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Measurements of the reactor antineutrinos with the DANSS experiment

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Abstract. The detector of the reactor antineutrino DANSS is placed on a movable platform below a 3.1 GW industrial reactor of Kalininskaya Nuclear Power Plant. The sensitive volume of the detector is a cubic meter of plastic scintillator assembled from 2500 strips with dual readout by Silicon Photo Multipliers (SiPM) and conventional PMTs (in groups of 50 strips). The detector position provides simultaneously a high neutrino flux and an overburden of about 50 m.w.e., resulting in a high counting rate of inverse beta-decay events and cosmic muons induced background as low as 1.9%. The distance between the reactor core and the detector is changed in a week cycle through three positions 10.7, 11.7 and 12.7 m. This allows systematic-free comparison of the antineutrino spectra measured at different distances by the same detector.

This article presents results of the 2.5 year of data collection with more than 2 million of neutrino events collected.

The main feature of the DANSS experiment is an ability to move a neutrino detector in a close proximity to a 3.1 GW_{th} industrial reactor. The motion is provided by a platform, which allows to change the detector vertical position for 2 m. So we measure neutrino spectrum at different distances using the same apparatus. In the top position the detector is illuminated by neutrino flux of $5 \cdot 10^{13}$ $\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The experiment also gains from its position below the reactor body, which provides a moderate protection from cosmic rays. Inverse beta-decay (IBD) is used for neutrino detection: $\bar{\nu}_e + p \rightarrow e^+ + n\,,\ E_{e^+} = E_{\bar{\nu}} - 1.80$ MeV. Our data are sensitive to the short range neutrino oscillations with $\Delta m^2 \sim 1$ eV. Hints of these oscillations were found in the accelerator [1], radioactive source [2] and reactor [3, 4] experiments. For the data presented a weekly cycle of three one-meter-spaced positions was maintained. This cancels out most of the systematic uncertainties connected to the detector and environment drifts, as well as we do not need to rely on reactor models or measurements of neutrino spectrum by different experiments for the oscillation analysis.

The details of the DANSS setup are published here: [5]. The analysis of our data from April 2016 till September 2017 was published in [6]. This contribution is focused on the improvements in the data and analysis achieved after the mentioned publication.

The new data set includes the statistics collected before March 2019, when the scheduled reactor maintenance was finished, so now it includes two fuel campaigns and two reactor off periods. With significantly stricter selection criteria (see below) the data sample now includes

2.1 million IBD events.

We are using now an improved signal wave form analysis, which leads to a better energy estimation and the SiPM and PMT noise rejection. It also improves signal arrival time measurement, which in turn allows to reduce the SiPM time window from 30 to 20 ns. Nevertheless we tighten the SiPM hit rejection criteria even more and require PMT confirmation for all SiPM hits. As a result the residual SiPM uncorrelated noise energy contribution to the total event energy dropped from 100 to less than 5 keV. The current version of the analysis implements an improved longitudinal correction for the light attenuation, different for the PMT and SiPM. More frequent and regular calibration procedure was developed: SiPM gain from the noise spectra every 20-25 min and all the channels by MIP (cosmic muons) every 2 days.

We have a good progress in the Monte-Carlo (MC) simulation: (a) signal wave form simulation was included in the MC data analysis; (b) better treatment of Birks effect and Cherenkov light; (c) better implementation of the strip geometry; (d) new γ-cascades for simulation of Gd neutron capture provided by the STEREO collaboration [7] which use FIFRELIN method [8]. Nevertheless resolution for calibration sources is still worse than the MC prediction and we keep additional smearing $17\%/\sqrt{E}$ added to MC. A comparison of our MC with the neutron capture measured using ^{248}Cm fission source is shown in fig. 1.

Large collected statistics allows to find the events of ^{12}B-decay, which gives a new energy scale calibration. A reaction of the charge exchange by muon induced fast neutrons is used: $^{12}\mathrm{C}(n,p) \rightarrow ^{12}\mathrm{B}$. Measured cluster energy is shown in fig. 2(left) in comparison to the MC simulation of the decay. Time between an event, containing muon and recoiled proton, and ^{12}B-decay is shown in fig. 2(right). The decay time is in an agreement with the table value. Despite of all this progress in the energy calibration a 2% systematic uncertainty is kept in the analysis.

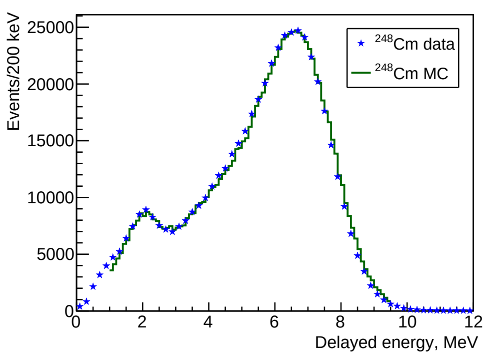

Figure 1. Detector response to neutrons from ^{248}Cm-fission. Experimental points (stars) in comparison to the MC simulation using FIFRELIN γ-cascades [7, 8].

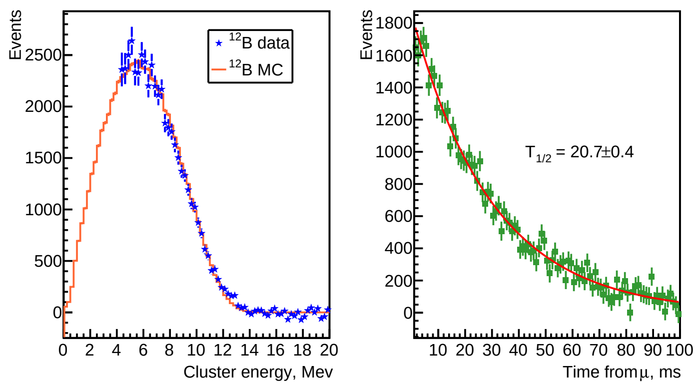

Figure 2. ^{12}B-decay events. Experimental cluster energy (stars) in comparison with the MC simulation (solid line) - left. Experimental ^{12}B-decay time distribution (squares) fit with an exponent (solid line) - right.

The DANSS veto system has a poor coverage at the bottom part of the detector. In order to improve the rejection of muons coming close to the horizontal plain at the bottom of the detector the two lowest strip plains of the detector body are added to the veto. Additional selection criteria, requiring some hits in the detector from the annihilation γ-quanta, are introduced for single hit clusters, because events with such a pattern have a large fraction of accidental and fast neutron background. As a result of these improvements the amount of the accidental background changes from 71 to 29 %.

The second scheduled reactor shutdown period allows to improve the statistics of the background measurement with the reactor off. Measurements during both of the periods are in good agreement. A summary spectrum acquired during the reactor off periods is shown in fig. 3 together with the visible muon induced events spectrum. A fraction of the events produced by fast neutrons, estimated from a linear extrapolation from 10-16 MeV, is also shown. The resulting positron energy spectrum is shown in fig. 4.

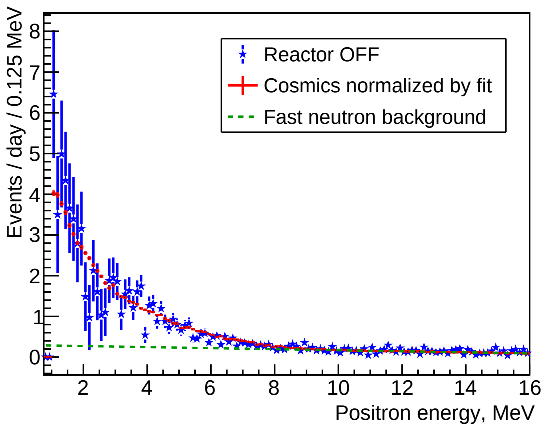

Figure 3. Reactor off positron spectrum (stars) compared to the cosmic muon induced background (small dots) and fast neutron background (dashed line).

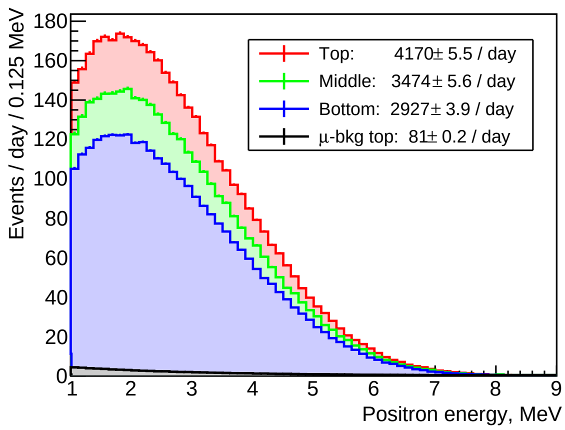

Figure 4. Positron energy spectra for top, middle and bottom positions with all backgrounds subtracted. Cosmic muon induced background at top position is also shown.

A large data sample together with the analysis improvements allows us to calculate the ratio of the experimental spectrum to the MC simulated one. The simulation uses P. Huber [9] and T.A. Mueller [10] reactor spectrum model with the averaged over the data taking period fission isotope composition. The preliminary result is shown in fig. 5. The spectra are normalized in the range 1.5-3.0 MeV, where no mysterious bump structure is expected. The RENO collaboration data [11] are also shown for comparison. The result is preliminary and the visible shape is very sensitive to the energy scale, so no conclusion on the bump existence is made now. DANSS energy resolution, which is about $32\%/\sqrt{(E[\mathrm{MeV}])}$, smooths the shape making it different from other measurements.

Oscillation to sterile neutrino analysis is performed using Gaussian CL_s method [12] with four times finer grid of points on the $(\Delta m^2_{14},\ \sin^2(2\theta_{14}))$ plane and improved systematic error treatment than in our publication [6]. Only the ratio of bottom to top spectra and the limited energy range (1.5-6.0 MeV) is used so far. The preliminary figure of the exclusion regions in $(\Delta m^2_{14},\ \sin^2(2\theta_{14}))$ plane is shown in fig. 6. Systematics studies include discrete variations in several parameters with respect to their central values: (a) detector energy resolution $\pm 10\%$; (b) energy scale $\pm 2\%$; (c) level of cosmic background $\pm 25\%$; (d) level of flat background $\pm 30\%$. The best χ^2 over all possible discrete combinations of (a)-(d) is used in the further analysis. No evidence of oscillations is observed. Our data exclude most of the regions indicated previously as allowed [13].

The experiment collected the first data in April 2016 and is running now. Our future plans include improvements in the detector calibration, data analysis and systematic errors study. An upgrade of the detector is being prepared. It is aimed at better energy resolution and larger sensitive volume.

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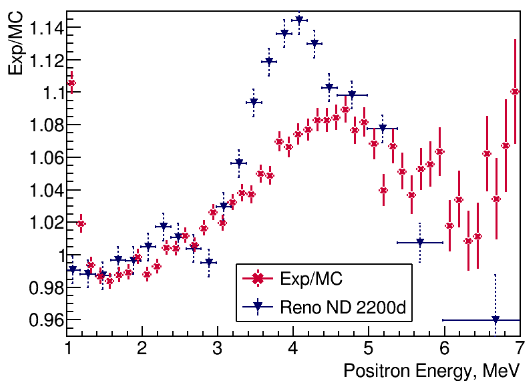

Figure 5. Ratio of the measured positron spectrum to MC-simulated using Huber-Mueller [9, 10] model spectrum (crosses). **Preliminary**. RENO collaboration data [11] are also shown (triangles).

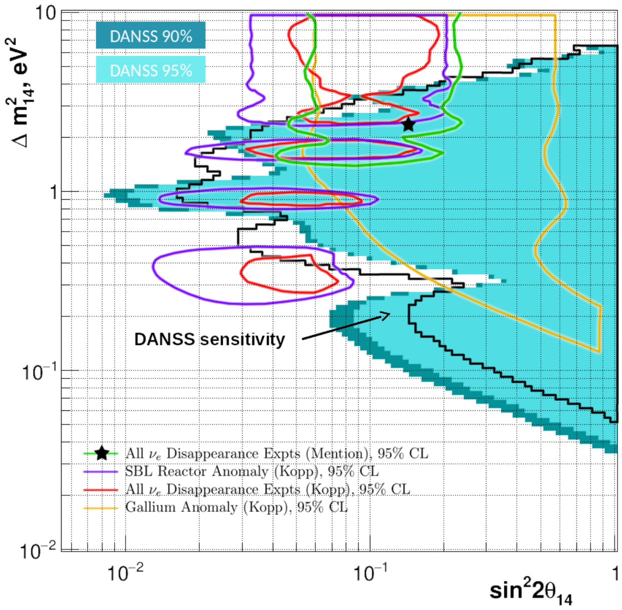

Figure 6. DANSS exclusion and DANSS sensitivity regions. **Preliminary**. Allowed regions from compilation in [13] are also shown.

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