Reactor antineutrino measurements with DANSS experiment

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There are several indications in favor of existence of the 4th neutrino flavor - “sterile” neutrino seen in short distance oscillations

$$P_{ee}^{2\nu}(L) = 1 - \sin^2(2\theta_i) \sin^2 \left( 1.27 \frac{\Delta m_i^2 [\text{eV}^2]}{E_{\nu_e} [\text{MeV}]} \right)$$


$$|\Delta m_{\text{new}}^2| > 1.5 \text{ eV}^2 \ (95\%) \ \text{and} \ \sin^2(2\theta_{\text{new}}) = 0.14 \pm 0.08 \ (95\%)$$

**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
Inverse Beta-Decay (IBD)

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

- Fast (prompt) signal
- Delayed signal

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

- Continuous ionization cluster
- Gamma flush in the whole detector
- Neutron thermalization and capture

Prompt

Delayed

\[ T \sim \text{tens us} \]

H. Bethe and R. Peierls 1934.
F. Reines and C. L. Cowan 1953-56
Detector of the reactor AntiNeutrino based on Solid-state Scintillator

- Scintillation strips 10x40x100 mm$^3$ with Gd-dopped coating
- Double PMT (groups of 50) and SiPM (individual) readout
- Strips along X and Y – 3D-picture
- 2500 strips = 1 m$^3$ 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 $\mu$-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 $\mu$-veto signal
- Individual channel selftrigger on SiPM noise (with decimation)

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KNPP - Kalinin Nuclear Power Plant, Russia, 
~350 km NW from Moscow

- No flammable or dangerous materials – can be put just after reactor shielding
- 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 top position corresponds to ~15000 IBD events per day for 100% efficiency
Calibration is done using cosmic muons

We have average $\approx 18(20)$ p.e./MeV SiPM (PMT)

Additional 15% resolution smearing is added to MC to describe muon energy loss

SiPM response linearity better 0.7%

Basing on MC simulation positron energy is corrected for missed energy and $\gamma$’s overlapping the cluster
Neutron source check of the calibration

\[ _{248}^{\text{Cm}} \text{fission – neutron source} \]

- Gaussian fit position and width of neutron capture by protons are in reasonable agreement with MC
- Comparison of the right edge of the energy spectrum between \[ _{248}^{\text{Cm}} \text{data} \] and MC simulation is very sensitive to calibration and resolution

\[ \begin{align*}
\text{a)} & \quad \chi^2=20.0 \quad \text{n.d.f.}=23 \\
\text{b)} & \quad \chi^2=198.8 \quad \text{n.d.f.}=23 \\
\text{c)} & \quad \chi^2=112.2 \quad \text{n.d.f.}=23
\end{align*} \]

MC Energy + 1%  
MC Resolution + 5%

Variation of energy scale and resolution
Check with $^{22}\text{Na}$ and $^{60}\text{Co}$ radioactive sources

$^{60}\text{Co}: \gamma \rightarrow 2\gamma$

$\Sigma = 2.506\ \text{MeV}$

Reasonable agreement between MC simulations and experiment

$^{22}\text{Na}: \gamma + e^+ \rightarrow 3\gamma$

$\Sigma = 2.297\ \text{MeV}$

Check with $^{22}\text{Na}$ and $^{60}\text{Co}$ radioactive sources
- 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 ± 15 ns
  - Single pixel 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
VETO ‘OR’:
- 2 hits in veto counters
- veto energy >4MeV
- energy in strips >20 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
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
Cosmic muon induced background

Fast neutron tails: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra ~ 13 events/day

Amount of rejected by the VETO cosmics ~50% of neutrino signal

Cosmic background fraction 2.7% of neutrino signal (up position), subtracted

Neighbor reactors at 160 m, 334 m, and 478 m, 0.6% of neutrino signal at up position, subtracted

$^9$Li and $^8$He background estimates: 4.4±1.0 events/day
Reactor power seen by neutrino flux

Normalization by 12 points

Block 4 power

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

Normalization by 12 points

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 now.

No fuel evolution correction

Data used for sterile neutrino analysis
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.
Positron spectrum

966k events: April 2016 – September 2017

Events / day / 0.25 MeV

- Top: $4910 \pm 11$ / day
- Middle: $4101 \pm 11$ / day
- Bottom: $3490 \pm 8$ / day
- $\mu$-bkg top: $133 \pm 0.3$ / day

Statistical errors only
DANSS recorded the first data in April 2016 and now takes statistics at full speed of about 5000 antineutrino events per day in the closest position after subtraction of the muon induced background about 130 events per day.
The experiment is running. About $2.2 \times 10^6$ IBD events are already collected

See next presentation by Natalia Skrobova for sterile neutrinos analysis

- Data analysis is in progress. We plan:
  - Analyze all the data collected
  - Do more detector calibrations and tests
  - Continue systematic studies
  - Elaborate more analysis methods for better sensitivity

More results are coming!

The detector construction was supported by the Russian State Corporation ROSATOM (state contracts H.4x.44.90.13.1119 and H.4x.44.9B.16.1006). The operation and data analysis became possible due to the valuable support from the Russian Science Foundation grant 17-12-01145. The collaboration appreciate the permanent assistance of the KNPP administration and Radiation and Nuclear Safety Departments.
Thank you!
Positron spectrum - compare to the theory

- MC simulated DANSS response use theoretical antineutrino spectrum by Huber and Mueller
- Very preliminary – more work on calibration and simulations needed and planned

Events/(day*0.25 MeV)

Monte Carlo

DANSS data

Monte Carlo – how DANSS could see

Events/(day*0.25 MeV)

Monte Carlo

DANSS optimistic

DANSS pessimistic

Positron energy, MeV

Monte Carlo

RENO data

DANSS optimistic

DANSS pessimistic
Fuel contribution during the campaign

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<th>Begin 4</th>
<th>End 4</th>
<th>Begin 5</th>
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<tr>
<td>$^{235}\text{U}$</td>
<td>63.7%</td>
<td>44.7%</td>
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<td>$^{238}\text{U}$</td>
<td>6.8%</td>
<td>6.5%</td>
<td>6.7%</td>
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<tr>
<td>$^{239}\text{Pu}$</td>
<td>26.6%</td>
<td>38.9%</td>
<td>24.9%</td>
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<tr>
<td>$^{241}\text{Pu}$</td>
<td>2.8%</td>
<td>8.5%</td>
<td>2.3%</td>
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$^9$Li and $^8$He background $\sim$ 4 events per day

$\chi^2 / \text{ndf}$

47.67 / 47

Const.

$4.16 \pm 0.03$

$^9$Li

0.3429 $\pm$ 0.0809

4.4 $\pm$ 1.0 Events/Day

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

$^9$Li Lifetime 257.2 ms