Reactor antineutrino measurements with DANSS experiment

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Abstract. Experiments with reactor antineutrino provide a wide range of physics opportunities. Solid state scintillator detector DANSS is placed just below the core of 3.1 GWth industrial reactor of Kalininskaya Nuclear Power Plant. The detector features the world highest counting rate of 5000 neutrino events per day with the cosmic rays induced background as low as 130 events per day. The talk covers detector performance of a year and a half operation, reactor power measurements via neutrino flux and effects of fuel burning over the reactor campaign.

1. Introduction

Neutrinos are perhaps the most interesting fundamental particles, being for many years at the very frontier of the modern physics. We already know that there are only three generations of light active neutrino and that these neutrinos can transform into each other through the oscillation mechanism [1]. Nevertheless the world neutrino data contains indications of possible existence of one more sort of neutrino [2]. The indication assumes short distance oscillations which can not be explained by known neutrino types, but a number of active neutrino generations is already limited by Z-boson width measurements. A sterile neutrino was proposed. A combined fit of the data from reactor and gallium measurements has the best point with $\Delta m^2_{14} = 2.3 \text{ eV}^2$ and $\sin^2 2\theta_{14} = 0.14$ [3].

One of the best sources of the neutrino available for experiments are industrial reactors. But placement of the detector in the close proximity of an industrial reactor assumes many limitations, the strongest of which come from the fire safety considerations. This completely excludes application of the liquid scintillator, commonly used in neutrino experiments. The sensitive volume of the DANSS detector was assembled from solid state plastic scintillator making it possible to place the detector just below the concrete shielding of the 3.1 GWth WWER1000 reactor of Kalininskaya NPP 350 km NW from Moscow. In the top position of the detector it is exposed to the antineutrino flux about $5 \cdot 10^{13} \text{ cm}^{-2} \text{s}^{-1}$. On the other hand reactor materials above the detector provide an overburden about 50 m.w.e., which gives about 6 times suppression of the cosmic muons.

The detector is placed on the movable platform, which allows to change the distance between it and the reactor core in the range 10.7-12.7 m (center to center), so the neutrino flux and energy
distributions are measured at different distances by one and the same detector. This gives an
unique opportunity to search for sterile neutrinos without additional uncertainties introduced
into the analysis either by the reactor flux calculations or by performing measurements with
two separate detectors. A high neutrino counting rate of the DANSS detector can be also used
in applied reactor studies such as independent reactor power measurement or fuel evolution
estimates.

2. The experiment
Antineutrino detection is based on the inverse beta-decay (IBD) $\bar{\nu} + p \rightarrow n + e^+$, where the
positron kinetic energy with precision of a few tens of keV is related to the energy of the original
neutrino by the equation: $E_{e^+} = E_{\bar{\nu}} - 1.8 \text{ MeV}$. This reaction has a very good signature of
two consecutive time separated events. The first, called "prompt", corresponds to the positron
stopping and annihilation. Its visible energy consists of the positron kinetic energy and two
annihilation gammas 511 keV each. The second, called "delayed", corresponds to the gamma
flash from neutron capture by gadolinium. Its visible energy is about 8 MeV, which is well above
gamma energies of the natural radioactivity.

The sensitive volume of the DANSS detector is formed from 2500 scintillation strips (figure 1). The
strips have a white reflective outer layer doped with gadolinium to ensure neutron capture.
Each strip has 3 grooves with wavelength shifting fibers in. The middle fibers are read out
individually by SiPMs. The strips are arranged in 100 layers, 25 strips in each. Consecutive
layers are orthogonal to each other (figure 2). Sections of $5 \times 10$ strips form a module, 50
modules in total. Side fibers of the strips in each module are read out by a conventional PMT.
The sensitive volume is surrounded by a multilayer passive shield of copper, lead and borated
polyethylene (figure 3). Five sides of the detector cube are covered with double layer scintillation
veto system. More details about the setup can be found in [4]. Data acquisition is based on 64-
channel VME wave form digitizer (WFD) modules with 12 bit 125 MSPS digitization [5]. Fifty
signals from conventional PMTs are fed to a single WFD module to form a physics trigger from
an instant sum of all signals. For the statistics presented in this paper the trigger threshold was
set to 0.7 MeV energy deposit in PMTs. Another trigger is based on 40 signals from the veto
counters, connected to another dedicated WFD module. The triggers cause readout of 512 ns
wave forms from all channels with data different from the pedestal value. Each WFD module
forms a data stream, asynchronously transferred to the main server, where events are built and
stored on a disk.

DANSS started its operation in April 2016, but after 2 months stopped for cooling system
repair and veto upgrade. Regular data taking was resumed in October 2016 and continued
till March 2018, when a month of the detector shutdown was used for the PMT grounding
improvement. This allowed to decrease the trigger threshold to 0.5 MeV. We are running now
and plan to run at least for another year. A weekly detector moving cycle is used, with three
positions: top (10.7 m), middle (11.7 m) and bottom (12.7 m).

Detector calibration is done with signals from cosmic muons, vertically passing sensitive
volume. Two days statistics provide enough data to calibrate each strip. It is checked with $^{22}\text{Na}$,
$^{60}\text{Co}$ and $^{248}\text{Cm}$ sources, placed in Teflon tubes passing through the detector body. Profound
study of the detector calibration and stability can be found in [6]. Unlike most of the experiments
with large uniform volumes of liquid scintillator, we have a fair space resolution and separation
of positron track, but a moderate hermeticity, so that large portion of annihilation energy can
escape. As a consequence we do not use the total prompt event energy in the analysis, but the
pure positron energy instead. Visible ionization cluster energy is corrected for the attenuation
in the strip, the energy loss in the dead layers at strip edges and some portion of annihilation
energy overlapping signal strips.
3. Analysis
Data processing is performed in several stages [7]:

- Waveforms are analyzed and their parameters such as energy and time are determined.
- SiPM noise is filtered by ±15 ns time cut. Single pixel hits are required to have PMT confirmation.
- General trigger parameters such as total energy, energy and position of continuous ionization cluster etc are calculated.
- Signal time correlated pairs of prompt and delayed triggers are searched for in the data stream in 50 us windows. Accidental pairs are searched in parallel in 16 windows far away from the signal region.
- Selection criteria are applied to both signal and accidental events. Distributions are plot as a difference between signal and accidental distributions.
• Ratios of positron energy distributions at various distances from the reactor are calculated and statistical analysis is performed.

Relatively soft selection criteria aimed at statistics maximization are used in the data analysis presented here [7]. Distance between the ionization cluster of the prompt event (positron) and averaged position of the hits in the delayed event is shown in figure 4 to illustrate the idea. The most of the IBD events have this parameter below 55 cm cut, while significant portion of the accidental background is rejected. Spectrum of the residual background collected during the scheduled maintenance of the reactor is shown in figure 5. Contribution by the three other reactors of Kalininskaya NPP is subtracted. Scaled by 5.6% spectrum of the muon tagged pairs is also shown with the addition of the fast neutron background, linearly extrapolated from high energies into the signal region. Both spectra, reactor-off and cosmic, look fairly the same, so we can conclude that the main portion of the residual background originates from muons escaping the veto. We subtract fraction of 5.6 % of veto tagged events and fast neutrons from the signal spectra for the further analysis. The resulting spectra is given in figure 6.

**Figure 4.** Distance between IBD vertex and neutron capture.

**Figure 5.** Positron spectrum, when the reactor was switched off for the scheduled maintenance.

**Figure 6.** Positron spectrum for the detector positions at 10.7, 11.7 and 12.7 m from the reactor core.
4. Reactor monitoring

High counting rate allows DANSS to monitor reactor power by means of the neutrino flux. The results of such measurements from October 2016 till March 2018 are shown in figure 7. Our data is normalized to the reactor power during a monthly period in December 2016. Points at different detector positions are scaled using simple $1/r^2$ approximation with a correction to the height of the reactor core. Blue line presents the power measurement from the reactor control system. The period covers scheduled reactor shutdown in summer 2017, when about of $1/3$ of the fuel rods was replaced. It is seen that our points go lower than the reactor power before the shutdown and are above the power level right after the fuel replacement. This behavior is due to the fuel burnup, as the fission fraction of $^{235}\text{U}$ becomes smaller, and at the same time the part of $^{239}\text{Pu}$ and $^{241}\text{Pu}$ becomes larger, while the neutrino production rate and spectrum are different for the fission parent isotopes [8]. Fission fractions of the main fuel components are given in table 1. A correction using Huber [9] and Mueller [10] neutrino flux calculations was applied. The result is in figure 8. We can observe a good compensation for all the data with the exception of the beginning of the reactor campaign (September 2017). The disagreement has a natural explanation by the samarium poisoning of the reactor, which is not accounted in the fission isotope fractions data provided by the power plant.

![Figure 7. Reactor power measured via neutrino flux compared to reactor control measurements. Statistical errors only. No compensation for the fuel burnup.](image1)

![Figure 8. Reactor power measured via neutrino flux compared to reactor control measurements. Statistical errors only. Compensation for the fuel burnup applied.](image2)

Positron spectrum ratio for the most different fission mixtures is shown in figure 9 compared to the Monte Carlo simulations of the detector response, using Huber and Mueller neutrino spectra. No contradiction is seen.
Table 1. Fission isotopes fractions for reactor campaigns 4 and 5.

| Campaign stage Date | Begin 4 | End 4 | Begin 5 |
|---------------------|---------|-------|---------|
|                     | March 2016 | July 2017 | August 2017 |
| $^{235}\text{U}$    | 63.7 %    | 44.7 %   | 66.1 %   |
| $^{238}\text{U}$    | 6.8 %     | 6.5 %    | 6.7 %    |
| $^{239}\text{Pu}$   | 26.6 %    | 38.9 %   | 24.9 %   |
| $^{241}\text{Pu}$   | 2.8 %     | 8.5 %    | 2.3 %    |

Figure 9. Positron spectrum ratio for the 3 month periods at the end of campaign 4 to the begin of campaign 5. The first month of the campaign is skipped.

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