Outline of the talk

- Why sterile neutrino? Experimental hints;
- How can we confirm or disproof the hints towards sterile nu?;
- SOX: Short Distance neutrino Oscillations with boreXino;
Sterile neutrino search: experimental hints

**ν_e, anti-ν_e DISAPPEARANCE**

**Reactor anomaly ~2.5σ**
Re-analysys of data on anti-neutrino flux from reactor short-baseline (L~10-100 m) shows a small deficit of R=0.943 ±0.023


**Gallex/SAGE anomaly ~3σ**
Deficit observed by Gallex in neutrinos coming from a \(^{51}\text{Cr}\) and \(^{37}\text{Ar}\) sources

\[ R = 0.76^{+0.09}_{-0.08} \]


**Accelerator anomaly ~3.8σ**

Confirmed by miniBooNE (which also sees appearance of ν_\(e\) in a ν_\(\mu\) beam) A.Aguilar et al. (MiniBooNE Collaboration) Phys.Rev.Lett. 110 161801 (2013)

Possible explanation: mixing of the active flavours with a sterile neutrino \(\Delta m^2 \sim 1\) eV^2

**ν_e, anti-ν_e APPEARANCE**

Some observations

- It is not possible to accommodate all the anomalies in a three flavour scenario: we need at least one sterile neutrino;
- (3+1), (3+2), (3+1+1) scenarios fit similarly well the data (but 3+1 maybe preferrable for cosmological reasons);
- However there is a tension between appearance and disappearance data (due to the fact that ν_\(\mu\) disappearance experiments give no hints for disappearance);
Sterile neutrino search: experimental hints

In the (3+1) scenario,

\[
\begin{bmatrix}
U_{e1} & U_{e2} & U_{e3} & U_{e4} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} \\
U_{s1} & U_{s2} & U_{s3} & U_{s4}
\end{bmatrix}
\]

\[\Delta m_{41}^2\]

\[\Delta m_{21}^2 << \Delta m_{31}^2 << \Delta m_{41}^2\]

\[|U_{e4}|^2, |U_{\mu 4}|^2, |U_{\tau 4}|^2 << 1\]

\[|U_{s4}|^2 \cong 1\]

**\(\nu_e\) disappearance**

(Gallex+Sage+reactors)

\[\sin^2 2\theta_{ee} = 4|U_{e4}|^2 (1-|U_{e4}|^2) = \sin^2 2\theta_{14}\]

**\(\nu_\mu\) disappearance**

(CDHS, miniBooNE+MINOS..)

\[\sin^2 2\theta_{\mu\mu} = 4|U_{\mu 4}|^2 (1-|U_{\mu 4}|^2)\]

**\(\nu_\mu \rightarrow \nu_e\) appearance**

(miniBooNE+LSND.)

\[\sin^2 2\theta_{\mu e} = 4|U_{e4}|^2 |U_{\mu 4}|^2\]

Global fit of all data isolates a very narrow region of the parameter space

\[ 0.82 < \Delta m_{14}^2 < 2.19 \text{ eV}^2 \]

Fit in the (3 + 1) scenario, including all data (appearance and disappearance) with the exception of the low energy excess by MiniBooNE; C. Giunti, M. Laveder, Y. F. Li, H. W. Long arXiv:1308.5288 v3 [hep-ph], Phys. Rev. D 88, 073008 (2013)
Sterile neutrino search using nuclear decays

These experimental anomalies deserve independent confirmation or disproval.

It is possible to investigate the relevant parameter space region by means of neutrinos (or anti-neutrinos) produced in nuclear decays;

In order to be sensitive to $\Delta m^2 \sim 1 \text{ eV}^2$

- Need a source with $E \sim 1-10 \text{ MeV}$
- Located at a distance $L \sim 1-10 \text{ m}$

1) Look for disappearance of $\nu_e$ emitted by the source;
2) Look for oscillation waves within the detector volume (oscillometry);
Sterile neutrino search using nuclear decays

Several advantages of using nuclear decays

- Intrinsically pure $\nu_e$ (or anti-$\nu_e$) beam;
- Neutrino spectrum known very precisely;
- Neutrino cross-sections in the $\sim$MeV region known more precisely than at $\sim$ GeV;
- Neutrino flux known with high precision ($\sim$1-5 % level);
## Possible sources

<table>
<thead>
<tr>
<th>ν type</th>
<th>Source type</th>
<th>Life ( τ )</th>
<th>Decay mode</th>
<th>Energy [MeV]</th>
<th>Production mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>( ν_e )</td>
<td>( ^{51}\text{Cr} )</td>
<td>40 d</td>
<td>EC</td>
<td>0.75 (90%) 0.43 (10%)</td>
<td>Neutron irradiation of (^{50}\text{Cr} ) in reactor ( \Phi_n \geq 5 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1} )</td>
</tr>
<tr>
<td>( ν_e )</td>
<td>( ^{37}\text{Ar} )</td>
<td>35 d</td>
<td>EC</td>
<td>0.811</td>
<td>Fast neutron irradiation of Ca oxide in reactor</td>
</tr>
<tr>
<td>( \bar{ν}_e )</td>
<td>( ^{144}\text{Ce}-^{144}\text{Pr} )</td>
<td>411 d</td>
<td>( β^- )</td>
<td>&lt;2.997</td>
<td>Chemical extraction from spent fuel</td>
</tr>
<tr>
<td>( \bar{ν}_e )</td>
<td>( ^{90}\text{Sr} )</td>
<td>40 y</td>
<td>( β^- )</td>
<td>&lt;2.27</td>
<td>RHS (RadioNuclide Heat Source)</td>
</tr>
<tr>
<td>( \bar{ν}_e )</td>
<td>( ^{8}\text{Li} )</td>
<td>868 ms</td>
<td>( β^- )</td>
<td>&lt;12.9</td>
<td>Beam of neutrons on a (^7\text{Li} ) target (ISODAR facility)</td>
</tr>
</tbody>
</table>

### Neutrino source
- detecting reaction \( ν + e \rightarrow ν + e \) radioactive background is a problem; not possible to put the source inside the detector;
- monocromatic; lower energy;

### Anti-neutrino source
- detecting reaction \( \bar{ν} + p \rightarrow n + e^+ \) very little background; may be feasible to put the source inside the detector;
- Continuum spectrum; higher energy;
Possible sources: $^{51}\text{Cr}$

Source characteristics: $\nu$ source, $E_\nu = 750 \text{ keV}$ $\tau = 40 \text{ days}$

ADVANTAGES
- $\gamma$ emitted by the source ($E=320 \text{ keV}$) not too difficult to handle;
- Cr used by Gallex still available (36 Kg enriched at 38.6% in $^{50}\text{Cr}$);

DISADVANTAGES
- detecting reaction is $\nu + e^- \rightarrow \nu + e^-$, radioactivity is a serious background (unless reaction with coincidence tag-like in LENS);

Production mode
- thermal neutrons impinging on $^{50}\text{Cr}$ (high neutron capture cross-section $\sim 17 \text{ barn}$);
- High neutron flux is needed ($>5 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$);
- Possibility at the OakRidge High Flux Isotope Reactor (HFIR);

Source activity $\sim 10 \text{ MCI} \sim 370 \text{ PBq} \ (3.7 \times 10^{17} \nu/\sec)$
Possible sources: $^{144}\text{Ce}-^{144}\text{Pr}$

Source characteristics: anti-$\nu$ source, $E_\nu < 2.99$ MeV, $\tau = 411$ d

Production mode:
- extracted from exhausted nuclear fuel;
- Possibility at the Mayak industrial complex (Russia)

ADVANTAGES
- detecting reaction is $\bar{\nu} + p \rightarrow n + e^+$ very little background;
- Long lifetime;

DISADVANTAGES
- high energy $\gamma_s$ ($E = 2.2$ MeV) emitted by the source are difficult to handle;

Source activity $\sim 100$ kCi $\sim 3.7$ PBq ($3.7 \times 10^{15} \nu$/sec)
Possible sources: $^8\text{Li}$

Source characteristics: anti-$\nu$ source, $E_\nu < 13$ MeV $\tau = 868$ ms

**ADVANTAGES**
- Long data taking time possible;
- High Energy;

**DISADVANTAGES**
- Anti-$\nu$ flux known only at ~5% level;
- Production point of $^8\text{Li}$ is not point-like (dominated by $z$ uncertainty (150 cm);
- $^8\text{Li}$ is produced

**Production mode**

**IsoDAR: Isotropic Decay At Rest**
- proton beam (60 MeV) impinging on a $^9\text{Be}$ tgt to produce neutrons;
- neutrons moderated and multiplied by a $\text{D}_2\text{O}$ shield 5 cm thick;
- the Be tgt is surrounded by a sleeve of $^7\text{Li}$ (d=200cm, h=150cm)

Source activity $\sim 8.2 \times 10^{14} \nu/$sec

Still in the R&D phase:
- Need to produce compact cyclotron with x6 intensity with respect to medical isotope industry;
- Prototype by ~2016
Candidate detectors

Requirements

- Underground location;
- Large mass, ultra-pure detectors;
- Capability to measure E and L (oscillometry);

Existing large liquid scintillator experiments (Borexino, KamLAND, Daya-Bay)

Future large liquid scintillator experiments (SNO+, LENS, JUNO)

Future experiments based on other techniques (RICOCHET, BEST)
## Several papers and ideas

<table>
<thead>
<tr>
<th>Technique</th>
<th>Detector</th>
<th>Sources</th>
<th>Reaction</th>
<th>Activity</th>
<th>Reference</th>
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<td><strong>Large Liquid scintillator detectors</strong></td>
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<tr>
<td>SOX (Borexino)</td>
<td></td>
<td>$^{51}$Cr,</td>
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<td>KamLAND</td>
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<td>$^{8}$Li (ISODAR)</td>
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<td>Daya-Bay</td>
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<td>$^{144}$Ce-$^{144}$Pr</td>
<td>$\bar{\nu} + p \rightarrow e^++n$</td>
<td>500k Ci</td>
<td>[arXiv:1109.6036]</td>
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<tr>
<td>LENS</td>
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<td>$^{51}$Cr</td>
<td>$\nu + ^{115}$In $\rightarrow ^{115}$Sn*+e</td>
<td>10M Ci</td>
<td>[Phys.Rev.D75 093006(2007)]</td>
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<tr>
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<td>BEST</td>
<td>$^{51}$Cr</td>
<td>$\nu + ^{70}$Ga $\rightarrow ^{71}$Ge+e</td>
<td>3M Ci</td>
<td>[arXiv:1204.5379]</td>
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<td>Bolometers</td>
<td>Richochet</td>
<td>$^{37}$Ar</td>
<td>$\nu + N \rightarrow \nu + N$</td>
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<td>[Phys. Rev. D85, 013009, (2012)]</td>
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Several papers and ideas

BEST (Baksan experiment on Sterile Transition)
- 50 tons of liquid Gallium divided into two separate concentrical regions;
- $^{51}$Cr source in the center (3 MCi);
- Radiochemical reaction $\nu_e + ^{71}$Ga $\rightarrow ^{71}$Ge + e$^-$;
- After exposure of few days, transfer the liquid and count Ge produced (same as SAGE technique);
- If no oscillation: ~65 atoms/day of Ge in each region should be produced;

RICOCHET
- 10,000 Si bolometers (total mass 500 Kg) arranged in a column of 0.42m x 2 m;
- $^{37}$Ar source (~5 MCi);
- Coherent scattering of neutrinos on Ar nuclei;

POSTER: “Status of the BEST *project (Baksan Experiment on Sterile Transitions)” Dr. Ibragimova Tattiana
Several papers and ideas

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The onion-like structure of Borexino

Core of the detector:
300 tons of scintillator (pseudocumene+PPO)

2214 photomultiplier tubes pointing towards the center to view the light emitted by the scintillator;

PIT under the detector where the source can be located.

SOX: Short distance $\nu_e$ Oscillations with boreXino

Water tank
R=9m h=16.5m

Stainless Steel Sphere
R~ 7 m

Inner Vessel
R=4.25m

Each layer of increasingly pure material protects the core from external radioactivity.
SOX: the tunnel under the detector

Steel Floor of the Water Tank

100 cm
SOX: Short distance $\nu_e$ Oscillations with boreXino

The SOX project
- Source in position A: plan to use both $^{51}$Cr neutrino and $^{144}$Ce-$^{144}$Pr anti-neutrino sources;
- Future possibility: put the $^{44}$Ce-$^{144}$Pr in the center; more invasive $\rightarrow$ needs significant refurbishment of the apparatus;

Borexino in a nut-shell
- Borexino is taking data since 2007 in the Gran Sasso Laboratory;
- Capability to detect neutrinos has been demonstrated by results on solar neutrinos (see dedicated talk by G.Ranucci);
- Capability to detect anti-neutrinos has been demonstrated by results on geo-neutrinos (see poster n. 12 (board 58) by L.Miramonti);

Detection of $\sim$ 500 pe/MeV
Energy resolution $\sigma_E/E \sim$5% (@1MeV)
Position resolution $\sigma_x \sim$ 10 cm (@1MeV)
SOX: Short distance $\nu_e$ Oscillations with boreXino

It is both a technical and a burocratical challenge

- High activity requires appropriate shielding and suitable transportation containers;
- Many authorizations (transportation, handling, storage) are required;

Source design is driven by

- Production process technique;
- Biological shielding requirements (tungsten alloy shielding);
- Thermal constraints;
- Mechanical constraints (tunnel dimensions, total weight);
- Transportation requirement and containers design and production;
- Hot cell manipulation;
- Handling in the experimental Hall;
- Calorimeter integration (to measure precisely the activity of the source);
SOX-Cr: production of the $^{51}$Cr source

Source characteristics: $E_\nu = 750$ keV  \( \tau = 40 \) days

- 36 Kg of Cr (enriched in 50Cr (38.6%) used for Gallex calibration is still available;
- Needs to be activated with neutron irradiation;
- OakRidge National Laboratory is the best choice;
- Easiest solution: cast the Cr chips in cylindrical rods;
- Probably need two cycles of the reactor;
- Needs a 10 MCi source (or two 5 MCi sources);

Short data taking period: ~ 2-3 months
SOX-Cr: sensitivity to sterile neutrino of the $^{51}\text{Cr}$ source

- $\nu_e + e^- \rightarrow \nu_e + e^-$: the signal (electron recoil) is relatively featurless;
- To distinguish signal from radioactive background
  1. use the fact that the source decays while background remains constant;
  2. Also use the position distribution of events;
- Since the source is external the distribution of expected neutrino interaction is not uniform in the volume;
- For some values of the oscillation parameters, waves will be observed;

$$\sin^2 2\theta_{14} = 0.3 \quad \Delta m^2_{41} = 2 \text{ eV}^2$$
SOX-Cr: sensitivity to sterile neutrino of the $^{51}$Cr source

**Source characteristics:** $E_\nu = 750$ keV  $\tau = 40$ days

- $\nu_e + e^- \rightarrow \nu_e + e^-$
- Data taking time: 100 days; accumulated neutrino events $\sim 14000$
- Activity of the source must be known at 1-2%

$$L_{osc} (m) = \frac{E(\text{MeV})}{1.27 \Delta m^2 (\text{eV}^2)}$$

- $\Delta m^2 > 10 \text{ eV}^2 \; L_{osc} \ll \sigma_x$
  $P \sim 1/2 \sin^2 2\theta$
- $\Delta m^2 < 0.05 \text{ eV}^2 \; L_{osc} \gg$
  detector dimensions
  $P \sim \Delta m^2 \sin^2 2\theta$
- $0.05 < \Delta m^2 < 5 \text{ eV}^2$ best sensitivity window;

SOX-Ce: production of the $^{144}$Ce- $^{144}$Pr source

Source characteristics: $E_\nu < 2.99$ MeV $\tau = 411$ days

- Spent nuclear fuel (Kola Nuclear Power Plant (Murmansk, Russia));
- Processing of the spent fuel in Mayak complex.
- Possibility to obtain $^{144}$Ce-$^{144}$Pr source with activity $\sim 100$ kCi;

Kola Nuclear Power Plant

POSTER ‘Search for a 4th light nu state with a 5 PBq 144Ce-144Pr electron antineutrino generator next to a large liquid scintillator detector’”
Dr.LASSERRE, Thierry
SOX-Ce: production of the $^{144}$Ce- $^{144}$Pr source

Complicated transportation logistic in order to comply with safety regulations for transport of radioactive material:

- Spent nuclear fuel will be shipped from Kola reactor to Mayak ~ end of 2014;
- $^{144}$Ce source ready for shipment to Gran Sasso by Fall 2015;
- Transportation to Gran Sasso in November 2015;

DIFFICULT from Mayak to Gran Sasso; IMPOSSIBLE from Mayak to Japan
SOX-Ce: sensitivity with the $^{144}$Ce- $^{144}$Pr source

Source characteristics: $E_\nu < 2.99$ MeV  $\tau = 411$ days

- $\nu_e + p \rightarrow n + e^+$
- Data taking time: 1.5 years; events accumulated ~10000
- Energy resolution more important than position resolution;
- Activity of the source must be known at 1-2 %

$^{144}$Ce; Time~1.5 years, activity=100 kCi; R<4.25m

$\Delta m^2 > 5 \text{ eV}^2$ $L_{osc} << \sigma_x$  $P \sim 1/2 \sin^2 2\theta$;
$\Delta m^2 < 0.1 \text{ eV}^2$ $L_{osc} >>$ detector dimensions  $P \sim \Delta m^2 \sin^2 2\theta$;
$0.1 < \Delta m^2 < 5 \text{ eV}^2$ best sensitivity window;

$L_{osc} (m) = \frac{E(\text{MeV})}{1.27 \Delta m^2 (\text{eV}^2)}$

SOX: sensitivity to sterile neutrino

\[ \Delta m^2_{41} \]

\[ \sin^2 2\theta_{14} \]
SOX: sensitivity to sterile neutrino

Global fit. Giunti et al.  
Conclusions and perspectives

• Searching for sterile neutrino is a challenging enterprise (high risk/ high gain);

• SBL disappearance experiments with sources have some advantages over SBL reactor/accelerator experiments (better control of neutrino spectra, flux and purity; possibility to do oscillometry);

• Several proposals/ideas of experiments which should address this issue;

• MOST IMPORTANTLY: first data available with SOX-Ce by the end of 2015 / beginning 2016;