Measurements of the Reactor antineutrinos with DANSS experiment

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Below 3.1 GW\textsubscript{th} commercial reactor
~ 5\times 10^{13} \, \nu \cdot \text{cm}^{-2}\text{c}^{-1}

DANSS on a lifting platform
A week cycle of up/middle/down position

- Detector of the reactor AntiNeutrino based on Solid-state Scintillator - no flammable or dangerous materials – can be put just after reactor shielding
- Inverse Beta-Decay (IBD) to measure antineutrinos:

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

- Reactor fuel and body with cooling pond and other reservoirs provide overburden ~50 m w.e. for cosmic background suppression
- Lifting system allows to change the distance between the centers of the detector and of the reactor core from 10.7 to 12.7 m on-line
- The setup details: JINST 11 (2016) no.11, P11011
There are several indications in favor of existence of the 4\textsuperscript{th} neutrino flavor - “sterile” neutrino seen in short distance oscillations

\[
P_{ee}^{2\nu}(L) = 1 - \sin^2(2\theta_i) \sin^2 \left( 1.27 \frac{\Delta m^2_{i}[eV^2]}{E_{\nu e}[MeV]} L[m] \right)
\]

Expected parameters (G. Mention et al. Phys. Rev D83 073006 (2011):

\[|\Delta m^2_{\text{new}}| > 1.5 \text{ eV}^2 \ (95\%) \text{ and } \sin^2(2\theta_{\text{new}}) = 0.14 \pm 0.08 \ (95\%)
\]

DANSS: Measure ratio of neutrino spectra at different distance from the reactor core – both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.

Naïve ratio without smearing by reactor and detector sizes and the resolution
The first results published Phys. Lett. B787(2018)56 – one year of running
Progress in the experiment and analysis

1. More data:

DANSS statistics accumulation

- Period in the publication
- New data
- Scheduled fuel replacement
- DANS maintenance
2. Improved signal wave form analysis: better energy estimation and SiPM noise rejection. SiPM time window reduced from 30 to 20 ns.

3. Require PMT confirmation for all SiPM hits. As a result residual SiPM noise energy contribution to total event energy dropped from 100 to 5 keV.

4. Improved longitudinal correction, different for PMT and SiPM.

5. More frequent calibration:
   - SiPM gain by SiPM noise spectra every 20-25 min;
   - All channels by MIP (muons) every 2 days.

6. Improved MC simulation:
   - Signal wave form simulation;
   - Better treatment of Birks effect and Cherenkov light;
   - Better implementation of strip geometry;
   - FIFRELIN generated γ-cascades for simulation of Gd neutron capture (see STEREO: H. Almazan et al. arXiv:1905.11967).

Nevertheless resolution for calibration sources is still worse than MC and we kept additional smearing $17\%/\sqrt{E}$ added to MC.

7. Large statistics allowed to find events of $^{12}$B-decays – new energy scale calibration.
Initial calibration is done using cosmic muons.

Energy scale is fixed close to found from $^{12}$B-decay, which is similar to $e^+$ signal we measure [we measure the positron energy, not the total prompt event energy] with some correction inspired by radioactive sources.

Energy scale uncertainty estimated as 2% is added to systematical error.

![Energy spectrum plots](image)

**MC-data, %**

- $^{12}$B-decay: -0.5
- Gd($n, \gamma$): +1.0
- $^{60}$Co: +2.0
- $^{22}$Na: +3.0
8. Two lowest strip layers added to VETO ‘or’.

9. New cut: for single strip positron clusters – some activity from annihilation gammas is required.

As a result:

✓ Accidental background is reduced from 71 to 29 % (of up position neutrino counts)
✓ Cosmic induced background is reduced from 2.8 to 1.9 %
Fast neutron tails: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra ~ 12 events/day
Amount of rejected by the VETO cosmics ~31% of neutrino signal
Cosmic background fraction 1.9% of neutrino signal (up position), subtracted
Neighbor reactors at 160 m, 334 m, and 478 m, 0.6% of neutrino signal at up position (~25 events/day), subtracted
$^9$Li and $^8$He background estimates: 4.4±1.0 events/day
10. Twice finer positron energy binning.

2.1M events: April 2016 – March 2019

- Top: 4156 ± 5.5 / day
- Middle: 3462 ± 5.5 / day
- Bottom: 2918 ± 3.9 / day
- μ-bkg top: 79 ± 0.2 / day

Statistical errors only
Theoretical spectrum from Huber and Mueller
Strong dependence on energy scale
Analysis of isotope contribution separation is planned

Normalization 1.5 – 3 MeV
Counting rate dependence on the distance from the reactor core

\[ \chi^2/n.d.f = 8.23/5 \]

- Detector fiducial volume divided into 3 vertical sections
- 1 – 8 MeV e\(^+\) energy range
- Individual section normalization
- Section/position background subtracted individually based on 2 reactor off periods
- Rough agreement with 1/R\(^2\) dependence

### Table: Section and Position

| Position | Top | Mid | Bottom |
|----------|-----|-----|--------|
| Section  | U   | M   | D      |
| Top      | U   | M   | D      |
| Mid      | U   | M   | D      |
| Bottom   | U   | M   | D      |
11. Four times finer grid of points on the $(\Delta M^2, \sin^2(2\theta))$ plane.
12. Improved systematic analysis.
Only ratio of positron spectra at different R is used → independent of neutrino spectrum, detector efficiency, reactor models and so on.

The best fit of the whole data set:
$\Delta M^2 = 0.35 \text{ eV}^2,
\sin^2 2\theta = 0.15,
\Delta \chi^2 = 7.8$

The best fit around $\Delta M^2 \sim 1.3 \text{ eV}^2$:
$\Delta M^2 = 1.33 \text{ eV}^2,
\sin^2 2\theta = 0.03,
\Delta \chi^2 = 4.3$

Fits include systematic errors

Fit range 1.5-6 MeV
Probing for sterile neutrino

- Gaussian CLs method (X. Qian et al. Nucl.Inst. Meth. A 827 (2016) 63) – a conservative estimate. In most cases more conservative than Confidence Intervals method.
- 1.5 – 6 MeV positron energy range is used.
- Only Bottom/Top ratio used so far.
- Theoretical curves for each $\Delta m^2$ and $\sin^2(2\theta)$ calculated based on:
  - Model neutrino spectrum from Huber and Mueller;
  - Fuel burning profile from NPP;
  - Detector size;
  - Detector response including tails.
- Systematics studies include discrete variations in:
  - Detector energy resolution ±10%;
  - Energy scale ±2%;
  - Level of cosmic background ±25%;
  - Level of flat background ±30%.
- The best $\chi^2$ over all possible discrete variations combinations above used in the further analysis.
- Systematic influence is small.
Exclusion region

The new data allowed to extend the published DANSS excluded region (PLB787(2018)56)

A large fraction of allowed parameter space is excluded by DANSS results using only ratio of $e^+$ spectrum at different $L$ (independent on $\nu$ spectrum, detector efficiency,...)

2.1 million neutrino events

Allowed regions from arXiv:1512.02202:
- All $\nu_e$ Disappearance Expts (Mention), 95% CL
- SBL Reactor Anomaly (Kopp), 95% CL
- All $\nu_e$ Disappearance Expts (Kopp), 95% CL
- Gallium Anomaly (Kopp), 95% CL

2.1 million neutrino events
DANSS recorded the first data in April 2016 and is running now.
With new analysis we record more than 4 thousand antineutrino events per day in the closest position after subtraction of the muon induced background about 80 events per day.
We doubled data set compare to the published results and the new data has no sign of oscillations.
We clearly observe antineutrino spectrum and counting rate dependence on fuel composition.
We measure reactor power with 1.5% precision in two days during more than a year operation.
We are still working on improvements in data analysis. We plan:
  - Refine detector calibration;
  - Improve MC description of the detector response;
  - Elaborate more analysis methods for better sensitivity.
DANSS upgrade is planned with installation of new strips with SiPM only readout from both ends. This will allow:
  - achieve better energy resolution;
  - Get larger sensitive volume and increase counting rate.

More results are coming!

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Thank you !
Inverse Beta-Decay (IBD)

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

Continuous ionization cluster

Fast (prompt) signal

\[ E_e \approx E_\nu - 1806 \text{ MeV} \]

Delayed signal

Gamma flush in the whole detector

Prompt

Delayed

T ~ tens us

(n,\gamma)

H. Bethe and R. Peierls 1934.
F. Reines and C. L. Cowan 1953-56

Neutron thermalization and capture

\( X(A,Z) \)
Detector of the reactor AntiNeutrino based on Solid-state Scintillator

- Scintillation strips 10x40x100 mm³ with Gd-dopped coating
- Double PMT (groups of 50) and SiPM (individual) readout
- Strips along X and Y – 3D-picture
- 2500 strips = 1 m³ of sensitive volume

- Multilayer closed passive shielding: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm
- 2-layer active μ-veto on 5 sides
- Dedicated WFD-based DAQ system
- Total 46 64-channel 125 MHz 12 bit Waveform Digitisers (WFD)
- System trigger on certain energy deposit in the whole detector (PMT based) or μ-veto signal
- Individual channel selftrigger on SiPM noise (with decimation)

JINST 11 (2016) no.11, P11011
Reactor vertical burning profile for 100% power during the campaign

Fuel contribution during the campaign

|        | Begin 4 | End 4  | Begin 5 |
|--------|---------|--------|---------|
| $^{235}\text{U}$ | 63.7%   | 44.7%  | 66.1%   |
| $^{238}\text{U}$ | 6.8%    | 6.5%   | 6.7%    |
| $^{239}\text{Pu}$ | 26.6%   | 38.9%  | 24.9%   |
| $^{241}\text{Pu}$ | 2.8%    | 8.5%   | 2.3%    |
- Trigger = digital sum of PMT > 0.7 MeV or VETO
  - Total trigger rate ≈ 1 kHz
  - Veto rate ≈ 400 Hz
  - True muon rate ≈ 180 Hz
  - Positron candidate rate ≈ 170 Hz
  - Neutron candidate rate ≈ 30 Hz
  - IBD rate ~ 0.1 Hz
- IBD event = two time separated triggers:
  - Positron track and annihilation
  - Neutron capture by gadolinium
- SiPM noise cut:
  - Time window ± 10 ns
  - SiPM hits require PMT confirmation

### Building Pairs

- **Positron candidate:** > 1 MeV in continuous ionization cluster (PMT+SiPM)
- **Neutron candidate:** > 3.5 MeV total energy (PMT+SiPM), SiPM multiplicity >3

Search positron 50 µs backwards from neutron

Significant background by uncorrelated triggers. Subtract accidental background events: search for a positron candidate where it can not be present – 50 µs intervals 5, 10, 15 ms etc. away from neutron candidate. Use 16 non-overlapping intervals to reduce statistical error. All physics distributions = events - accidental events/16
Muon Cuts

VETO ‘OR’:
- 2 hits in veto counters
- veto energy > 4 MeV
- energy in strips > 20 MeV
- energy in two bottom strip layers > 3 MeV

Two distinct components of muon induced paired events with different spectra:
- ‘Instantaneous’ – fast neutron
- ‘Delayed’ – two neutrons from excited nucleus

‘Muon’ cut: NO VETO 60 µs before positron
‘Isolation’ cut: NO any triggers 45 µs before and 80 µs after positron (except neutron)
‘Showering’ cut: NO VETO with energy in strips > 300 MeV for 200 µs before positron
$^9$Li and $^8$He background ~ 4 events per day

\[ \chi^2 / \text{ndf} = 47.67 / 47 \]

\[ \text{Const.} = 4.16 \pm 0.03 \]

\[ ^9\text{Li} = 0.3429 \pm 0.0809 \]

$4.4 \pm 1.0$ Events/Day

$E_{\text{shower}} > 800$ MeV

$^9$Li Lifetime 257.2 ms
**Analysis cuts**

**Cuts – suppress accidental and muon induced backgrounds:**

- Positron to neutron distance is less than 55(45) cm for 3D(2D) case.
- Fiducial volume - positron cluster position: 4 cm from all edges
- Energy in the prompt event beyond the cluster $< 1.8$ MeV
- The most energetic hit beyond the cluster $< 0.8$ MeV
- Multiplicity beyond positron cluster: $< 11$
- For events with single hit positron cluster additional requirement of at least two hits out of the cluster with energy $> 0.2$ MeV and the hit closest to the cluster should be closer than 15 strip layers.
Reactor power seen by neutrino flux

Normalization by 12 points
Block 4 power

Points at different positions equalized by simple $1/r^2$

Reactor at low power
Reactor off

Data accumulation:
April-June 2016 – start of data taking
July-September 2016 – shutdown for cooling system repair
October 2016 – March 2018 – the first run ~ $1.63 \times 10^6$ IBD events
April 2018 – shutdown to improve grounding and recover ~50 SiPM channels. Trigger threshold was lowered to 0.5 MeV.
May 2018 – the second run started
We are running…

No fuel evolution correction
Compensation of the fuel evolution

Normalization by 12 points

No compensation

With compensation

The first month after shutdown – samarium poisoning of the reactor is clearly seen
Fuel evolution

Spectra ratio: 3 months at the very end of campaign 4 to 3 months a month after campaign 5 start.

The first month at the start of campaign skipped because of samarium poisoning of the reactor.

No contradiction to Monte Carlo simulations using Huber and Mueller spectra seen.