The SoLid Experiment

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Why measure reactor anti-neutrinos?
Challenges of reactor neutrino experiments
The SoLid experiment
Current and future detectors
Recent re-calculation of reactor spectrum shows $2.7\sigma$ deficit in previously measured rates at distances between 9 m and 1 km (PRD 83 073006).
Other short baseline neutrino anomalies

- LSND/MiniBooNE
- $3 \, \sigma \, \bar{\nu}_e / \nu_e$ excesses

- Gallium anomaly
- SAGE / GALLEX Ga solar neutrino detectors
- Calibrations with $^{51}\text{Cr}$ and $^{37}\text{Ar}$
- Intense, calibrated sources
- Observed / expected neutrino ratio
- Combined $R = 0.84 \pm 0.05$
- JHEP 1305:050, 2013

PRL 110, 161801
The 5 MeV bump

- 5 MeV $\bar{\nu}_e$ excess
  - Daya Bay
  - Double Chooz
  - RENO
- All Gd doped liquid scintillator
- All low enriched power reactors
- High neutrino stats
- Starting to probe structures in reactor anti-neutrino spectrum
Reactor monitoring

- Reactors produce Plutonium
- Aim to detect diversion for weapon production
- Pu $\bar{\nu}_e$ spectrum softer than U
- Spectrum sensitive to isotopic composition
- Current method measure power
- Hard to recover from loss of measurement
- Neutrino detectors can significantly reduce uncertainty in quantity of Plutonium removed from a reactor

PRL 113, 042503
Why measure reactor anti-neutrinos?

- Neutrino anomalies
  - Search for oscillations within 10 m
- 5 MeV bump
  - Measure spectrum from highly enriched core
  - Use different technology to Gd doped liquid scintillator
- Reactor monitoring
  - Demonstrate spectrum evolution measurement
  - Demonstrate plug and play detector
Why measure reactor anti-neutrinos?

Challenges of reactor neutrino experiments

The SoLid experiment

Current and future detectors
Reactor anti-neutrinos

- Neutrinos from $\beta$ decays in fuel
- Fuel contains $^{235}/^{238}U$, $^{239}/^{241}Pu$ + decay products
- $6 \bar{\nu}_e$ per primary fission
- $10^{20} \bar{\nu}_e/s$ from GW reactor
- Detected by inverse beta decay:
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
- Prompt $e^+$ detection
- Delayed ($< 200\mu s$) $n$ capture
- IBD identified by $\Delta t(e^+, n)$
- 1000s IBD/day/tonne at $< 10m$
Experimental challenges near a reactor

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Experimental challenges

**Backgrounds**
- Cosmics at ground level
  - Spallation neutrons
  - Cosmogenic decays
- Fast neutrons
  - Nuclear recoil identified as $e^+$, real neutron detection
- Reactor $\gamma$s
  - Increase accidentals
  - Impact $e^+$ energy measurement
  - Can impact neutron detection

**Detector constraints**
- Small - tonne scale
- Reactor safety - e.g. dislike flammable liquids
- Limited access
Overview

- Why measure reactor anti-neutrinos?
- Challenges of reactor neutrino experiments
- The SoLid experiment
- Current and future detectors
- 5 - 10 m from BR2 reactor core
- 2.88 T detector
- $5 \times 5 \times 5$ cm$^3$ PVT cubes
- Cubes optically isolated
- $^6$LiF:ZnS(Ag) layers
- Wavelength shifting fibres
- Silicon photomultipliers
Detection principle - composite scintillator

\[ n + ^6\text{Li} \rightarrow ^3\text{H} + \alpha + 4.78 \text{ MeV} \]

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

\[ ^6\text{LiF}:\text{ZnS(Ag)} \]

\[ \text{PVT} \]

\[ 5 \text{ cm} \]

\[ \gamma \]

\[ \bar{\nu} \]

\[ e^+ \]

\[ \gamma \]

\[ \text{neutron} \]

\[ \text{signal amplitude [pixel avalanches]} \]

\[ \text{time [samples]} \]

\[ \text{e}/\gamma/\mu \]

\[ \text{channel 1} \]

\[ \text{channel 7} \]

\[ \text{channel 3} \]

\[ \text{signal amplitude [pixel avalanches]} \]

\[ \text{time [samples]} \]

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Detection principle - segmentation/topology

Inverse beta decay event

Fast neutron event
Detection volume and optics

- Detector split into vertical planes
- Optically isolated scintillator cubes
- 16 vertical and 16 horizontal fibres
- 3 $\times$ 3 mm square WLS fibres
- Sensors alternate top/bottom or left/right
Light sensors - MPPCs

- Silicon photomultiplier
- $3 \times 3$ mm active area
- 3600 parallel Geiger mode APDs
- Charge sum from number of pixels that avalanche
- Operating voltage $< 70$ V
- Temperature dependant breakdown voltage
- High dark count rate (MHz @ single pixel)
- Cross talk (10 - 30%)

![Photograph of MPPCs](image)

** Photon detection efficiency vs. overvoltage **

(Typ. $T_a=25$ °C, $\lambda=408$ nm)

<table>
<thead>
<tr>
<th>Overvoltage (V)</th>
<th>Photon detection efficiency (%)</th>
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<tbody>
<tr>
<td>0</td>
<td>0</td>
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<tr>
<td>0.5</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>1.5</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>40</td>
</tr>
<tr>
<td>2.5</td>
<td>50</td>
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<tr>
<td>3</td>
<td>60</td>
</tr>
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S12572-025C
S12572-050C
S12572-100C
Readout system

- Individual sensor bias control
- Front end amplification and shaping
- 50 MS/s digitisation
- FPGA based neutron/EM discrimination
- Signals buffered in FPGA
- Data read out following neutron trigger
Neutron trigger scheme

- Buffer signals in on all channels
- Front end neutron ID
- Unambiguous neutron location
- eg 5 - 5 channels
- 250 $\mu$s window
- Independent of neutrino energy
- No trigger bias in spectrum
- Neutron is lowest rate background
- Large data reduction
BR2 reactor at SCK CEN

- Highly enriched uranium
- Compact reactor core
- Low background rate
- No nearby experiments
- Approx. 50% duty cycle
- SCK\textbullet CEN are awesome
BR2 has complex, unusual twisted geometry
Calculation a collaboration between SCK and Subatech
SCK understand BR2 reactor well, usually do calculations for neutrons
Subatech experts in calculating neutrino spectra
The SoLid experiment - summary

- Novel detector design for challenging measurement
- Composite solid scintillator
  - Clear neutron signal for trigger and analysis
  - Neutron ID insensitive to high $\gamma$ background
- Highly segmented detector
  - Event topology to select IBD from large backgrounds
- World’s best reactor for these measurements
- Experts to calculate expected spectrum

BR2 at SCK•CEN
• Why measure reactor anti-neutrinos?
• Challenges of reactor neutrino experiments
• The SoLid experiment
• Current and future detectors
Experimental phases

<table>
<thead>
<tr>
<th>Year</th>
<th>2013</th>
<th>15</th>
<th>17</th>
<th>19</th>
<th>2021</th>
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<tbody>
<tr>
<td>8 kg prototype</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>288 kg module</td>
<td></td>
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<td></td>
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<tr>
<td>Full detector</td>
<td></td>
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8 kg prototype detector

- 4 layers of $4 \times 4$ cubes
- 32 fibres / MPPCs
- 4 muon veto panels w/ PMTs
- Front end amplifier only
- V1724 14 bit 100 MS/s ADC
- Coincidence trigger in layer
- 5 pixel avalanche threshold
- Concurrent DAQ software in Go
8 kg prototype detector

- Deployed 5.5 m from BR2 core
- Ran summer 2013 - spring 2015
- neutron calibration tests planned
- Easily ID neutron vs $e^+/\gamma/\mu$
- See time EM/neutron time coincidences
- Measured background rates
- Hints of neutrino signals?
288 kg detector module

- 9 layers of $16 \times 16$ cubes
- 288 fibres / MPPCs
- Running Feb - May
- 1 week with reactor on
- Should measure c. 1000 of $\bar{\nu}$
- Now: source calibrations

**Goals:**

- Proof of event topology concept
- Measure $\bar{\nu}_e$ rate and spectrum
- Compare with calculated spectrum
288 kg detector module - construction

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288 kg detector module - electronics
288 kg detector module - Front end electronics

- Custom 32 channel board
- 1 detector layer / board
- Individual MPPC bias control
- Charge injection system
- Transimpedance amplifier
- 14 bit, 65 MS/s ADCs
- On detector temperature sensors
- Control via Cortex M0+ board
288 kg detector module - Back end electronics

- GLIB FPGA board
- 2 detector layers / board
- Per channel time alignment
- Per channel threshold trigger
- Programmable waveform length
- Vertical / horizontal coincidence
- All communication by IPbus
Concurrent program design
Go runtime handles parallelism
Go IPbus implementation
Single GLIB per goroutine
Run level configuration
Polls readout buffer for data
Data merged data into single file
288 kg detector module - reactor calculations

The diagram shows a schematic of a reactor module, with labels for H$_2$O, Al Cladding, Be Matrix, and UAl$_2$ Fuel. The graph illustrates the masses of $^{235}$U, $^{238}$U, $^{239}$Pu, and $^{241}$Pu over days, with data from MCNPX/CINDER90 (SCK.CEN) and MURE ENDFB6.8 (SUBATECH).
288 kg detector module - deployment
288 kg detector module - neutron ID

Neutron signal

EM signal

Corrected integral [ADC counts]

Amplitude [ADC counts]

Entries: 1.259739e+08
Mean x: 335.2
Mean y: 104.6
RMS x: 148.6
RMS y: 152.7

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288 kg detector module - muons
288 kg detector module - source measurements

Neutrons

Gammas

AmBe source

Reactor only

Entries 832487
Mean x: 526.6
Mean y: 2.52
RMS x: 300.9
RMS y: 416

Entries 1.259739e+08
Mean x: 335.2
Mean y: 104.6
RMS x: 148.6
RMS y: 152.7

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288 kg detector module - analysis goal
Next phase: 2.88 tonne detector

Purposes:

- Measure or rule out short baseline oscillations
- Compare measured and calculated flux and spectrum
- Near/far oscillation search
- Industrial detector production
- Online long reactor monitoring
- Fuel composition measurements
- Running 2016-2018+
Next phase: Upgrades

- Readout upgrade:
  - Noise reduction
  - Neutron trigger
  - Cost reduction

- Large scale production

- Detector optimisations:
  - energy resolution
  - cost reduction
Conclusions

- Range of motivations for very short baseline reactor anti-neutrino experiment
- Challenging environment needs new detector technologies
- SoLid collaboration built and deployed 8 and 288 kg detectors
- Neutrino measurements from these detectors in preparation
- Construction of 2.88 T detector starting soon
- Full scale experiment to run 2016 - 2020+