Search for sterile neutrinos at the DANSS experiment

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Motivation

There are several indications in favor of existence of the 4th neutrino flavor — "sterile" neutrino seen in short distance oscillations

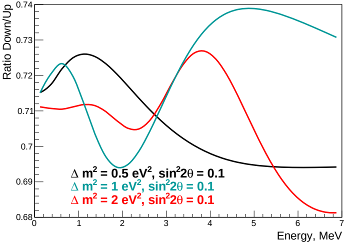
$$P = 1 - \sin^2 2\theta_{14} \sin^2 \left(\frac{1.27 \Delta m^2_{14}[\mathrm{eV}^2] L[\mathrm{m}]}{E_\nu [\mathrm{MeV}]} \right)$$

Expected parameters: (G. Mention et al., arXiv:1101.2755)

$$|\Delta m^2| > 1.5 \mathrm{eV}^2 \text{ and } \sin^2(2\theta) = 0.14 \pm 0.08 \text{ at } (95\%\mathrm{CL})$$

DANSS:

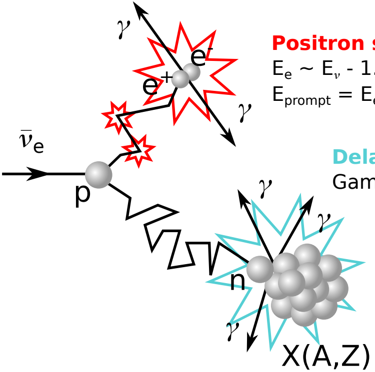
Measure ratio of neutrino spectra at different distance from the reactor core — both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.



Antineutrino registration

Inverse Beta-Decay (IBD) reaction:

$$\tilde{\nu}_e + p \rightarrow n + e^+$$



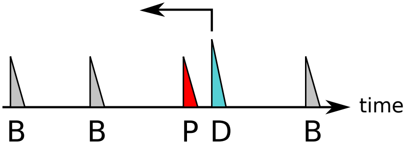
Positron signal

$E_e \sim E_\nu$ - 1.806 MeV

$E_{prompt} = E_e + E_{2\gamma}$

Delayed signal

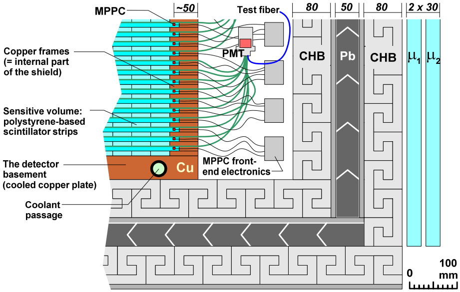
Gamma flush in the whole detector

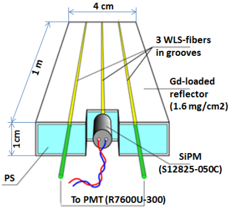


Due to high granularity DANSS is able to meseare positron energy

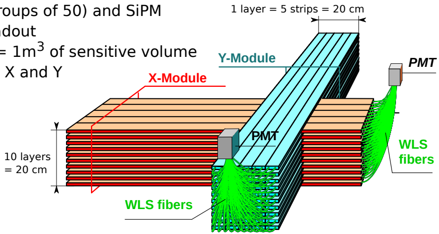
DANSS design [JINST 11 (2016) no.11, P11011]

- 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)

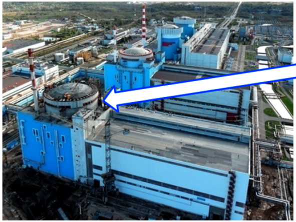


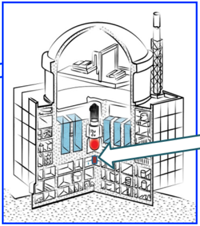


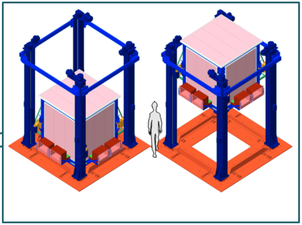
- Dual PMT (groups of 50) and SiPM (individual) readout
- 2500 strips = 1m^3 of sensitive volume
- Strips along X and Y
- – 3D-picture



Detector site





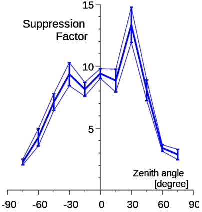


KNPP - Kalinin Nuclear Power Plant, Russia, ~350 km NW from Moscow

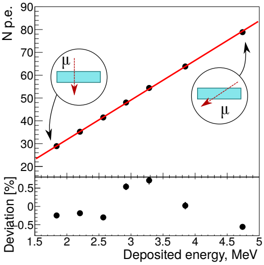
Below 3.1 GW commercial reactor $\sim 5 \cdot 10^{13}\ \nu \cdot cm^{-2} c^{-1}$ at detector position

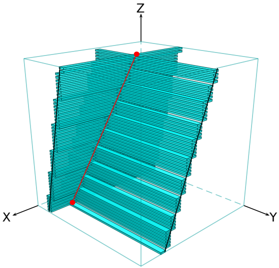
DANSS on a lifting platform
A week cycle of up/middle/down position

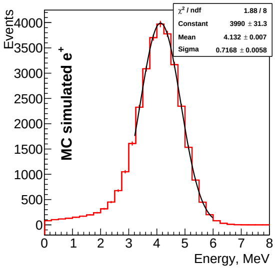
- No flammable or dangerous materials – can be put just after reactor shielding
- Reactor fuel and body with cooling pond and other reservoirs provide overburden ∼50 m w.e. for cosmic background suppression
- Lifting system allows to change the distance between the centers of the detector and of the reactor core from 10.7 to 12.7 m on-line
- The top position corresponds to ∼15000 IBD events per day for 100% efficiency



Cosmic muon suppression measured

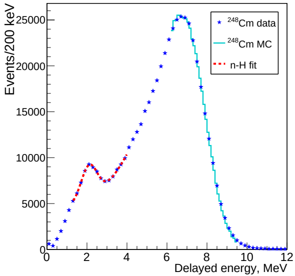


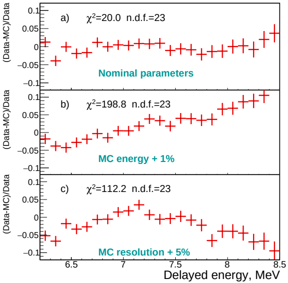


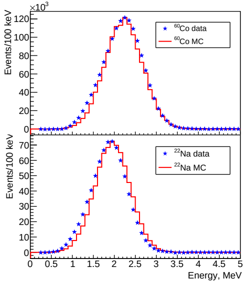


- DANSS response is linear with energy within 0.7%
- Additional 15% resolution smearing is added to MC to describe muon energy loss
- Positron energy is corrected for energy missed in passive layers and γ's overlapping the cluster on the basis of MC simuations

Calibration: radioactive sources





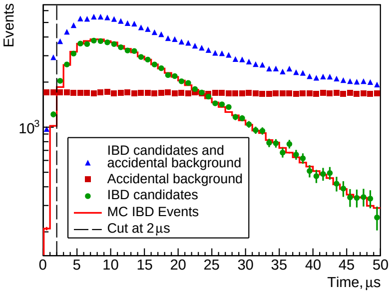


- Energy spectrum of the delayed signals measured with the ^{248}Cm neutron source
- Gaussian fit position and width of neutron capture by protons are in reasonable agreement with Monte Carlo
- Comparison of the right edge of the energy spectrum between ^{248}Cm data and MC simulation is very sensitive to calibration and resolution and agrees with nominal MC value
- Reasonable agreement between MC simulations and experiment for ^{22}Na and ^{60}Co

	E, data	E, MC	σ, data	σ, MC
^{22}Na	1.90	1.96	0.40	0.42
^{60}Co	2.22	2.22	0.46	0.45
^{248}Cm – H(n,γ)	2.04	1.97	0.49	0.49
^{248}Cm – Gd(n,γ)	6.76	6.80	1.08(*)	1.03(*)

(*)effective description of the peak right slope by two isotopes ^{157}Gd and ^{155}Gd

Event building and background



Building Pairs

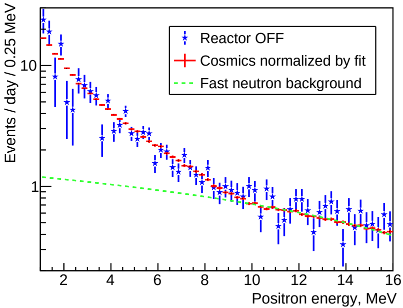
- Neutron candidate: 3.5-15 MeV total energy (PMT+SiPM), SiPM multiplicity > 3
- Search positron 50 μs backwards from neutron
- Positron candidate: 1-20 MeV in continuous ionization cluster
- No other signals in the vicinity of IBD signal

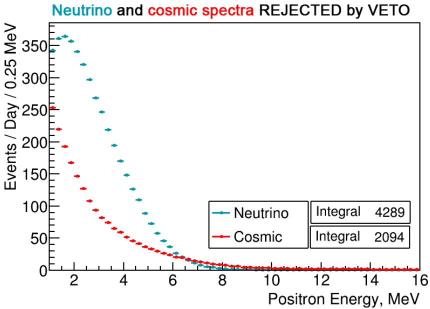
Accidental coincidence background

Fake one of the IBD products by uncorrelated triggers

- Background events from data: search for a positron candidate where it can not be present — 50 μs intervals far away from neutron candidate (5, 10, 15 etc ms)
- Enlarge statistics for accidentals by searches in numerous non-overlapping intervals
- Accidental rate is smaller but comparable to IBD rate
- Mathematically strict procedure, does not increase statistical error
- Cuts for the accidental coincidence exactly the same as for physics events
- Selection of cuts to reduce accidental contribution → smaller statistical error

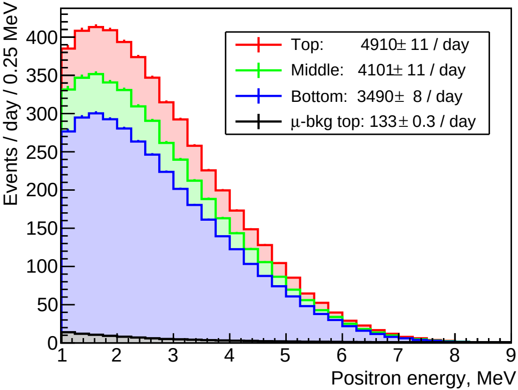
Cosmic background





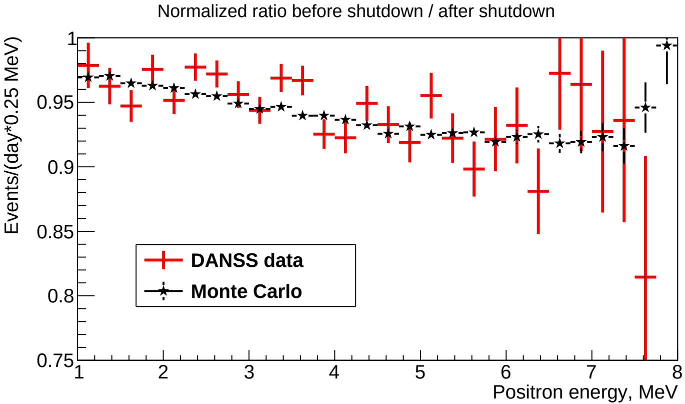
- Fast neutron tails: linearly extrapolate from high energy region and subtract separately from positron and cosmic spectra rejected by VETO
- Amount of rejected by the VETO cosmics ∼50% of neutrino signal
- Veto inefficiency was determined using the Reactor Off data
- Remaining cosmic background fraction 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

Positron spectrum



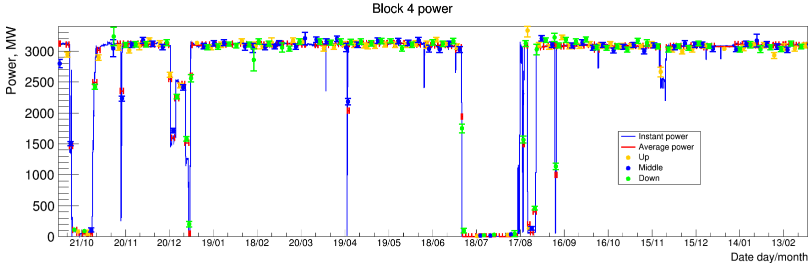
- 3 detector positions
- Pure positron kinetic energy (annihilation photons not included)
- About 5000 neutrino events/day in detector fiducial volume of 78% ('Up' position closest to the reactor)
- μ - induced neutron background not rejected by VETO system is 2.7% only

Spectrum evolution



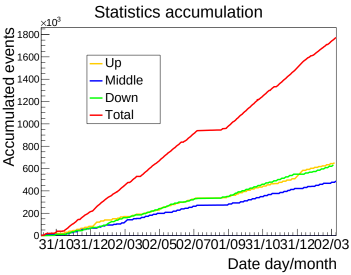
- Ratio of positron energy spectra collected during the last 3 months of the reactor campaign in 2017 and during the $2^{nd} - 4^{th}$ months from the beginning of the next campaign
- The average ^{239}Pu fission fractions for these periods are 37.7% and 27.1% correspondingly
- The stars are the Huber-Mueller MC model prediction

Comparison of reactor power and DANSS rate



On power graph:

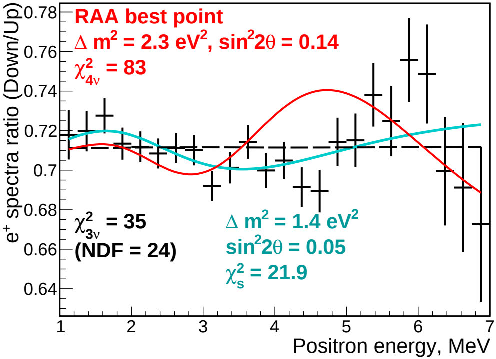
- Points at different positions equalized by $1/r^2$
- Normalization
  by 12 points in November-December 2016
- Adjacent reactor
  fluxes subtracted (0.6% at Up position)
- Spectrum
  dependence on fuel composition is included



Search for sterile neutrinos

For every Δm^2 and $\sin^2(2\theta)$ e^+ spectrum was calculated for Up and Down detector positions taking into account:

- reactor core size
- reactor burning profile (provided by NPP)
- detector energy response including tails (obtained from cosmic muon calibration and GEANT4 MC simulation identical to data analysis)



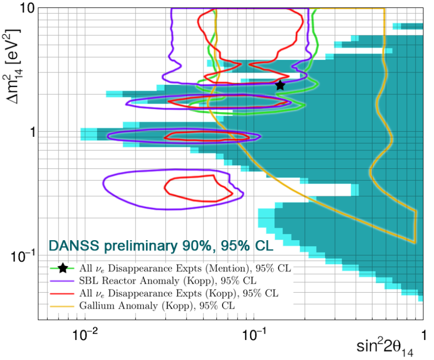
Ratio of Down/Up spectra was calculated and compared with experiment (independent on ν spectrum, detector efficiency, and many other problems!)
Most plausible parameter set from Reactor and Galium anomalies is excluded!

Preliminary results

Exclusion region was calculated using Gaussian CL_s method (X.Qian et al. NIMA, 827, 63 (2016)). CL_s method is more conservative than usual Confidence Interval method

Systematics studies include variations in:

- Burning profile in reactor core
- Energy resolution ±10%
- Level of cosmics background 0.5%
- Energy intervals used in fit (1.5-6)MeV



Systematics is small

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

- DANSS plans to collect more data and to include into analysis all available data
- Detector calibration and systematics studies will be continued

Summary

- DANSS records about 5000 antineutrino events per day with cosmic background <3%
- DANSS counting rate is consistent with reactor power within $\sim$2%
  During reactor shutdown it is consistent with 0 after subtraction of $\sim$3% cosmic background and 0.6% flux from adjacent reactors
- Antineutrino spectrum and counting rate dependences on fuel composition are clearly observed
- Preliminary DANSS analysis based on data collected till September 2017 excludes a large and the most interesting fraction of available parameter space for sterile neutrino using only ratio of e^+ spectra at two distances (with no dependence on $\tilde{\nu_e}$ spectrum and detector efficiency!)
- Significance of the best fit point will be evaluated using more elaborated methods and more statistics

We plan to collect more data, to improve MC for perfect description of detector response, to refine detector calibration, to continue systematic studies, to include all available statistics into analysis.

Thank you!

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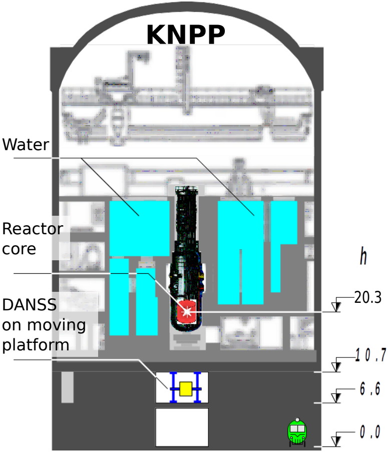
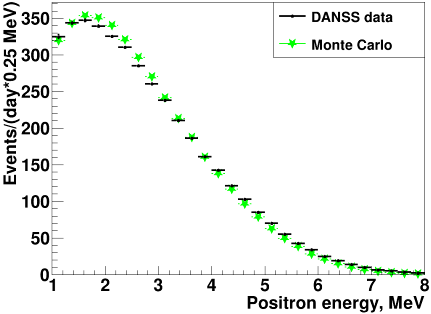
Fuel

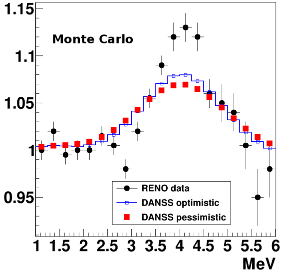
	begin 4	end 4	begin 5
^{235}U	63.7%	44.7%	66.1%
^{238}U	6.8%	6.5%	6.7%
^{239}Pu	26.6%	38.9%	24.9%
^{241}Pu	2.8%	8.5%	2.3%

core: $h = 3.7$ m, $d = 3.2$ m



Positron spectrum





Rough agreement with MC. (Theoretical neutrino spectrum was taken from Huber and Mueller.)

More work on calibration is needed before quantitative comparison.

Limits on the sterile neutrino parameters practically DO NOT depend on the spectrum shape