Very short distance neutrino oscillations

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Recent anomalous results

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

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- re-analysis of calibration source data
  - (L/E ~1m/0.1MeV)

- rate deficit of 14 ± 6 %

  - Gallium anomaly

- 2011 re-evaluation of reactor antineutrino flux and update on cross-section parameters
  - 3.5% new conversion of ILL beta spectra
  - 1.5% off-equilibrium
  - 1.5% neutron lifetime $\tau_n$

- rate deficit 6.5 %
  - Reactor anomaly
Recent anomalous results

Giunti Laveder 1006.3244
J. Kopp et al., hep/ph:1303.3011

- re-analysis of calibration source data
  - (L/E ~1m/0.1MeV)

- rate deficit of 14 ± 6 %

- Gallium anomaly

Sterile neutrino hypothesis

• current rate anomalies due to unknown effect or to new physics?
• additional(s) light fermion mixing with active neutrinos could be one explanation
  • a generic extension of SM
  • help with phenomenology (connection to DM is possible)
• tension exists between oscillation data sets
• in modest tension with PLANCK data

$\Delta m^2 \sim 1 \text{ eV}^2$

$\bar{\nu}_e \rightarrow \nu_s$

$$P_{ee} = 1 - 2|U_{e4}|^2(1 - |U_{e4}|^2)$$

Effect as a function of distance

Effect as a function of energy

J. Kopp et al., hep/ph:1303.3011

$\Delta m^2 = 2.35 \text{ eV}^2$

$\sin^2 2\theta_{ee} = 0.165$
• Combined no oscillation disfavored at more than 99.9% C.L. (3.3$\sigma$)
• Two techniques in $\nu_e$ disappearance to address this on a short timescale:
  • Large source, large detector experiments
  • very short baseline [5-20] m reactor experiments

Sterile neutrino white paper arXiv:1204.5379

J. Kopp et al., hep/ph:1303.3011

Thursday, 31 July 14
Recent reactor data

- Total rate measurements compatible with other experiments
  - 2.4\(\sigma\) sigma deficit including Daya Bay nu2014 result

- Deviation in e+ spectrum observed at all three experiments (D-CHOOZ, RENO, Daya Bay)
  - 4\(\sigma\) excess in [4,6] MeV window in Daya Bay data
  - no effect on \(\theta_{13}\) measurement

\[ E_V \approx E_{e^+} + m_n - m_p \]
New experiment at short distance

- $\Delta m^2 \sim 1 \text{ eV}^2 \sim 1-3 \text{ m oscillation length}$
  - require compact reactor core
- remeasure at very short distance using two distance measurement ratio
- no assumption on shape of spectrum
- similar precision to $\theta_{13}$ search needed
- challenging above ground / near reactor measurement
- large gamma-ray and neutron backgrounds expected

J. Kopp et al., hep/0803.3011

$\Delta m^2 = 2.35 \text{ eV}^2, \sin^2 2\theta_{ee} = 0.165$
New reactor experiments
<table>
<thead>
<tr>
<th>Tech</th>
<th>Reactor</th>
<th>P [MW]</th>
<th>L (m)</th>
<th>M (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nucifer (Fr)</td>
<td>LS+Gd</td>
<td>OSIRIS</td>
<td>70</td>
<td>0.8</td>
</tr>
<tr>
<td>POSEIDON</td>
<td>LS+Gd</td>
<td>PIK</td>
<td>100</td>
<td>~3</td>
</tr>
<tr>
<td>STEREO (Fr)</td>
<td>LS+Gd</td>
<td>ILL</td>
<td>57</td>
<td>1.75</td>
</tr>
<tr>
<td>Neutrino-4 (Ru)</td>
<td>LS+Gd</td>
<td>SM3</td>
<td>100</td>
<td>1.5</td>
</tr>
<tr>
<td>PROSPECT (US)</td>
<td>LS + Gd/\textsuperscript{6}Li</td>
<td>ORNL HFIR</td>
<td>85</td>
<td>1 &amp; 10</td>
</tr>
<tr>
<td>SoLid (UK/B/Fr)</td>
<td>PVT + \textsuperscript{6}LiF:ZnS</td>
<td>SCK•CEN BR2</td>
<td>45-80</td>
<td>1.44/2.88</td>
</tr>
<tr>
<td>DANSS (Ru)</td>
<td>PS + Gd</td>
<td>KNPP</td>
<td>3000</td>
<td>0.9</td>
</tr>
<tr>
<td>Hanaro (KO)</td>
<td>PS + Gd/\textsuperscript{6}Li</td>
<td>Hanaro/Younggwang</td>
<td>30-2800</td>
<td>~1</td>
</tr>
</tbody>
</table>
SoLid experiment overview

- Source: SCK-CEN BR2 MTR reactor
  - 45-70 MWth power, 150 days/year
  - Relatively low level of reactor background
- Baseline $L = 5.5 - 11$ m
- 2.88 tonnes fiducial mass
- Modest passive shielding
- Data taking in early 2016

- IBD efficiency 41% (416ν/day/tonne)
- 300 days running at 6.8m baseline
- flux normalisation (4.1%), detector efficiency (2%) systematics and backgrounds ($S:B \sim 5-6$)
- large bins to account for energy smearing effects
- Tank in Pool MTR research reactor
- Licensed to run at power up to 100 MW
  - variable operating power
  - 5/6 cycles per year
  - low reactor backgrounds
Detector principle

\[ \bar{\nu}_e + p \rightarrow e^+ + n \]

- Neutron / gamma-ray discrimination from pulse
- distinctive response for prompt and delayed signal
- neutron used to trigger event read out
- Voxelisation of target volume
- neutron captured in neighboring cube increasing localisation of IBD event

\[ \frac{\alpha}{3} Li + n \rightarrow \frac{\alpha}{4} He \ (2.05 \text{ MeV}) + \frac{1}{3} T \ (2.75 \text{ MeV}) \]

\[ \Delta t \sim 1-200 \text{ us} \]
Advantages

- Use of topology to discriminate between antineutrino events and others
- Flexibility to choose size of target volume selection
- Handle external backgrounds
- Monitor background
- Effective Compton scattering cuts possible
- Further reduction of accidentals
Status of technology

- NEMENIX (8 kg, 64x cubes) prototype upgrade
  new DAQ + muon veto
  demonstrate expected response
  study background rate and IBD analysis
- Mars-May 2014 cycles analysis in progress

- 288 kg module (2304 cubes) construction started
  (1.2 m H x 1.0 m W x 0.4 m D)
- Deployment planned before end of year 2014 at BR2

Raw data
reactor ON
reactor OFF
NEMENIX Construction
Detector response

- Peak amplitude [PE] range: 0 to 800
- Integrated charge range: 0 to 60 × 10^3

Labels:
- EM signal: γ, e±
- Cosmic muons
- Neutrons

Legend:
- Color scale: 10^5 to 1

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Monitoring reactor ramp up

Reactor turn on

- reactor power
- $10^4 \times$ neutrons
- $e^+ / \gamma$

Rate [Hz]

Reactor relative power [%]

Time [hr]
Summary

- Recent anomalies in neutrino sector need to be addressed
  - more precise data at very short distance
  - Results from high precision reactor data show interesting features but no obvious hint for explanation yet
- Percent level measurement at \(~10\) m baseline would severely constrain sterile neutrino hypothesis
  - but challenging environment at reactor and above ground
- The SoLid experiment proposes to do a precise measurement using a novel technique and low background site
  - BR2 MTR reactor in Mol, Belgium
  - Voxelisation of target volume with specific signature for neutron
  - use of topology to handle backgrounds
- One of several proposals with planned results as early as 2016!
Thank you
Back up
New flux conversion

\[
\sigma_{V-A}(E_\nu) \propto \frac{1}{\tau_n}
\]
SoLid detectors

- Based on MARS detector technology (patent)
  - Segmented detector (2.88 t) divided in 10 sub-modules (1.2x1.2x0.2 m³)
  - Robust to background, mitigate better background than passive shielding

- Detector element:
  - EJ-200 PVT cubes 5 cm x 5 cm x 5 cm
  - 6LiF:ZnS(Ag) screens 5 cm x 5cm x 250um
  - Covered with Tyvec sheets
  - Carbon fibre tray to hold cubes in layer
  - Scintillator light collected by fibre
  - MPPC read out at one end of fibre
  - Detector read on X et Y (10 sub-modules = 23040 cubes, 1920 read out channels)
  - Electronics developed by Oxford / Bristol / Antwerp
Energy response

- Tested light yield for 5cm cube with 3mm² MPPC read out using cosmics setup
- Large light yield based on real dimension PVT cubes with BCF-91A fibre and MPPC read out
  - 40-50PE @ 1 MeV (2 MPPC)
  - dE/E ~ 17%
- Optical model tuned on data
- High IBD reconstruction efficiency
- Flat in energy both for e⁺ and neutron

Correction of MPPC linearity response not included
Backgrounds at BR2

Background rates

- Neutrons
  - Large system to measure atm neutrons
  - Reactor ON: small neutron counter: $R_n < 10^{-5}$ Hz
- Reactor ON gamma-rays
  - HPGe detector w and w/o shielding
  - $R_{gam} \sim 41$ Hz/cm$^2$ (> 500 KeV) Pb 5cm

BR2 HPGe detector
BR2 portable neutron detector
Oxford Large neutron detector

No shielding
Pb shield 5 cm

<table>
<thead>
<tr>
<th>Entry</th>
<th>Mean</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>12291</td>
<td>773.1</td>
<td>776.7</td>
</tr>
</tbody>
</table>
IBD efficiency

• Simple IBD selection
• Look for a neutron trigger
• apply time cut  300 ns < Δt < 100,000 ns
• Select MPPC pair E > ~600 keV around trigger
• apply position cut (2 cubes max around trigger)

<table>
<thead>
<tr>
<th>cut</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>n trigger</td>
<td>0.71</td>
</tr>
<tr>
<td>coincidence</td>
<td>0.58</td>
</tr>
<tr>
<td>Energy cut (20PE/600keV)</td>
<td>0.48</td>
</tr>
<tr>
<td>spatial cut</td>
<td>0.47</td>
</tr>
<tr>
<td>multiplicity cut</td>
<td>0.45</td>
</tr>
</tbody>
</table>
Experimental parameters and
SoLid electronics

- Developed in Oxford / Bristol
- Front-end cards: **DEIMOS 32chan amplifier card**
  - first board produced and under tests
- Back-end card: **DPC 32chan Digital Processing card**
  - fast digitisation: 80MS/s 12bit cADC
    - 200-400 us memory buffer
  - dead-timeless
  - on board digital processing: pedestal suppression, readout threshold, PSD etc..
  - use neutron signal features to trigger on IBD event
- version 0 of card used to develop basic functionalities

First version of Digitiser Board: DPC

~15 μs

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