Reactor anomaly and searches of sterile neutrinos in experiments at very short baseline

G. MENTION

CEA Saclay
Irfu / SPP

July 17th, 2013

Workshop Invisibles 13
Is the standard 3 neutrino mixing picture correct?

- The peaceful realm of the 3 active $\nu$
- The disturbing anomalies
- Outlooks and prospects
- White paper and foreseen experiments to tackle these anomalies
- Conclusion
Large Electron-Positron collider data: exactly 3 active, light $\nu$ flavors

We also know of 3 $\nu$'s: $\nu_e$, $\nu_\mu$, $\nu_\tau$

3 $\nu$’s require two independent sets of $\Delta m^2$ mixing
Neutrino oscillations

This is observed and confirmed!

Confirmation with Super-K, K2K and MINOS data

Confirmation with SNO, Kamland data
Neutrino oscillations

However...

Evidence for high $\Delta m^2$ mixing from LSND experiment
some hints from cosmology and reactor data as well

Confirmation with Super-K, K2K and MINOS data

Confirmation with SNO, Kamland data
LSND

Channel: anti-$\nu_\mu \rightarrow$ anti-$\nu_e$
Baseline: $L \sim 30$ m
Energy range: $20$ MeV $<$ $E$ $<$ $200$ MEV

Highly controversial!

$\Delta m^2_{\text{LSND}} \gtrsim 0.2$ eV$^2$ \quad ($\gg \Delta m^2_{\text{ATM}} \gg \Delta m^2_{\text{SOL}}$)
MiniBooNE $\nu$

Channel: $\nu_\mu \rightarrow \nu_e$
Baseline: $L \sim 541$ m
Energy range: $475$ MeV $< E < 3$ GeV

But $\Rightarrow$ Low-Energy Anomaly!
MiniBooNE anti-$\nu$

Channel: anti-$\nu_{\mu} \rightarrow$ anti-$\nu_e$  [arXiv,hep-ex:1303.2588]
Baseline: $L \sim 541$ m
Energy range: $475 \text{ MeV} < E < 3 \text{ GeV}$

Agreement with LSND anti-$\nu_{\mu} \rightarrow$ anti-$\nu_e$ signal! ... ? ... 
Similar L/E but different L and E, different backgrounds, beam,...
The Gallium anomaly

Radiochemical experiments Gallex (left) & Sage (right)

GALLEX (GaCl$_3$) and SAGE (liquid Ga) were radiochemical experiments, counting the conversion rate of $^{71}\text{Ga}$ to $^{71}\text{Ge}$ by (solar) neutrino capture [cannot detect anti-$\nu_e$]

GALLEX

30.3 tons of Gallium in an aqueous solution: GaCl$_3$ + HCl

SAGE

30 to 57 tons of Gallium (metal) In 10 tanks

Calibration Data

2 runs at GALLEX with a $^{51}\text{Cr}$ source (720 keV $\nu_e$ emitter)
1 run at SAGE with a $^{51}\text{Cr}$ source
1 run at SAGE with a $^{37}\text{Ar}$ source (810 keV $\nu_e$ emitter)

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

All observed a deficit of neutrino interactions compared to the expected activity:

$R = \text{meas./pred. rates} = 0.86 \pm 0.06$ (1$\sigma$)
The Gallium anomaly

Effect reported in C. Giunti & M. Laveder in PRD82 053005 (2010)
Significance reduced by additional correlations in our analysis
No-oscillation hypothesis disfavored at 97.7% C.L.
Revised reactor neutrino spectra & VSBL reactor ν anomaly

- Triggered by evaluation for single Double Chooz far detector phase.
- Improved conversion from β to ν spectra
  - Anchored to experimental ILL BILL-spectra of fission products
  - Conversion of individual β branch level; residuals fitted as in original ILL conversion
  - Off-equilibrium effects included
- Improved (& increased) neutron life time measurement; also improved weak magnetism and radiative corrections inclusion

\[
\sum_{A,Z} \{ \frac{AX}{Z+1}Y \rightarrow e^- + \bar{\nu}_e \}
\]

Implications for SBL reactor experiments: the reactor antineutrino anomaly

\[ \chi^2 = \left( r - \bar{R} \right)^T W^{-1} \left( r - \bar{R} \right) \]

Weights: \[ W = \Sigma_{unc.}^2 + \Sigma_{cor.}^2 \Sigma_{cor.}^2 \]

with \[ \Sigma_{unc.}^2 = \Sigma_{tot.}^2 - \Sigma_{cor.}^2 \]

The synthesis of published experiments at reactor-detector distances \( \leq 100 \) m leads to a ratio \( R \) of observed event rate to predicted rate of

\[ \mu = 0.976 \pm 0.024 \text{ (OLD flux)} \]

With **NEW flux** evaluation, this ratio shifts to

\[ \mu = 0.943 \pm 0.023, \text{ [2011 result]} \]

leading to a deviation from unity at 98.6% C.L.

\[ \chi^2_{min} = 19.6/18 \]

Update in White Paper on sterile neutrinos:

[hep-ph:1204.5379]

\[ \mu = 0.927 \pm 0.023, \text{ [2012 result]} \]
Update with km scale experiments

Update of 2011 reactor anomaly publication [PRD83, 073006] ongoing, to be submitted soon

- Includes a refined and detailed treatment of correlations between the different measurements and predictions
- Includes all known nuclear corrections to $\beta$-$\nu$ spectra. [combining: T. Mueller et al., PRC83, 054615 & P. Huber, PRC 84, 024617]
- Corrected for a statistical bias in the previous method
- Includes the latest updated neutron lifetime ($\tau_n = 881.5$ s).
- Includes km-scale baselines through correcting for $\theta_{13}$ deficit from Daya Bay’s measured value.

[2013 result to be submitted soon]

Preliminary updated result

$\mu = 0.936 \pm 0.024$

$\chi^2_{\text{min}} / \text{dof} = 29.7 / 22$

p-value = 13 %
Energy spectrum shape information

\[ \text{Distance (m)} / \langle E_{\nu} \rangle \text{ (MeV)} \]

\[ \text{Ratio} = \frac{N_{\text{obs}}}{N_{\text{pred}}} \]

\[ \begin{array}{cccccccc}
2 & 3 & 4 & 5 & 6 & 7 & 8 & 10 \\
0.6 & 0.7 & 0.8 & 0.9 & 1 & 1.1 \\
\end{array} \]

\[ \begin{array}{cccc}
\text{BR} & \text{B3} & \text{GI} & \text{K} \\
\text{S} & \text{RI} & \text{RS} & \text{KM} \\
\end{array} \]

Energy spectrum shape information for Bugey-3 and ILL.
Combining all indications and exclusions
The global picture

The measured anomalies could curiously be explained by a 4th (& 5th?) sterile neutrino with $\Delta m^2$ around the eV$^2$.

The picture in $\nu_e$ to $\nu_e$ sector is globally coherent

Some severe tension in $\mu$ to $e$ appearance with respect to $\mu$ disappearance experiments
Another global picture

Reactor experiments from 30 feet to 110 miles

- Reactor Antineutrino Anomaly (2011-)
- Solar Neutrino Anomaly (1968-2001)
- No oscillation line

Terra Incognita to be explored > 15 projects...
Anomalies overview

- Agreement between anomalies:
  - LSND and MiniBooNE anti-$\nu_\mu \rightarrow$ anti-$\nu_e$
  - Gallium anomaly and Reactor antineutrino anomaly

- Two experimental tensions among the anomalies:
  - [LSND & MiniBooNE anti-$\nu_\mu \rightarrow$ anti-$\nu_e$] vs. MiniBooNE $\nu_\mu \rightarrow \nu_e$
  - [LSND & MiniBooNE anti-$\nu_\mu \rightarrow$ anti-$\nu_e$] vs. anti-$\nu_e$ & anti-$\nu_\mu$ disappearance limits

- [+ Further info from Cosmology pointing toward sterile neutrino, not addressed here.]

- A white paper on this topic reviewing the current status about sterile neutrino oscillations:

- Despite tensions, there are a number of results and hints that suggest that there may be oscillations to sterile neutrinos with $\Delta m^2 \sim 1 \text{ eV}^2$

- Further running and new experiments are being planned to address this possibility
  - Establishing the existence of sterile neutrinos would be a major result!
  - These are certainly exciting times for neutrino physics!
Near future

- Already scheduled experiments to work on non-proliferation
- They add up to their potentials the study of sterile neutrino at short baselines (high $\Delta m^2$): Nucifer, SCRAAM, DANSS, MARS=>Solid...
- New dedicated efforts specific for sterile neutrino searches: Stereo, CeLAND, SOX, ICARUS-NESSiE,...
# Experimental projects

## White paper on sterile neutrinos  [hep-ph:1204.5379](#)

<table>
<thead>
<tr>
<th>Experiment type</th>
<th>Appearance / Disappearance</th>
<th>Oscillation channel</th>
<th>Projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor</td>
<td>Disappearance</td>
<td>$\nu_e$ bar to $\nu_e$ bar</td>
<td><strong>Nucifer, Stereo, Scraam, Neutrino-4, DANSS, Poseidon, Solid, CARR...</strong></td>
</tr>
<tr>
<td>Radioactive source</td>
<td>Disappearance</td>
<td>$\nu_e$ bar to $\nu_e$ bar $\nu_e$ to $\nu_e$</td>
<td><strong>CeLAND, SoX, Sage2, SNO+, LENS-S,...</strong></td>
</tr>
<tr>
<td>Cyclotron</td>
<td>Disappearance</td>
<td>$\nu_e$ bar to $\nu_e$ bar</td>
<td>IsoDAR</td>
</tr>
<tr>
<td>Pion/Kaon decay-at-rest</td>
<td>Appearance &amp; Disappearance</td>
<td>$\nu_\mu$ bar to $\nu_e$ bar $\nu_e$ to $\nu_\mu$</td>
<td>OscSNS, CLEAR, DAEδALUS, KDAR</td>
</tr>
<tr>
<td>Pion decay in flight</td>
<td>Appearance &amp; Disappearance</td>
<td>$\nu_\mu$ to $\nu_e$ $\nu_\mu$ bar to $\nu_e$ bar $\nu_e$ to $\nu_\mu$ $\nu_\mu$ to $\nu_\mu$</td>
<td><strong>MINOS+, MicroBooNE, Lar Iktont  +MicroBooNe, Icarus/Nessie @ CERN</strong></td>
</tr>
<tr>
<td>Low-E neutrino factory</td>
<td>Appearance &amp; Disappearance</td>
<td>$\nu_e$ to $\nu_\mu$ $\nu_e$ bar to $\nu_\mu$ bar $\nu_\mu$ to $\nu_\mu$ $\nu_e$ bar to $\nu_e$ bar</td>
<td>$\nu$STORM @ Fermilab</td>
</tr>
</tbody>
</table>

Next slides are just a few of them: projects in bold = in Europe.
Nucifer

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]
\[ n + \text{Gd} \rightarrow 3\gamma \text{ (8MeV)} \]

Initial goal: non-proliferation prototype detector.

Reactor core size: \( \sim (60 \text{ cm})^3 \)
Detector size: 1.2x0.7m (850 L)
baseline \( \langle L \rangle = 7.0 \text{ m} \)
\( \delta L = 0.3 \text{ m} \)
\( \Rightarrow \Delta m^2 \sim \text{eV}^2 \) oscillations are not washed out!

Detector ready and operational.

Currently: two reactor cycles of data (2x 20 days). Large \( \gamma \) bkg from reactor yet. Will improve shielding again. Reactor is off for maintenance and will start again before end of year.

Nucifer is not an optimized detector for such a measurement BUT can be the first at this so short baseline to bring information on this anomaly after ILL exp. in 1981.

Stay tuned!!!
Stereo

- Detect antineutrino via well known inverse beta decay reaction
- Detect neutron via Gadolinium capture ($<3\gamma$, $E \sim 8 \text{ MeV}$)
- Short time coincidence (15 $\mu s$, 0.2% Gd), localization of interaction in cells
- Good energy resolution (5%@1MeV)
- 480 $\nu$/day; challenge S/B $\sim 1.5$ [ILL exp. (1981) $\sim 1$]
- Short baseline $\sim 10 \text{ m}$ to probe $\Delta m^2 \sim 1 \text{ eV}^2$
- Compact reactors: ILL (France) [core size $< 40 \text{ cm}$]
- Shape only oscillation search, and rate+shape analysis
- Start data taking in 2015.
SoLi\(\text{d}\)

- Detect antineutrino via well known inverse beta decay reaction
- Detect neutron via reaction on Lithium-6 capture
- Time coincidence and 3D localisation of interaction
- short baseline < 10 m to probe \(\Delta m^2 \sim 1 \text{ eV}^2\)
- compact reactors: ILL (France), BR2 (Belgium) [small cores < 50 cm]
- use ratio of spectra at two distances from the reactor
- Start data taking in 2015.
A strong 75 kCi $^{144}\text{Ce}$ anti-$\nu_e$ source @ KamLAND
- Anti-$\nu_e$ detection (20 to 40 kevts/yr)
- A good resolution in position (15 cm)
- Background free thanks to anti-$\nu_e$ coincidences
- Lifetime ~ 1 yr (285 d)
- Compactness of the source (~ 5 cm)
- W and Cu shield

Real oscillation pattern vs. both radius & energy

Phase I: 2015
- 75 kCi

Phase II: 2016-2017 if feasible
- 50 kCi

[ M. Cribier et al., PRL 107 (2011) 201801 ]
**SOX**

Detector: **KamLAND** (Borexino?)

**CL-A (2015)**
75 kCi $^{144}$Ce in the WT
6 months of data taking

**CL-B (2016/2017)**
50 kCi $^{144}$Ce source in the center
1.5 y of data taking

Detector: **Borexino**

**SOX-A (2015)**
10MCi $^{51}$Cr in Icarus pit
8.25 m from the center
3 months of data taking

**SOX-B (end 2015)**
75 kCi $^{144}$Ce source in W.T.: PPO everywhere to enhance sensitivity

**SOX-C (2016/2017)**
50 kCi $^{144}$Ce source in the center. Only after the end of solar program
ICARUS-NESSiE

- Using CERN-SPS new $\nu_\mu$ beam ($E_\nu \sim 2$ GeV)
- 2 LAr-TPC (from ICARUS): near: 150 t, far: 600 t
- +magnetic spectrometers for charge determination
- Should start (both beam and detector data taking by end of 2015).

$\nu_\mu$ to $\nu_e$  
$\bar{\nu}_\mu$ to $\bar{\nu}_e$  
$\nu_e$ to $\nu_e$
Foreseen sensitivities to the Reactor anomaly

Contours comparison (95 % CL, 2 dof)
• These anomalies provide an exciting topic from the experimental and theoretical point of view.

• Not all the anomalies are consistent with each other. Ambiguous situation!

• These anomalies can be tested and either confirmed or refuted within near future (5-6 years time scale)

• A lot of experimental projects are foreseen to tackle this point.

• Most of the experiments focus on both L (baseline) and E (energy) information to provide a clear L/E unambiguous oscillation pattern if any.

• Establishing the existence of sterile neutrinos would be a major result!

• These are certainly exciting times for neutrino physics!