
<td>39.8</td>
<td>pJ/K</td>
<td>TES electron heat capacity</td>
</tr>
<tr>
<td>$G_{ep}$</td>
<td>37.5</td>
<td>nW/K</td>
<td>TES-Si thermal conductance</td>
</tr>
<tr>
<td>$G_{pb}$</td>
<td>0.30</td>
<td>nW/K</td>
<td>Si-bath thermal conductance</td>
</tr>
<tr>
<td>$T_b$</td>
<td>7.5</td>
<td>mK</td>
<td>Cold bath temperature</td>
</tr>
<tr>
<td>$T_c$</td>
<td>15</td>
<td>mK</td>
<td>TES temperature</td>
</tr>
<tr>
<td>$R_o$</td>
<td>3</td>
<td>mΩ</td>
<td>Quiescent TES resistance</td>
</tr>
<tr>
<td>$I_o$</td>
<td>18.3</td>
<td>µA</td>
<td>Quiescent TES current</td>
</tr>
<tr>
<td>$P_o$</td>
<td>1.0</td>
<td>pW</td>
<td>Quiescent TES power</td>
</tr>
<tr>
<td>$\alpha = \frac{T_c}{R_o} \frac{dR}{dT}$</td>
<td>80</td>
<td>-</td>
<td>TES sensitivity</td>
</tr>
<tr>
<td>$\tau_o$</td>
<td>276.7</td>
<td>ms</td>
<td>Natural decay time $C_{tot}/G_{pb}$</td>
</tr>
<tr>
<td>$\tau_{eff}$</td>
<td>20.0</td>
<td>ms</td>
<td>Response time with TES speedup</td>
</tr>
<tr>
<td>$\tau_{decay}$</td>
<td>11.8</td>
<td>ms</td>
<td>Decay time with readout circuit</td>
</tr>
<tr>
<td>$L$</td>
<td>13</td>
<td>µH</td>
<td>Readout inductance</td>
</tr>
</tbody>
</table>
Detector Assumptions

- Each detector is a Si cube ranging in mass from 20–100 g. The heat capacity is determined from Debye theory.

- The conductance between the Si and the cold bath, $G_{pb}$, can be engineered to give a desired value. The value is chosen to give a thermal impulse response time of 20 ms as measured by the thermometer readout.

- The thermometer is a Mo/Au TES bilayer with a superconducting transition engineered to a specific temperature between 10–100 mK. Mo/Au TES X-ray detectors have achieved resolutions of $\Delta E_{\text{FWHM}} = 2$ eV [?].

- The TES heat capacity and electron-phonon coupling are taken from the literature and are a function of the chosen volume of the TES and the temperature.