Search for oscillations with $^6\text{Li}$ detector at short distance from the BR2 MTR reactor

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for the SoLid collaboration
Outline

• Anomalies in neutrino sector
• SoLid experiment overview
• SoLid technology
• recent developments
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
  - \((L/E \sim 1\text{m}/0.1\text{MeV})\)
- rate deficit of 14 ± 6 %

- \textit{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 %
  - \textit{Reactor anomaly}

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

Friday, 6 February 15
2011 Reactor anomaly

- Oscillation in a new kind of matter?

![Graph showing observed to expected ratio with 2.7σ deficit.](image)

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1988 Solar anomaly

Deficit explained: solar neutrinos oscillate into other neutrinos!

Are we in a similar situation?
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

\[ \Delta m^2 \sim 1 \text{ eV}^2 \]

\[ P_{ee} = 1 - 2|U_{e4}|^2 (1 - |U_{e4}|^2) \]

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:

1. Large source, large detector experiments
2. Very short baseline [5-20] m reactor experiments
Look for rate and energy variations

Effect as a function of energy

Δm² = 2.35 eV²
sin²2θee = 0.165

Data scarce at short distance:

Need better experiments!

Control of background is key for best sensitivity
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
  - Is it a real feature of the spectrum or something else?
  - Measurement with HEU and different technology

$$E_V \approx E_{e^+} + m_n - m_p$$
New Reactor experiments

Prospect - ORNL

SoLid - BR2

STEREO - ILL

POSEIDON - PIK

Neutrino-4 - SM3

DANSS - KNPP

Korean project

CARR project
SoLiđ
SoLid Collaboration

- 3 countries, 9 institutes, ~40 people
SCK•CEN BR2 reactor

- Tank in Pool MTR research reactor
- Licensed to run at power up to 100 MW
  - variable operating power (45-80 MW)
  - 6 cycles per year*
- Beam ports not in use
- Primary circuit pipes away from experimental site
- ~10 mwe overburden on level 3

* will increase from 2016
BR2 Twisted core

Beryllium matrix and assemblies

Aluminum pressure vessel

Technical Data
- Height: 10 m
- Core diameter: ± 1.1 m
- Operation pressure: 12 bar
- Water temperature: 50 °C
- Construction materials:
  - vessel: aluminium
  - covers: stainless steel
  - channels: stainless steel & beryllium
BR2 background measurements

Background rates at level 3

- Neutrons
  - Large system to measure atm neutrons
    - \( R_n \sim 1 \text{Hz} \) \( E_n < 15 \text{ MeV} \)
  - Reactor ON: portable neutron counter:
    - \( R_n < 10^{-5} \text{ Hz} \) (2-20 MeV)
- Reactor ON gamma-rays
  - HPGe detector w and w/o shielding
  - \( R_{\text{gam}} \sim 0.4 \text{ Hz/cm}^2 \) (> 500 KeV) Pb 5cm

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Crosscheck with Floor 1

- Ge energy efficiency checked with nitrogen decay gammas
- 1st floor just behind concrete wall
- 1 hour exposure time
  - $R_{\text{gam}} \sim 140 \text{ Hz/cm}^2 (> 500 \text{ KeV})$
  - rate x350 and hard spectrum
Reactor core calculations

- Neutron flux
- Fissile material + FY
- Core geometry

- Reactor Simulation + Evolution Code
- MURE

- fission rates
- Off-equilibrium corrections

- Weighted $\Sigma$

- Revisited conversion of ILL $\beta$-spectra from $^{233}\text{U}$, $^{239,241}\text{Pu}$:

- Converted $\nu_e$ spectra

- Total $\nu_e$ spectra

- Complete error treatment at 12h and 1.5d

- $^{235}\text{U}$, $^{236}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$

- Al Cladding

- H$_2$O

- Be Matrix

- Masses (g)

- Days
SoLId experiment set up

- Baseline $L = 5.5-11$ m
  - reconfigurable to reduce detector systematics
- 2.88 tonnes total fiducial mass
- Limit passive shielding
- Data taking in early 2016

- Good energy resolution
  - $E_{\text{res}} \sim 17\%$ @ 1 MeV
- Use high position resolution
  - (<5cm)
Expected sensitivity

Event rate $416 \, \nu_e / \text{day/ton}$
2.88ton detector mass
Energy resolution : 0.17 at 1 MeV
300 days running (140 days/year)
Positron threshold (600 keV)
S:B of 6:1 assumed
Systematics
Spectrum norm.: 1.8%
Spectrum shape: 0.7-4%
Thermal power: 3%
Detection efficiency 2%
SoLiðt
technology
SoLid concept

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

- 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

\[ ^6\text{Li} + n \rightarrow ^2\text{He} (2.05 \text{ MeV}) + ^1\text{T} (2.75 \text{ MeV}) \]
Optimisation of Voxel size

- Require good containment for e+ energy
- 85% are contained within one cube of 5 cm
- neutrons caught in proximity of positron
- reduce volume for event selection
- background reduction
Energy response

Tested light yield for 5cm cube with 3mm² MPPC read out using cosmics setup

- Large light yield measured on real dimension PVT cubes with BCF-91A fibre and MPPC read out
  - 40-50PE @ 1 MeV (x2 MPPC)
  - dE/E ~ 17%
- Optical model tuned on data
- Very good uniformity within cube (>95%)
- High IBD reconstruction efficiency
  - Flat in energy both for e⁺ and neutron

Correction of MPPC linearity response not included!
Enabling imaging of interactions

- Locate precisely neutrino interaction
- New way to reject ALL class of backgrounds
- Mitigate unknown backgrounds

\[ \bar{\nu}_e \]

Homogenous volume:

\[ = 1 \text{ Hit} + \text{neutron capture} \]

Volume divided in voxels:

\[ = N \times 3D \text{ Hits} + \text{neutron capture} \]
Additional discrimination

99.90% rejection

96.86% rejection

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Expected IBD efficiency

IBD selection:

Look for a neutron trigger

apply time cut $300 \text{ ns} < \Delta t < 100,000 \text{ ns}$

Select MPPC pair $E > \sim 600 \text{ keV}$ around trigger

apply position cut (2 cubes max around trigger)

<table>
<thead>
<tr>
<th>cut</th>
<th>Efficiency</th>
</tr>
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<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>
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<tr>
<td>multiplicity cut</td>
<td>0.41</td>
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</table>
SoLi\text{d} detectors
SoLid Technology development

2013

- NEMENIX 8kg
  64 voxels, 32 chan.

2014-2015

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

2016

- SoLid modules 1.440 tonnes
  11520 voxels, 1920 chan.
  need 2x

Proof of concept of composite scintillator technique TRL 2-3
1. demonstrate neutron PID
2. Measure bkgs
3. measure PVT-n concidence

Large scale system TRL 3-5
1. demonstrate scalability and test production schedule
2. demonstrate segmentation capability
3. do some physics?
Current set up

- SM1: 288 kg
- NEMENIX: 8 kg
- HDPE
- Pb

muon veto

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Oxford 2013 prototype

- 8 Kg, 64 cubes, 32 read out channels
• 2013: good dynamic range of signal but deadtime
• 2014: new PVT cubes and upgraded DAQ with no deadtime but threshold slightly higher and dynamic range reduced for cosmics
• PID technique demonstrated
Reactor studies

- can monitor neutron and PVT events
- Accidentals from gamma-rays low as expected
- dominated by environmental background at R1 alcove
- Correlated signal measured
- more data on tape to be analysed

Pth = 60 MW
~7 days exposure

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2014 Large scale module (x20)

- 0.3 Tonnes, 9 planes, 2304 cubes, 288 channels, Fast digitiser electronics
- 8 months from construction to commissioning!
Construction and target mass

- All material composing planes weighed to better than 1%
Plane testing
October 2014

• First characterisation of plane response
  • using final electronics!
• ON-OFF response
  • using Cs and Co sources
• First measurement of attenuation length
  • Indication of $L_{\text{att}} \sim 15\%/m$
SM1 installation at BR2

Detector wrapping

Loading at Gent

alignment in front of R1
position known to ~2mm

Detector in position
27th November 2014
As of today SM1 currently under commissioning

• commissioning trigger

• BR2 running until end of February

• Rate measurement at 5.5m: Aim to reach <5% statistical accuracy

• measure IBD efficiency and reconstruct energy spectrum
The SoLid experiment can achieve unprecedented sensitivity to short baseline oscillations

It is designed for high sensitivity

if sterile neutrinos are the explanation it will be ground-breaking discovery!

BR2 reactor well suited for a low risk and precise experiment

Main phase of experiment planned for 2016

Concept has been validated with first prototype

Large scale module under commissioning at closest distance

Technology has real potential for antineutrino detection which opens the path to various applications
The End
## 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>7</td>
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<tr>
<td>POSEIDON</td>
<td>LS+Gd</td>
<td>PIK</td>
<td>100</td>
<td>5-8</td>
</tr>
<tr>
<td>STEREO (Fr)</td>
<td>LS+Gd</td>
<td>ILL</td>
<td>57</td>
<td>8.8-11.2</td>
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<tr>
<td>Neutrino-4 (Ru)</td>
<td>LS+Gd</td>
<td>SM3</td>
<td>100</td>
<td>6-12</td>
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<tr>
<td>PROSPECT (US)</td>
<td>LS + Gd/6Li</td>
<td>ORNL HFIR</td>
<td>85</td>
<td>7-18</td>
</tr>
<tr>
<td>SoLid (UK/B/Fr)</td>
<td>PVT + 6LiF:ZnS</td>
<td>SCK•CEN BR2</td>
<td>45-80</td>
<td>5.5-11</td>
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<tr>
<td>DANSS (Ru)</td>
<td>PS + Gd</td>
<td>KNPP</td>
<td>3000</td>
<td>9.7-12.2</td>
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<tr>
<td>Hanaro (KO)</td>
<td>PS + Gd/6Li</td>
<td>Hanaro/Younggwang</td>
<td>30-2800</td>
<td>6-?</td>
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