New results from the DANSS experiment

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LP 2019 @ Toronto
The DANSS design

- Cubic meter highly segmented neutrino spectrometer made of 2500 PS strips viewed by 2500 SiPMs & 50 PMTs.
- Multilayer passive shielding: Cu/CHB/Pb/CHB=5/8/5/8 cm
- Active muon veto made of 2 x 3 cm PS plates from all sides except bottom.

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The DANSS is located at Kalininskaya NPP (KNPP) under 3 GW WWER-1000 reactor (H=3.6 m, Ø =3.1 m), which provides ~ 50 m.w.e. (6-fold µ reduction and no cosmic n).

- The detector is built on a movable platform.

Data are taken at 3 distances 10.7 m (Up), 11.7 m (Middle), and 12.7 m (Down) from the reactor (center to center), changed sequentially 3 times per week.

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Main cuts (maximally relaxed):

- Prompt signal ($E > 0.7$ MeV)
- Delayed signal ($E > 3$ MeV)
- Time between signals is in $[2, 50]$ μs
- No muons before prompt signal in 60 μs

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Additional cuts:

- Hit multiplicities for both signals
- Positron clustering pattern cuts
- Spatial cut on distance between fast and slow signal vertexes

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Improvements in analysis*

- Improvement in signal processing (use of SiPM and PMT signal shapes for \(T_0\) and charge determination) and MC simulations (signal WF simulations, taking into account Birks effect & Cherenkov radiation).

- Cut modification (requirement for PMT-SiPM coincidences to suppress noise, requirement of annihilation photons for 1strip positron clusters to reduce accidental/neutron background for low energy positrons).

- More frequent energy calibrations (gain – each 15min, MIP – each 2 days).

- Usage of \(^{12}\)B spectrum for energy scale calibration.

- Two lowest detector layers added to the VETO system.

- Four times finer grid of points on the \((\Delta m^2, \sin^2(2\theta))\) phase space

*) in comparison with our last published result Phys.Lett. B787 (2018) 56
Results of improvements

- Accidental energy in event has been reduced from 100 keV to 5 keV
- Accidental background was suppressed from 71% to 29% (up position)
- Cosmic background is reduced from 2.8% to 1.9%
- Statistics has been increased from 0.97 to 2.1 million IBD events: old data (10/2016-07/2017) + new data (09/2017-01/2019)
- Sensitivity of experiment has been improved by a factor of ~1.4
- Energy resolution for calibration sources is still worse than in MC and additional smearing of 17%/√E has been added to MC (as in published results)
Accidental coincidence of 2 uncorrelated signals (e+-like and neutron-like) in a IBD window [2-50] μs → accidental coincidence background (ACB)

ACB spectrum is constructed directly from data applying the same physics cuts as for IBD signal except coincidence time taken outside IBD time window [2-50] μs in numerous non-overlapping intervals (large statistics is essential to decrease statistical errors of subtraction).

ACB rate is ~29% of IBD rate (up detector position)

Selection of cuts (e.g. geometric) to reduce ACB ⇒ smaller statistical errors
Subtraction of residual backgrounds

- **Fast neutrons**: linearly extrapolate from high energy region and subtract separately from positron and visible cosmic spectra.

- **Visible cosmic background (CB)** has been directly rejected by VETO, it is 30.9% of neutrino signal (for up position).

- Additional CB presents in the IBD-signal due to VETO inefficiency, which was found to be 6.2% from reactor OFF spectra.

- **Not vetoed CB fraction** (due to VETO inefficiency) at level of ~1.9% (=6.2%*30.9%) of IBD-signal has been subtracted from IBD signal (positron spectrum).

- **Final anti-neutrino spectrum** ($E_e^+ + 1.8$ MeV) has no background!

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Energy scale has been fixed using $\beta$-spectrum of $^{12}$B, which is similar to positron signal.

Systematic error on E scale of +/-2% has added due to source response uncertainties.

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Pure positron spectra @ 3 positions (no annihilation photons)

> 4000 eve/d in detector fiducial volume (78% of full volume) @ ‘Up’ position (closest to the reactor).

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Experimental spectrum is in rough agreement with MC using Huber-Muller theoretical neutrino spectrum.

Indication of a bump (normalization in 1.5-3 MeV), but no conclusion on the bump existence now due to strong sensitivity to energy scale.

More work on calibration is required before precision comparison.
The figure shows the ratio (bin per bin) of the $e^+$ energy spectrum collected in the last 4 months of the campaign to the one collected in the 2-5 months of the next campaign.

Clear evidence for spectrum evolution, which is consistent with MC.

Result is for old + fraction of new data. For full data set more work is needed for absolute efficiency calibration of the new data (not important in oscillation analysis).

<table>
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<tr>
<th>Fission fractions [%]</th>
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<tbody>
<tr>
<td>$^{235}\text{U}$</td>
</tr>
<tr>
<td>End</td>
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<tr>
<td>Start</td>
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</tbody>
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Points at different positions equalized by $1/r^2$; normalization by 12 points in November-December 2016

Cosmics and adjacent reactor fluxes (0.6%) has been subtracted; spectrum dependence on fuel composition has been included

Reactor power is measured by the DANSS with neutrino flux with 1.5% accuracy in 2 days

Result is for old + fraction of new data. For full data set more work is needed for absolute efficiency calibration of the new data (not important in oscillation analysis).

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In the first data (2016-2017) 4ν hypothesis had smaller $X^2$ than 3ν one ($\Delta X^2=12.5$).

This triggered a lot of excitement in the field although we clearly stated that significance of this difference would be studied taking into account systematics after collection of more data.

On the new statistics 2017-2018 (1 million events) we see no indication of 4ν signal ($\Delta X^2=2.3$ for 4ν hypothesis).
The best 4ν point ($\Delta m^2 = 0.38 \text{ eV}^2$, $\sin^2(2\theta) = 0.15$, $\Delta \chi^2 = 7.8$) has CL of 1.8σ: no statistically significant sign of the sterile neutrino effect.

Best point in old data ($\Delta m^2 = 1.33 \text{ eV}^2$) is also shown.

The DANSS: result with full dataset

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15/17
Exclusion region was calculated using Gaussian CLs method (for e+ in 1.5-6 MeV to be conservative), which is also more conservative than usual CI method.

Systematics included:
- Energy resolution +/-10%
- Energy scale +/-2%
- Cosmic background +/-25%
- Flat background +/-30%

Systematics influence is small, results of our method are independent from shape of $\nu$-spectrum and detector efficiency.

New data allowed to extend excluded area of 4$\nu$ phase space in comparison with old results published in 2018.
DANSS is in operation since April 2016 with regular (physics) data taking since October 2016 at a rate of ~4000 events per day with cosmic background ~ 1.7%.

Antineutrino spectrum and counting rate dependence on fuel composition is clearly demonstrated.

Reactor power was measured using anti-$\nu$ rate with statistical error of ~1.5% in two days during > 1 year of operation.

With doubled data set we have no sign of sterile $\nu$ oscillations.

Preliminary DANSS analysis (based on 2 million statistics) excludes a large fraction of available parameter space for sterile neutrino using only ratio of $e^+$ spectra at two distances. This method is independent from shape of $\nu$-spectrum and detector efficiency (+ small systematics influence).

Future plans: further improvements of MC & calibrations; detector upgrade; precision comparison of $\nu$ spectra with theory (bump problem).
Backup slides
Background monitoring

- Permanent monitoring of gamma-BG with four NaI (3’x3’): 1 inside + 3 outside the DANSS shield
  - no (ON – OFF) visible difference

- Permanent monitoring of neutron flux with three $^3$He neutron counters: 1 inside + 2 outside the shield
  - $\Phi_n =$ 0.57 outside (OFF)
  - $\Phi_n =$ 300.4 outside (ON)
  - $\Phi_n =$ 0.03 inside (OFF)
  - $\Phi_n =$ 0.04 inside (ON)
  - $\Phi_n =$ 6.0 en plein air

- Episodic measurements with HPGe and “MuMeter”
Time distribution spectra (PMT only)

$\tau_m = 4.01 \pm 0.07$
$\tau_c = 13.68 \pm 0.23$

$N = 1.52 \pm 0.05$
$N = 3.20 \pm 0.02$

$\text{Events / 200 ns / day}$
Reactor monitoring: Up – Middle – Down data

- The DANSS is constantly monitoring reactor since October 2016.
- We are sensitive to the fuel composition (U-Pu content in fuel)

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IBD intensity follows reasonably the $1/L^2$ dependence.

Effective distance $L$ takes into account real spatial distribution of the detection efficiency and the reactor core burning profile (monitored permanently by the KNPP staff).

The time variation of reactor core burning profile is available with a precision of 30 min and ~10 cm.

Average core burning profile has been used in analysis, and it has negligible effect for the results.