Status of the SoLid experiment

Search for Oscillations with Lithium-6 detector at the SCK-CEN BR2 reactor

Conseil Scientifique IN2P3
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for the SoLid Collaboration

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Physics Motivations

- Reactor Antineutrino Anomaly (RAA) ➔ Sterile Neutrino search at eV-scale

- Antineutrino energy spectrum deviation (4-6 MeV), observed by all $\theta_{13}$ experiments
  
  - Flux prediction (fission yields, beta spectrum shape …) and detector energy response linearity scrutinized
  
  - SoLiD will procure direct $^{235}$U antineutrino spectrum
Experimental Challenges

2D Neutrino Oscillometry

Search for Absolute/Relative Energy Spectrum & Rate distortion with distance

Using identical detectors at different baselines

- **Detector(s)**
  - High Energy resolution: Large statistics, low systematics
  - High Spatial resolution: Good vertex reconstruction
  - Homogenous / well inter-calibrated
  - Effective background rejection: Low overburden (on surface), Reactor radiation (neutron, \( \gamma \))

- **Reactor**
  - Compact core
  - Access as close as possible
  - Security implications (access rights, safety issue, data transfert, …. )
### Very Short Baseline Experiments (~10 m)

<table>
<thead>
<tr>
<th>Tech</th>
<th>Segmentation</th>
<th>Fuel</th>
<th>$P_{th}$ [MW]</th>
<th>$L$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>STEREO</td>
<td>Gd-doped LS</td>
<td>1D (25 cm)</td>
<td>HEU</td>
<td>57</td>
</tr>
<tr>
<td>Neutrino-4</td>
<td>Gd-doped LS</td>
<td>2D (10 cm)</td>
<td>HEU</td>
<td>100</td>
</tr>
<tr>
<td>PROSPECT</td>
<td>Li-doped LS</td>
<td>2D (15 cm)</td>
<td>HEU</td>
<td>85</td>
</tr>
<tr>
<td>NEOS</td>
<td>Gd-doped LS</td>
<td>-</td>
<td>LEU</td>
<td>2800</td>
</tr>
<tr>
<td>SoLid</td>
<td>Li screens - PS</td>
<td>3D (5 cm)</td>
<td>HEU</td>
<td>60</td>
</tr>
<tr>
<td>DANSS</td>
<td>Gd-doped PS</td>
<td>2D (5 cm)</td>
<td>LEU</td>
<td>3000</td>
</tr>
</tbody>
</table>
SoLid overview

- Composite solid scintillators (PVT/LiF:ZnS)
  - 1.6 t fiducial mass (highly segmented)

- BR2 reactor @ SCK-CEN (Mol, Belgium)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Objectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline</td>
<td>6.2 - 9.2 m</td>
</tr>
<tr>
<td>Anti-neutrinos</td>
<td>~1200 int.d⁻¹</td>
</tr>
<tr>
<td>IBD efficiency</td>
<td>&gt; 30 %</td>
</tr>
<tr>
<td>Threshold</td>
<td>200 - 500 keV</td>
</tr>
<tr>
<td>Signal/Background</td>
<td>~3</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>&lt; 14 % à 1 MeV</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>2.5 - 4.5 %</td>
</tr>
</tbody>
</table>

\[
\sin^2(2\theta_{ee}) = 0.09, \; \Delta m^2_{41} = 1.78 \text{ eV}^2
\]

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Belgian Reactor 2 @ SCK-CEN

- Major MTR-type reactors
  - Material testing/Isotopes production…
  - No others project in fundamental/particle physics
  - Non-proliferation : statutory tasks

- SCK-CEN collaboration
  - Technical support, funding (shielding, source, maintenance…)
  - Reactor calculation expertise
  - No time limitation

- Neutrino parameters
  - Compact Core : $\Phi_{\text{eff}} = 50$ cm, $h = 90$ cm
  - Operating power : $P_{\text{th}} \sim 65$ (125) MW
  - Highly Enriched Uranium : 93% $^{235}\text{U}$
  - Neutrino flux : $\sim 10^{19} \bar{\nu}_e$/s
  - Duty cycle : 150 days/year
  - Low overburden (10 mw.e) / Low reactor neutron and gamma fluxes

Critical after 1.5 year refurbishment (1/06/2016)
Power operation resumed in July 2016
Detection Principle : Composite scintillators

- Inverse Beta Decay (IBD) : \( \bar{\nu}_e + p \rightarrow e^+ + n \)

  Reaction products detection within \( \Delta T \) windows

- Prompt positron signal in Polyvinyltoluene (PVT) \( \rightarrow ES \)
- Delayed neutron capture in \( ^6\text{LiF}:\text{ZnS} \) screens \( \rightarrow NS \)
  \[
  n + ^6\text{Li} \rightarrow ^3\text{H} + \alpha \ (4.8 \text{ MeV})
  \]

- Pulse Shape Analysis

  \( \rightarrow \) Neutron Tag (trigger) !
Detection Principle - High granularity (8,000 voxels/m³)

- Elementary cells [5x5x5 cm³]: PVT + ⁶LiF:ZnS(Ag) layers
- Optically isolated with Tyvek wrapping
- Light collection by Wavelength Shifting Fibers [3x3 mm²]
- Read-out by Silicon PMs [Hamamatsu S12572-050]

3D topology reconstruction → Background identification/rejection!

Inverse Beta Decay event

Fast neutron event
Project Timeline

**NEMENIX**
Proof of Concept
8kg - 64 voxels
32 channels

**SM1**
Real Scale System
288kg - 2304 voxels
288 channels

**SoLid**
Physics Scale Detector
1.6 t - 12 800 voxels
3200 readout channels

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- Physics Run -
SM1 Prototype Highlights

- Data from February - April 2015
  - 2 days reactor ON / 1 month reactor OFF
  - Detection principle and scalability demonstrated despite very low neutron detection efficiency < 5%

✓ Background rejection capabilities

✓ Pulse shape discrimination

✓ Muons tracking capabilities

[Y. Abreu et al., Performance of a full scale prototype detector at the BR2 reactor for the SoLid experiment, JINST 13 (2018) P05005.]
Optimize/Improve Light-yield and Plane Uniformity

- Double cladding fiber
- Thicker Tyveck reflector

- Cube polishing
- 4 (fibers + SiPMs + Al mylar fiber-end mirror) / cube

On target for $14\% / \sqrt{E}$ resolution

- $52 \pm 2$ PA/MeV/cube ($+150\%$)
- 6% total variation across detector plane

[ Y. Abreu et al., Optimisation of the scintillation light collection and uniformity for the SoLid experiment, arXiv:1806.02461.]
Full scale design

12,800 Elementary detection cells

50 Detection Planes (16x16 cubes array)

64 optical readout (fiber + SiPM + Al-mirror) / plane

5 Modules of 10 planes (1.6 t fiducial mass)

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CS IN2P3 - 06/2018
Electronic and Triggers

- Custom readout electronics
  - Analog amplification
  - Each detector plane can run stand-alone
  - Digitisation at 40 MHz - 2 Tb/s output for full detector (pre-trigger)
  - 20 MB/s post-trigger and after Zero-Suppression

- Three triggers (logic implemented in FPGAs)
  - Random: Full detector read-out at 1 Hz
    - Non zero suppressed waveforms for SiPMs monitoring
  - Threshold: XY coincidence > 2 MeV
    - Muon and high electromagnetic event tagger
  - Neutrino: ‘PSD’ algorithm for NS
    - Based on peak counting
    - Long time buffer: [-500 µs, +200µs]
    - Multiplane readout (+/ 3 planes)
Full scale design

- Detector inside container [2.4x2.6x3.8 m] cooled at ~10 °C  →  SiPM dark-count rate reduction (/10)
- Low Z Passive Shielding: Water wall on side (50 cm, 28 t)  &  Polyethylene ceiling (50 cm thick, 6 t)
- Cadmium lining (2mm thick)

- Environmental survey: Temperature, Pressure, Humidity and Luminosity sensors
- Background survey: NaI-PMT coupled and Radon detector
CROSS Calibration System

**In situ Calibration @ BR2**

- Automated Robot sits above detector planes
- Mechanically open/close gaps between modules (railway)
- Source free to move in gap (2D)
- Keep integrity/uniformity of the entire fiducial volume

Radioactive sources on both sides of each module

- Neutron sources (AmBe, $^{252}$Cf)
- Gamma sources ($^{22}$Na, $^{60}$Co, $^{137}$Cs, $^{207}$Bi)

Calibration campaigns (2 - 4 days) during Reactor-OFF period
Assembly line @ Ghent  [French shifts ~ 50 person.week]

- 13 000 cubes manually washed, weighted, wrapped, stacked
Detector Construction [end 2016-2017]

- 2 800 readout channels and 50 planes instrumented

- All components informations (batch, weight) stored in dedicated database

Proton content controlled at per-mil level

Frame PVT Mass

Frame Li Mass

Proton content controlled at per-mil level
Quality Assurance with CALIPSO

- Ensure quality and uniformity response of all the 50 planes
  - Automated calibration system: 2D-scanning robot
  - Radioactive sources in front of each cube
    - Two modes: neutron and gamma
  - Allowed qualification/calibration of 1 plane/day

- Early identification/fix of defective components
  - Bad $^6$LiF:ZnS screens batch, optical coupling loose …

- QA campaign was a success, and allowed an "in real condition" test of every components of the detector, trigger settings and event reconstruction
Light Yield QA with CALIPSO

- **Gamma mode**: $^{22}\text{Na}$ source with external trigger

- **Compton edge to determine PVT light yield (photopeak)**

**Kolmogorov test (K-S)**

Compare measured sample to a Geant4 MC sample

**Analytical fit**

Use pdf based on Klein-Nishina Cross-Section

Agreement between both methods at the 1% level!

Good control of systematics
Light Yield QA with CALIPSO

- Check linearity of the energy response (1 cube)

- Preliminary estimation of LY in all 12800 cubes

  - Homogeneous response, can be improved with correction from attenuation length
  - Exceeds SoLid requirements

  Light Yield  >  60 PA/MeV
Neutron QA with CALIPSO

- Neutron mode
  - $^{252}$Cf neutron source
  - Polyethylene collimator / reflector
  - MCNPX/Geant4 transport model
  - 25 positions per plane in 3 h
  - 100 M reconstructed neutron

Very good neutron reconstruction efficiency

> 60% and uniformity
November/December 2017
Commissioning with 4/5 modules: Reactor ON/OFF
Not fully shielded

February 2018
Physics Mode with 5 modules

3 years data taking planned
Detector operation

- Channel response (gain) equalized at 1.4% level
  - Voltage scans for individual SiPM breakdown voltages and amplification
  - Gain response of ~32.0 ADC/PA

- Online remote detector monitoring (Physics variables for subsample of data)

Stable data taking for both reactor on and off since February
ES Calibration

- First calibration campaign (94 hours) with $^{22}\text{Na}$ and AmBe
  - 100% of cubes (w/4ch) have been calibrated
  - Average of 77 PA/MeV
  - Currently running at higher OV (1.5 → 1.8V): LY should increase of ~ 15%

➔ Exceed the Energy Resolution requirement of 14% @ 1 MeV

- Next calibration campaign dedicated to linearity studies: $^{137}\text{Cs}$, $^{60}\text{Co}$, $^{207}\text{Bi}$ and muons
Calibration with AmBe (≈ 4 MeV) and $^{252}$Cf (≈ 2 MeV) sources
- Both calibrated below 2% level at National Physics Laboratory (UK)

Neutron reconstruction efficiency per cube
- 3% agreement between both sources
- Stat. uncertainties ≈ 2.5%

Global neutron reconstruction efficiency: 75.8% ± 0.02% (stat.) ± 3.10% (syst.)

Next step: Fine tuning of Monte-Carlo models (air gap thickness, … ) to reduce systematics
Muon Reconstruction

- Very good tracking capabilities: PSD, deposit energy, topology, timing

- Correlation with pressure

- Well known dE/dx
  - Online monitoring (detector stability survey)
  - Check Linearity at high energy
IBD-like events check

- IBD-like events monitored by using basic cuts: Timing, Topology, $\mu$-veto, Energy

**Spatially confined**

**Prompt-Delayed** Coincidence Candidate - 2017/12/05, 00:07:26

**$\Delta t$ consistent with thermalized n capture**

**Reactor On excess**

![Graph showing prompt and delayed coincidence rates](image)

- Prompt-Delayed Coincidence Candidate - 2017/12/05, 00:07:26

- Reactor On excess

- Reactor Off

- All Coincidences

- Accidental

**SoLid Preliminary**

![Graph showing excess per day per bin](image)

- $N_{\text{Excess per day per bin}}$

- $\Delta r$ (cubes)

- $B_{\text{Acc, Reactor}} - B_{\text{Acc, Off}}$

- Reactor On - Off

**SoLid Preliminary**

- $N_{\text{Excess per day per bin}}$

- $\Delta t$ (\mu s)

- $B_{\text{Acc, Reactor}} - B_{\text{Acc, Off}}$

- Reactor On - Off

**SoLid Preliminary**
French human resources

- 4 IN2P3 laboratories gathering 17 physicists, 3 PhDs, 1 Post-Doc: ~ 7.5 – 9.5 FTE

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Names (position)</th>
<th>Main contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPC Caen</td>
<td>M. Bongrand (CR), L. Simard (PR), Y. Amhis (CR), M.H. Schune (DR), L. Manzanilas (Post-doc), D. Boursette (PhD) / S. Jenzer (IE), A. Blot (TCN), A. Migayron (AI)</td>
<td>Mechanics, Analysis, Calibration, BiPo</td>
</tr>
<tr>
<td></td>
<td>B. Guillon (MCF), G. Lehaut (CR), D. Durand (DR), G. Bae (PR), V. Pestel (PhD) / B. Carniol (IE), D. Goupilliere (AI), B. Bougard (TCN), C. Vandamme (TCN), J. Perronel (AI)</td>
<td>Reactor modelization, Mechanics, Analysis, Calibration</td>
</tr>
<tr>
<td>LPC Caen</td>
<td>S. Monteil (PR), H. Chanal (MCF), P. Crochet (DR), D. Boumediene (CR) / S. Binet (IR)</td>
<td>Instrumentation, Analysis</td>
</tr>
<tr>
<td>Subatech</td>
<td>F. Yermia (MCF), B. Viala (CR), M. Settimio (CR), M. Fallot (MCF), L. Giot (MCF), D. Henaff (PhD) / H. Carduner (IE), J. M. Buhour (IE), T. Milletto (TCN), Y. Bortoli (TCN), S. Fresneau (TCN)</td>
<td>Analysis, Calibration, Mechanics, Reactor modelization</td>
</tr>
</tbody>
</table>

... also involved in others ν projects: SuperNEMO (LAL, LPC-Caen) Double-Chooz, JUNO (SUBATECH)

Next coming years focus on Data-Analysis
- Two Post-Doc positions (ANR-funded) in 2018
  @ LPC-Caen and SUBATECH

Sizeable technical supports during:
- SM1 design/construction (2014)
- SoLid design/construction (2016-2017)
... Decommissioning (2021)
French Impacts

- Common expertise and strong interplay: mechanics, reactor physics, neutron calibration, energy reconstruction, BiPo background, neutrino oscillation analysis …

- Central/Leading role and major responsibilities within the collaboration

  - Analysis Coordinator : Frederic Yermia (SUBATECH)
  - Run Co-Coordinator : Luis Manzanillas (LAL)
  - QA/Calibration Coordinator : Luis Manzanillas (LAL) / Valentin Pestel (LPC-Caen)
  - ES WG Coordinators : Benoît Viaud (SUBATECH) / Mathieu Bongrand (LAL)
  - NS WG Coordinators : Valentin Pestel / Benoît Guillon (LPC-Caen)
  - Reactor WG Coordinator : Muriel Fallot (SUBATECH)
  - Pub/Com Board : Mathieu Bongrand (LAL)

- CCIN2P3 ressources

  - Data transfer and storage (1.5 TB per day) on HPSS tapes : already 150 TB
  - Significant CPU resources for data processing used by French groups and some foreign partners
  - Computing tools are under preparation on grid side for UK and Belgium … not favoured at CCIN2P3
French fundings

- Detector construction (~1/3 of the overall) secured:
  - Mines-CARNOT (SUBATECH-2013): 100 k€
  - Own laboratory resources (LAL, SUBATECH, LPC-Caen-2015): 150 k€
  - ANR-16-CE31-0018-03, coord F. Yermia (LAL, SUBATECH, LPC-Caen): 600 k€
  - UCA (LPC-Clermont-2017): 20 k€
  - IN2P3 dotations (2016-2017-2018): 95 k€

- Funding needed for the next coming years:
  - Travel expenses, detector maintenance, decommissioning
Summary & Perspectives

- Successful NEMENIX and SM1 runs


- Detector construction & QA completed end 2017

  Funded by

  [ Y. Abreu et al., Optimisation of the scintillation light collection and uniformity for the SoLid experiment, arXiv:1806.02461.]
  [ ‘Quality assurance process for the Phase-I SoLid experiment’ … currently being written ]
  [ ‘Solid Phase-I detector design’ … currently being written ]

- Successful commissioning @ BR2

  - SiPMs equalized at the 1.4% level
  - LY > 60 PA/ MeV
  - Neutron trigger efficiency > 70 %
  - Stable running conditions
SoLid is currently taking good quality physics data

- First physics results coming real soon !!!
- Six BR2 cycles (150 days Reactor-On) in 2018
  - First Oscillation Analysis [Rate-Only]
  - $^{235}$U energy spectrum measurement

Intense activities the next four coming years within a competitive international framework

- SoLid data-taking planned for 3 years
- Sterile neutrino search at eV-scale
  - Event reconstruction under continuous development
    (Cut-based, MVA, Deep Learning ...)
- $^{235}$U energy spectrum measurement and deviation study
  - HEU-LEU fuel comparison (Double-Chooz,...)
  - ‘Ab initio’ summation method
- Enhance the technology development
  - Neutron detection, Non-proliferation