Sterile Neutrino Search at Reactors

Antonin Vacheret
Neutrino Telescope 2017
17th March 2017, Venice, Italy
Outline

• Sterile neutrino oscillation

• Antineutrino spectrum measurements and recent limits

• Very short baseline experiments
The sterile neutrino hypothesis

- Additionnal mass state participating to mixing give simple explanation of reactor antineutrino and Gallium anomalies
- not detectable through weak interaction, only indirect measurement possible via oscillation
- small correction from 3 x 3 neutrino mixing to explain active neutrino oscillation data
- Best fit gives $\Delta m^2 \sim 1.73 \text{ eV}^2$ and $\sin^2(2\theta) \sim 0.1$
- 3+1 model simplest
  - additional sterile neutrino allowed

$$P_{ee} \sim 1 - \sin^2(2\theta_{14}) \sin (1.267\Delta m_{14}^2 L[\text{m}]/E[\text{MeV}])$$
Sensitivity to a new neutral state

- Sterile neutrino oscillation in L and E
- Sensitivity strongly depends on stats and S:B
- large coverage in L/E possible with good energy resolution
- A strong test depends on the experimental strategy
  - optimum baseline
  - near-far ratio to cancel normalisation errors
  - control of normalisation allows for better limit but harder to achieve

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

$\sin^2 2\theta_{ee} = 0.165$
Sensitivity to a new neutral state

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\[
\Delta m^2 = 2.35 \text{ eV}^2 \quad \sin^2 2\theta_{ee} = 0.165
\]
2014: Reactor spectrum distortions

D-CHOOZ

\[ E_\nu \approx E_{e^+} + m_n - m_p \]

- Energy spectrum distortion seen by all three reactor experiments with high significance (dubbed “the bump”)

- Amplitude of effect correlated with reactor power

- Cancels in near-far ratio
NEOS

- Active target (Liquid Scintillator, LS)
- Homogeneous, 1000 L volume
- 0.5% Gd-loaded LS
- LAB- and Din-based LS (9:1): improved PSD
- 38x R5912 8” PMTs
- Muon veto planes

2.8 GWth commercial reactor
- Core size: 3.1 m diameter and 3.8 m height
- Low enriched uranium fuel (4.6% $^{235}\text{U}$)

Detector in Tendon Gallery
- ~24 m baseline and ~20 m.w.e overburden

- Cylindrical stainless steel tank with PTFE reflector
NEOS result

Data taking: Aug 2015 - May 2016
- Reactor-on period: 180 days
- Reactor-off period: 46 days
- S:B ~ 23
  - 5% energy resolution at 1 MeV

Comparison with Huber and Mueller’s flux model
  - 5 MeV excess is clear
  - Disagreement around 1 MeV
Data taking: Aug 2015 - May 2016
- Reactor-on period: 180 days
- Reactor-off period: 46 days
- S:B ~ 23

- 5% energy resolution at 1 MeV

Comparison with Huber and Mueller’s flux model
- Better agreement with Daya Bay spectrum
• Use Daya Bay spectrum to subtract flux distortions

• No significant effect found, RAA found to not fit well current data either

• Can significance be improved with subtraction from RENO data?
Isotopic composition study all data

- Look at previous data to infer which isotope could be causing the reactor anomaly if due to miscalculation of flux
- Deviations in cross section per fission for $^{235}\text{U}$ at 2.2 sigma
- Not much sensitivity on other isotopes

C. Giunti, 1608.04096
NEOS-Daya Bay isotopic composition study

P. Huber 1609.03910

- Combined analysis of NEOS and DAYA BAY spectrum data

- Based on double ratio to cancel flux shape related uncertainty

- Able to reject Pu isotopes to be sole responsible for the bump at 99% confidence level
Recent rate measurements

- Precision of results impacted by adverse conditions and show difficulty of measuring close to reactors
- Neutrino-4 currently taking more data and working on systematics
Very Short Baseline (VSBL) experiments

• Latest data sets are not yet conclusive about the (non-)existence of light sterile neutrino but the phase space is closing fast

• only experiments at ~ 10 m from reactor can really put strong constraints in the above 1 eV\(^2\) region

• Since the 2011 reactor anomaly more concerns about the flux model have emerged with the identification of distortion

  • Is the \(^{235}\text{U}\) spectrum the culprit?

• motivates even more the need for measurement at research reactors using highly enriched \(^{235}\text{U}\) fuel

  • Older data is patchy and not very precise

  • key ingredient for predicting antineutrino flux
## Very Short Baseline (VSBL) vs SBL

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Challenging background environment
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Normalisation precision limited
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VSBL reactor experiments

- Prospect - ORNL
- NuLat - NIST
- SoLid - BR2
- STEREO - ILL
- Neutrino-4 - SM3
- DANSS - KNPP
- NEOS

Legend:
- Green: data taking / run completed
- Blue: Taking data
- Red: Funded / construction phase
## Very Short baseline experiment

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<tr>
<th>Experiment</th>
<th>Tech</th>
<th>Reactor</th>
<th>Power/Fuel</th>
<th>P [MW]</th>
<th>L (m)</th>
<th>M (tonnes)</th>
</tr>
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<tr>
<td>STEREO (Fr/Ger)</td>
<td>LS+Gd</td>
<td>ILL-HFR</td>
<td>$^{235}\text{U}$</td>
<td>57</td>
<td>9-11</td>
<td>2</td>
</tr>
<tr>
<td>Neutrino-4 (Ru)</td>
<td>LS+Gd</td>
<td>SM3</td>
<td>$^{235}\text{U}$</td>
<td>100</td>
<td>6-12</td>
<td>1.5</td>
</tr>
<tr>
<td>PROSPECT (US)</td>
<td>LS + $^6\text{Li}$</td>
<td>ORNL HFIR</td>
<td>$^{235}\text{U}$</td>
<td>85</td>
<td>7-18</td>
<td>2</td>
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<td>SoLid (UK/B/Fr)</td>
<td>PVT &amp; $^6\text{LiF:ZnS}$</td>
<td>SCK•CEN BR2</td>
<td>$^{235}\text{U}$</td>
<td>45-80</td>
<td>6-9</td>
<td>2</td>
</tr>
<tr>
<td>DANSS (Ru)</td>
<td>PS + Gd</td>
<td>KNPP</td>
<td>$^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$</td>
<td>3000</td>
<td>9.7-12.2</td>
<td>0.9</td>
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• Detector segmentation provides relative measurement along oscillation length
  
  • combined with energy measurement is only way to demonstrate oscillation!
  
  • Finer segmentation provides additional capability to reject background and select positron energy

**STEREO**

- 6x inner 1D cells 90 x 90 x 35 cm³
- Buffer cells around the target
- 2000 L of Gd loaded LS

**PROSPECT**

- 120x 2D LS unit segment
- Dimension 15 x 15 x 120 cm³
- 3000 L of Li6 loaded LS

**SoLid**

- 5-6x modules 2560 cubes
- Dimension 5 x 5 x 5 cm³
- 1.6-2 tons PVT+LiF:ZnS
• Detector installed at 8.9-11m of ILL-HFR
• Overburden 15 mwe against muons
• Challenging reactor environment requiring external shielding in front and between other experiments
  • Detector shielding against fast neutrons, gamma-rays and magnetic field
  • Muon veto umbrella detector
• Installation completed in September 2016
Commissioning

First source calibration done:
- \(~280\) PEs/MeV in Target cells as expected
- Small top-bottom effect on the detector response: 2\% of differences

Buffer leak in cell 4 and one short gamma-catcher cell:
- Decrease by a factor 2.5 of the light collection
- LS and buffer oil chemically compatible

Data taking already started: after 10 days of commissioning
- Acquisition rate of \(~3\) kHz with \(~1.8\%\) deadtime at \(~250\) keV threshold
- Single rate in neutrino window \((2\) MeV < \(E_{\text{vis}}\) < 8 MeV\): \(~14\) Hz
Status and sensitivity

• Detector has been running since November 2016
  • short commissioning phase
• Data taking until March 2017
  • 80 days reactor ON
• Results coming soon
A model independent experimental approach to test for oscillation of eV-scale neutrinos

**Objectives**
- 4σ test of best fit after 1 year
- >3σ test of favored region after 3 years
- 5σ test of allowed region after 3+3 years
PROSPECT spectrum measurement

A precision measurement to address spectral unknowns

Phase I = AD-I only

Objectives
Measurement of $^{235}$U spectrum
Compare different reactor models
Compare different reactor cores
HFIR Reactor at ORNL

Compact Reactor Core

- Power: 85 MW
- Fuel: HEU ($^{235}$U)
- Core shape: cylindrical
- Size: $h=0.5m \ r=0.2m$
- Duty-cycle: 41%

- Established on-site operation
- User facility, easy 24/7 access
- Exterior access at grade
- Full utility access, incl. internet
PROSPECT R&D

PROSPECT-0.1
Characterize LS
Aug 2014-Spring 2015

PROSPECT-2
Background studies
Dec 2014 - Aug 2015

PROSPECT-20
Segment characterization
Scintillator studies
Background studies
Spring/Summer 2015

PROSPECT-50
Baseline design prototype
Spring 2016

PROSPECT AD-I
Physics measurement
2017
SoLid

• SoLid baseline: 6-9m from the BR2 MTR reactor at SCK•CEN mol, Belgium
  • 5-6x movable modules on rail system 1.6-2 tonnes fiducial mass
  • Refrigerated container to limit impact of MPPC sensors dark noise
  • CROSS calibration robot for absolute efficiency and energy scale calibration at % level (207Bi, 60Co, 22Na, AmBe, 252Cf)
  • Low Z external shielding based on H$_2$O bricks and PE slabs.
  • High Z gamma-ray shielding in front of beam ports, outside enclosure

ArXiv:1703.01683

Geant4 model of SoLid at BR2

Detector Modules and rail CROSS source calibration robot

Water Wall system

Refrigirating container

PE top shielding
3D segmented composite detector

- composite /dual scintillator detector element:
  - 5 cm x 5 cm x 5 cm PVT cube segmentation to contain positron energy and localise interaction
  - Layer of LiF:ZnS(Ag) for neutron detection close to interaction
  - WLS fibre to collect both scintillation light in X and Y direction
  - each cube voxel optically separated from each other by reflective coating
  - SiPM to read out fibre signal

\[ E_{tot} = 4.78 \text{ MeV} \]
SoLid R&D 2015-16

- SoLid Module 1 (SM1)
  - 288kg
  - 2304 voxels, 288 chan.
  - 9 detector planes

- Prototype SM1 system deployed to validate technology
  - 3 days Reactor ON, 1.5 month OFF
  - mechanical design
  - neutron PID
  - target mass estimation dNp < 1%
  - uniformity of cube energy response < 1%
  - Stability at 1% level
  - measurement of IBD background

![Graph showing relative rate with markers for SoLid Preliminary.]

- ~10x
- ~100x

![Image showing a cube with data visualization.]

![Graph showing average PA/cube = 37.2.]

![Image of a reactor room with researchers.]
Imaging IBD events
SoLid status

- Entered construction phase in October 2016
  - all parts ordered and received
- Electronics and trigger developments
- QA and calibration of planes starting this month
- Data taking expected this summer

\[ \Delta m^2_{14} \]
\[ 10^{-2} \quad 10^{-1} \quad 10^0 \quad 10^1 \]

\[ \sin^2 2\theta_{ee} \]

Gallium Anomaly 95% C.L.
Reactor Anomaly 95% C.L.
Global fit 95% C.L.
Global best fit
SoLid 95% C.L. - 150 days reactor on
SoLid 95% C.L. - 350 days reactor on
SoLid 30% C.L. - 350 days reactor on
Summary

- The search for sterile neutrino with mass ~ 1 eV has began at research reactors
- new dedicated experiments have started taking data or are about to come online this year
  - compact segmented detectors provide full coverage of L/E oscillation region
  - probing oscillation lengths not reachable by SBL experiments
- Since the re-evaluation of the reactor flux in 2011 many more questions about the spectrum have surfaced
  - high statistical samples of antineutrino spectra from 235U core will be available soon!
  - fix the lack of data for this crucial flux ingredient
  - measurements at different reactor will give welcome complementarity for a more robust interpretation of the data
- can confirm or reject sterile neutrino hypothesis (3+1 model) with unprecedented precision
- will provide new constraints to the antineutrino flux model
Back up
Signal localisation

- Positron energy contained in cube voxel
- Neutron capture efficiency uniform up to the edge of the detector
- Neutron capture one cube away from interaction gives directional sensitivity
SoLiδ Energy response calibration

- PVT response intercalibrated using muons
- cube response equalised to better than 1% for majority of channels
- stability over time of energy scale ~ 1%
SoLid Neutron trigger and data size

- Neutron pattern recognition in firmware
  - neutron rate is low: $R_n \sim 7$ Hz
- Buffer time $\pm 500$ us and $\pm 2$ planes around neutron
  - expect high detection efficiency above 70%
- Zero suppression threshold at 1.5 PA applied to other signals
  - limit data size and storage
  - Detector cooling to 5 deg to reduce dark counts

![Graph showing waveform, peaks, and threshold with entries, mean, and RMS values.]

![Histogram of number of peaks with triggers and entries.]

![Graph showing fallout vs. efficiency with different signal types.]
SoLi\text{d} Neutron ID and capture time

- Validated PID, neutron transport simulation (MCNP & G4) and Li capture efficiency