Compact segmented antineutrino detector

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SCK•CEN BR2 reactor building
Very short baseline experiment

- Upcoming experiments require percent level precision in antineutrino spectrum measurement

- Detector located close to reactor core
- Operating on the surface
Precise measurements at reactor

~ 100 m - 1 km baseline

Gd-doped liquid scintillator technology
- underground laboratory
- large external shielding
- homogenous, well contained energy
- achieve percent level antineutrino flux measurement at PWR

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

**Detection using IBD reaction**

\[ E_{\text{vis}} = E_{\bar{\nu}_e} - 0.782 \text{ MeV} \]

\[ E_{\text{vis}} = T_{e^+} + 2\gamma \ (511 \text{ keV}) \]
Precise measurements at reactor

~ 100 m - 1 km baseline

Challenges:

• sensitivity in E and L for oscillation search
• rejection of background
• security and safety constraint on site

Gd-doped liquid scintillator technology

• Underground laboratory
• Large external shielding
• Well contained energy
• achieve percent level antineutrino flux measurement at PWR

~ 10 m baseline
Precise measurements at reactor

~ 100 m - 1 km baseline

Gd-doped liquid scintillator technology
• Underground laboratory
• Large external shielding
• Well contained energy
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~ 10 m baseline

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Highly segmented detector
sufficiently compact to deploy meters away from core
Segmented neutrino detectors

Liquid scintillator

- ILL-81
  - LS cells
  - $^3$He tubes

- Bugey 3
  - LS + Li bars

- Karmen
  - LS cells
  - Gd sheets

Current generation

- STEREO
  - LS+Gd cells

- PROSPECT
  - LS+Li bars

Extruded plastic scintillator

- MINOS
  - extruded plastic & WLS fibre technique

- T2K near detector
  - extruded plastic
  - WLS fibres
  - MPPCs photo-sensors

- NOVA
  - Extruded plastic cells + LS APD sensors

- DANSS
  - Extruded plastic & WLS fibre
  - Gd coating
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

\[ E_{\text{tot}} = 4.78 \text{ MeV} \]
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
Visible energy reconstruction

- Summing all energy visible in 1 m$^3$ detector
- Gamma-ray leakage affects energy reconstruction
Visible energy reconstruction

- Energy estimation recovered by selecting two highest energy cube
Energy reconstruction

![Graph showing energy reconstruction]
Challenges of the design

• composite scintillator
• light collection with WLS fibres
• particle identification
• energy reconstruction
• uniformity
• data size
• efficiency
NEMENIX 2013-14

- small prototype: 64 voxels, 32 channels, 8 kg mass
Real scale system SM1

2010-2013

Proof of concept and small prototype

- NEMENIX 8kg
  64 voxels, 32 chan.

2014-2015

- SoLid Module 1 (SM1)
  288kg
  2304 voxels, 288 chan.
  9 detector planes
Learning how to build it
Target uncertainty

- Solid target intrinsically stable in time
- All 2304 cubes weighed
- Extracted Np
  - < 1% uncertainty
Deployment at BR2
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%
Neutron ID and capture time

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

- Demonstrated power of segmentation on background rejection
IBD candidate

Saffron event: 53636, time range: (19427.0, 20027.0) us

Prompt

Delayed

Data
Signal analysis

- Demonstrated power of segmentation on background rejection

- but SM1 had limited shielding and lower absolute neutron efficiency of \(~ 2.5\%\) due to high data rate
SoLid Module 1 (SM1)
- 288kg
- 2,304 voxels, 288 chan.
- 9 Detector planes
- Limited performance
- Data rate 0.45 TB/day

5x modules
- 1.6 tonnes
- 12,000 voxels, 3,200 read out channels
- High performance
- Data rate max 0.5 TB/day

2014-2015
- 0.8 m

Phase-I 2016-2017
- 2.5 m
Improvements for SoLiD

Neutron capture efficiency

- Additional LiF:ZnS sheets
  - $^6\text{Li}$ capture efficiency 0.55 to 0.7 +30%
  - Reduced capture time 105 to 66 us
- new screens with improved transparency

Light yield and uniformity of response

- 4 fibre read out
  - 37 PA/cube/MeV +66% increase in light yield from SM1
  - on target for 14%/sqrt(E) resolution
- 7% total variation of light yield across detector planes
Trigger and efficiency

- Neutron signal: large number of photons but distributed in time and large range of light output

- In SM1 direct threshold had to be set to 6.5 PA to limit data rate and required two channel in coincidence

- Reduced neutron detection efficiency to 5%

- Neutron trigger implementation
  - Limit reactor ON/OFF data sizes and rate
  - Maximise neutron and IBD efficiency
  - Reduce rate dependence to threshold

![Graph showing signal distribution over time](image)
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
    - can recover neutron detection efficiency from 5% to 70%!
  - remove inefficiencies of forming coincidence
- 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
Detector calibration

off-site XY calibration system (CALIPSO)
plane characterisation
neutrons and EM like signals
precise cube to cube equalisation

in-situ calibration system (CROSS)
Energy scale determination (% level)
Absolute neutron detection efficiency (a few % level or better)
Conclusion

• upcoming VSBL experiments require a detector technology suited for high precision measurement very close to reactor core

• a highly segmented detector based on solid scintillators provides higher containment, alternative energy reconstruction and background rejection based on topology

• deployment of real scale module shows that percent level measurement is feasible with a highly segmented target

• scaling up to a larger system with high efficiency requires a neutron trigger scheme and zero suppression of data
  
  • detector could achieve 30% IBD efficiency based on latest optical improvements, simple IBD selection and front-end trigger developments

• automated calibration system and remote control to further reduce on-site maintenance and operation
Outlook

- SoLid is the first step towards a cost-effective robust segmented detector
- Directionality sensitivity still to be explored
- Room to increase performance in the next 2-10 years:
  - Transmission design (Lattice): CHANDLER, NuLAT to improve the energy resolution
  - Adding more Lithium or new materials to raise neutron efficiency (>90%?)
- Low maintenance integrated design would enable easier future deployment:
  - Applications underground
  - Network of sensors