DANSS experiment: current status and future plans

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Abstract. DANSS is a solid scintillator antineutrino detector located right below a 3 GWth reactor of the Kalininskaya NPP. One cubic meter of the sensitive volume with fine segmentation makes it possible to achieve an unprecedented counting rate of about 5000 IBD events per day, keeping the level of cosmic background below 2%. New physics with sterile neutrino is searched for by performing spectral measurements at varying distance from the reactor core. Contributions to the applied antineutrino physics include reactor power measurements and fuel analysis. Commissioned in 2016, DANSS accumulated about 4 million antineutrino events by this fall. Advances in the data analysis will be reported, including improvements in the energy calibration and the optimization of the selection cuts. DANSS upgrade plans include new scintillator strips with higher light collection efficiency and better homogeneity. Expected improvement in the energy resolution will significantly increase the experiment sensitivity to the light sterile neutrino.

1. Introduction

Neutrino physics was always one of the most interesting parts of particle physics with a great potential for discoveries. Last decades of neutrino research lead to a well established picture of three neutrino flavors and their oscillations [1]. Nevertheless there are indications that this picture is not complete. One of these indications is in an existence of one more neutrino flavor — a sterile neutrino, which does not participate even in weak interactions but manifests itself in the oscillations [2]. Two very different accelerator experiments LSND [3] and MiniBooNE [4] observe an appearance of electron (anti)neutrinos in the beam consisting of muon (anti)neutrinos. Their combined significance reaches 6σ (accelerator anomaly). One more evidence came from gallium based solar neutrino experiments GALLEX [5] and SAGE [6]. Calibration of these detectors performed by neutrino sources $^{51}$Cr and $^{37}$Ar revealed a deficit of electron neutrinos at a level of 3σ (gallium anomaly). An analysis of antineutrino rate from several reactor experiments with improved reactor model also showed some deficit [7] (reactor anomaly). All these anomalies could be solved by introduction of a 4th neutrino with $\Delta m^2 \sim 1$ eV$^2$. The best point from a combined analysis of gallium and reactor data is $\Delta m^2_{14} = 2.3$ eV$^2$ and $\sin^2 2\theta_{14} = 0.14$. Resent results of the reactor experiment Neutrino-4 [8] give about 3σ indication of oscillations into sterile state $\Delta m^2_{14} \sim 7$ eV$^2$ and $\sin^2 2\theta_{14} \sim 0.35$.

A direct search for such a neutrino requires study of oscillations with characteristic $L/E \sim 1$ m/MeV. Nuclear reactors are widely recognized as the best available sources of neutrino are reactors, providing a large amount of pure flavor electron antineutrinos with energies of a few MeV. Measurements of the neutrino spectrum at different distances allows to look for the effect in...
the changes of the spectrum without any assumptions of the spectrum shape or neutrino source intensity.

2. The experiment
The DANSS detector [9] is located on a movable platform below an industrial 3.1 GWth WWER1000 reactor of Kalininskaya NPP about 350 km NW from Moscow. The position just below the biological shielding of the reactor core provides excellent opportunities for the experiment. The reactor, its apparatus and building itself above the detector give a screening from the cosmic particles about 50 m.w.e., removing the hadron component of cosmic rays and suppressing the muon component by a factor of 6. The close position to the reactor core ensures a high neutrino flux on the detector about $5 \cdot 10^{13}$ cm$^{-2}$s$^{-1}$, when it is moved to the ceiling of the experimental hall, where a world record counting rate of neutrino events is reached. But such an excellent detector cite forces a strong safety rules excluding the use of highly flammable liquid scintillators. The DANSS detector uses a cubic meter of low flammable plastic scintillator to meet these requirements. The cubic meter is formed by 2500 scintillation strips organized in 100 layers of 25 strips each. Strips in neighbor layers are mutually orthogonal. Each strip has 3 wavelength-shifting fibers placed in grooves along the strips. The central fiber is read out by an individual SiPM and the two side fibers form groups of 50 strips and are bundled together for vacuum PMT read out. The core of the detector is surrounded by a multilayer passive shielding of copper, lead and borated polyethylene. Five sides of the detector with an exception of the bottom side are covered by a double layer active shielding of scintillation counters.

An idea of DANSS search for sterile neutrinos is to measure reactor antineutrinos by the same detector at different distances. This approach excludes all the systematic uncertainties related to reactor models, spectrum expectations, absolute detector efficiency etc. To achieve this goal the detector is placed on a movable platform, which allows to change the distance between the detector and the reactor core centers in the range $10.9 - 12.9$ m on-line.

Detection of antineutrinos is done via the inverse beta-decay (IBD) $\bar{\nu}+p \rightarrow n+e^+$ [10]. In this reaction the neutrino energy with precision of a few tens of keV and exception of the threshold energy is transferred to the positron: $E_{e^+} = E_{\bar{\nu}} - 1.8$ MeV. The positron track ionization together with gammas from its annihilation forms an instant (prompt) signal. The neutron undergoes moderation in the plastic and the thermal neutron is captured by gadolinium, which is incorporated into the surface of the scintillation strips. This takes a few tens of microseconds, so gamma flash accompanying the capture forms a delayed signal providing a strong signature to be used in the reaction selection.

The DANSS detector was commissioned in April 2016. A stable data taking started in October 2016 after the installation of additional veto-counters and the cooling system repair. The statistic acquisition history is shown in Figure 1 till this February. The run goes on, but data analysis has not been performed for the data taken after this February. We have had only one month of the detector shutdown for the PMT grounding improvement in April 2018 so far. This allowed lowering trigger threshold from 0.7 to 0.5 MeV. We also had three periods of the detector not cycling between positions. These are excluded from the analysis for sterile neutrinos where detector cycling is important to suppress systematic errors connected to the fuel evolution or efficiency drift. We collected data during three scheduled reactor shutdowns for fuel rods replacement. Two of these periods are already analyzed, providing us with valuable reactor off information. Nearly 4 million of IBD events are collected in 3 detector positions at 10.9 (Top), 11.9 (Middle) and 12.9 (Bottom) positions. The results from the first year of data taking are already published [11]. Results of the intermediate last year analysis are also published [12]. We are going to concentrate on the new analysis features here.
3. Energy calibration

The initial energy calibration is done using cosmic muon tracks passing the detector in the nearly vertical direction [13]. The data allows to calibrate all PMT and SiPM channels approximately every two days. Yet this calibration appears to be offset relative to radioactive sources, $^{12}B$ and muon decays. As a result we fix the absolute scale using $^{12}B$, which signal is the most similar to the positron signal from IBD. The energy measured for electron clusters of the $^{12}B$ decays is shown in Figure 2 (a). The Figure 2 (b) demonstrate time between muon event and the decay. The measured decay time $29.0 \pm 0.6$ ms is in a good agreement with the tabulated value of 29.1 ms. An additional source of calibration comes from Michel electrons from cosmic muons decay. The total energy of the delayed events following stopped muon was reconstructed. The energy distribution is shown in Figure 3 (a) in comparison with the result of the Monte-Carlo simulations. Muon decay time is shown in Figure 2 (b). The time obtained $2.150 \pm 0.007$ us is in a reasonable agreement with the expectation 2.13 us. The best agreement to MC is achieved with MC energy scale shifted by -1.7%. Monte-Carlo simulation of decays of sources $^{22}Na$, $^{60}Co$, $^{248}Cm$, spallation $^{12}B$ and muons is still underestimating the experimental width of corresponding distributions. An additional term $12\%/\sqrt{E} \oplus 4\%$ was added to all simulations for better agreement. Despite of all this progress in the energy calibration a conservative estimate of the energy scale uncertainty 2% was kept as in earlier analysis.

4. Cut optimization

An optimization of cuts was done aimed to achieve the smallest relative statistical error in the resulting spectrum. The main sources of the background are accidental coincidence background and cosmic muons induced neutrino like events. The relative error is given by the equation:

$$\frac{\sigma}{N_\nu} = \sqrt{N_\nu + N_R + k_C \cdot N_C},$$

where $N_\nu$ is the number of selected IBD events, $N_R$ is the number of accidental coincidence background events, $N_C$ is the number of tagged neutrino like events induced by cosmic muons, and $k_C = 0.05$ is an untagged fraction of such events determined from the reactor off measurements. An example of $\frac{\sigma}{N_\nu}$ dependence over a cut value is given in Figure 4 (a) for the delayed energy. As the fraction of both backgrounds has a significant growth toward

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**Figure 1.** DANSs statistics accumulation till February 2020
Figure 2. Energy of the electron from $^{12}\text{B}$ decays (a) and the decay time in ms(b)

Figure 3. Energy of the Michel electrons from muon decays (a) and the decay time in us (b)

small positron energies, it looks justified to have stronger cuts for low positron energies. This introduces an explicit dependence of the detection efficiency over the positron energy and results in the distortion of the spectrum. Yet our other selection criteria also have dependence over positron energy though these have implicit origins. So the positron energy dependent cuts were introduced for the two most effective criteria — delayed energy and the geometrical distance between positron and neutron candidates based on the corresponding cut scans at various positron energies. The resulting cuts are shown in Figure 4 (b and c) and follow formulas:

$$E_N[\text{MeV}] > 1.5 + 3 \cdot e^{-0.13 \cdot E_e^2}, L_{2D}[\text{cm}] < 40 - 17 \cdot e^{-0.13 \cdot E_e^2}, L_{3D}[\text{cm}] < 48 - 17 \cdot e^{-0.13 \cdot E_e^2},$$

where $E_N$ is the delayed energy, $E_e$ is the positron energy in MeV, $L_{2D/3D}$ is the distance between positron and neutron candidates for 2 and 3-dimensional cases correspondingly.

5. Results
The resulting spectra at three detector positions are shown in Figure 5 (a), while Figure 5 (b) presents the data collected during the scheduled reactor shutdowns. Our counting rate in the closest to the reactor core position is nearly 5100 events per day with the background about 120 events per day including 30 events per day from the other reactors on site.

A ratio of the measured positron spectrum to the Monte-Carlo simulated spectrum is shown in Figure 6. The simulations were done for Huber [14] and Mueller [15] model of fission isotopes spectrum for the average over our data collection time fission fractions. RENO collaboration data [16] is drawn for comparison shifted by 1.02 MeV to correct for two 511 keV annihilation gammas. RENO data smoothed by DANSS energy resolution is also shown. To achieve
Figure 4. Scan over minimum delayed event energy (a). Optimum cut value as a function of positron energy for delayed event energy (b) and for is the distance between positron and neutron candidates (c).

Figure 5. Measured positron spectra for three detector positions (a). Measured positron spectrum during reactor off periods (b).

reasonable agreement between our measurements and Monte-Carlo in the range \(1.5 - 3.0\) MeV a 50 keV shift of unknown nature was introduced (a). Data without the shift is also shown (b) demonstrating a strong picture dependence on a relatively small shift. The statistical analysis of the spectra measured and the results of sterile neutrino search can be found here [17].

6. Upgrade
A serious problem of the experiment is a limited energy resolution about \(33\% / \sqrt{E}\), which smooths oscillation pattern. Main contributions to the resolution come from a small photo statistics (17.7 p.e./MeV with cross talk 0.37 for SiPM and 15.9 p.e./MeV for PMT), nonuniformity of the light collection and the reflective coating of the strips, which produces relatively thick dead layer with titanium in addition to gadolinium. The upgrade plan is to replace current strips with new strips with larger cross section and 8 wavelength shifting fibers. The new strips are going to be \(1200 \times 50 \times 20\) mm\(^3\) in size. We plan to have SiPM only readout from both sides of the strips. Abandoning of PMTs and some empty zones in the detector will allow to increase the side of the sensitive volume cube from 1.0 to 1.2 m, thus increasing the sensitive volume by 70%. We plan to keep the platform, passive and active shielding, digitization electronics. But the front end electronics placed inside the passive shielding will be changed to reduce the heating inside, which will allow us to cool SiPM down to 10°C. The result of the test with pion beam of strip prototypes is shown in Figure 7 (a). Newer prototypes made from better scintillator
demonstrated that the goal of 100 ph.e./MeV can be reached. The mass production of strips has started with the idea to complete the upgrade during 2021. The upgraded detector sensitivity to the sterile neutrinos is shown in Figure 7(b) for 1.5 years of running.

Figure 7. Transverse profile of the new strip prototypes measured at a pion beam (a) and expected sensitivity of the new detector to sterile neutrino oscillations after 1.5 years of running (b).

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