Neutrino Physics at Kalinin Nuclear Power Plant: 2002 – 2017

I Alekseev$^{1,2,3}$, V Belov$^4$, V Brudanin$^4$, M Danilov$^{2,3,5}$, V Egorov$^{4,6}$, D Filosofov$^4$, M Fomina$^4$, Z Hons$^{4,7}$, S Kazartsev$^{4,6}$, A Kobyakin$^{1,3}$, A Kuznetsov$^4$, I Machikhiliyan$^{1,2}$, D Medvedev$^4$, V Nesterov$^4$, A Olshevsky$^4$, N Pogorelov$^4$, D Ponomarev$^4$, I Rozova$^4$, N Rumyantseva$^4$, V Rusinov$^4$, A Salamatin$^4$, Ye Shevchik$^4$, M Shirchenko$^6$, Yu Shitov$^{4,8}$, N Skrobova$^{1,3,5}$, A Starostin$^{1,2}$, D Svirida$^{1,2}$, E Tarkovsky$^4$, I Tikhomirov$^4$, J Vlášek$^9$, I Zhitnikov$^4$, D Zinatulina$^4$

1 Alikhanov Institute for Theoretical and Experimental Physics, B. Cheremushkinskaya 25, Moscow, 117218, Russia
2 National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), Kashirskoe highway 31, Moscow, 115409, Russia
3 Moscow Institute of Physics and Technology, 9 Institutskiy per., Dolgoprudny, Moscow Region, 141701, Russia
4 Joint Institute for Nuclear Research, Joliot-Curie 6, Dubna, Moscow region, 141980, Russia
5 Lebedev Physical Institute of the Russian Academy of Sciences, 53 Leninskiy Prospekt, Moscow, 119991, Russia
6 Dubna State University, Universitetskaya 19, Dubna, Moscow Region, 141982, Russia
7 Nuclear Physics Institute, Řež 130, 250 68 Řež, Cz, Czech Republic
8 Imperial College London, South Kensington Campus, SW7 2AZ, London, United Kingdom
9 Czech Technical University in Prague, Zikova 1903/4, 166 36 Prague 6, Czech Republic

E-mail: starostin@itep.ru; igor.alekseev@itep.ru; dmitry.svirida@itep.ru

Abstract. The results of the research in the field of neutrino physics obtained at Kalinin nuclear power plant during 15 years are presented. The investigations were performed in two directions. The first one includes GEMMA I and GEMMA II experiments for the search of the neutrino magnetic moment, where the best result in the world on the value of the upper limit of this quantity was obtained. The second direction is tied with the measurements by a solid scintillator detector DANSS designed for remote on-line diagnostics of nuclear reactor parameters and search for short range neutrino oscillations. DANSS is now installed at the Kalinin Nuclear Power Plant under the 4-th unit on a movable platform. Measurements of the antineutrino flux demonstrated that the detector is capable to reflect the reactor thermal power with an accuracy of about 1.5% in one day. Investigations of the neutrino flux and their energy spectrum at different distances allowed to study a large fraction of a sterile neutrino parameter space indicated by recent experiments and perform the reanalysis of the reactor neutrino fluxes. Status of the short range oscillation experiment is presented together with some preliminary results based on about 170 days of active data taking during the first year of operation.
1. Introduction
The experimental neutrino physics is inseparably linked with nuclear reactors where powerful flows of antineutrino are generated in $\beta$-decays of nuclear fragments. A light water power reactor (LWR) with thermal power of 3 GW produces an antineutrino flux $\sim 2 \cdot 10^{13}$ $\nu$/cm$^2$·s at a distance of 15 m from the core center. The nuclear reactors were used for studying antineutrino fundamental properties at Savannah River Laboratory (the United States) in 1953–1955 [1] where in the experiment of the Reines and Cowen group interactions of neutrino with matter were observed for the first time. Starting from late 1970s, reactor experiments were initiated in Europe (Gösgen, Switzerland; Bugey and CHOOZ, France) and in the Soviet Union (Rovno and Krasnoyarsk Nuclear Power Plants). ITEP and LNP JINR started experiments on neutrino physics at Kalininskaya nuclear power plant (KNPP) fifteen years ago. KNPP is located in Tver region, about 350 km from Moscow. There are 4 energy units with thermal power of 3100 MW each. The scope of our projects includes both fundamental and applied directions. Experimental setups are GEMMA I and GEMMA II for searching of the neutrino magnetic moment and the DANSS detector (Detector of Anti Neutrino based on Solid Scintillator) for the remote measurements of the reactor parameters in real scale of time and for probing of short-range reactor antineutrino oscillations to the sterile state.

2. Neutrino Magnetic Moment
In recent years a series of remarkable results were obtained in looking for neutrino oscillations in the experiments with atmospheric, solar and reactor neutrinos. Joint analysis of experimental data provided possibility to conclude that neutrino has a finite mass and to define the process of neutrino states mixing. However, some fundamental neutrino properties are not determined up to now. One of them is a neutrino magnetic moment (NMM). Minimal Standard Model predicts very small value of NMM for a massive neutrino, which cannot be observed in present experiments:

$$\mu_\nu = \frac{3eG_F}{8\pi^2\sqrt{2}} \cdot m_\nu \approx 3 \cdot 10^{-19} \mu_B \cdot \frac{m_\nu}{\text{eV}}$$  \hspace{1cm} (1)

Here $\mu_B$ is Bohr magneton ($\mu_B = eh/2m_e$) and $m_\nu$ is a neutrino mass. On the other hand there is a number of extensions of the theory beyond the SM where the Majorana neutrino magnetic moment could be at the level of $10^{-10} - 10^{-12} \mu_B$ irrespective of the neutrino mass [2, 3, 4], whereas the Dirac neutrino NMM could not exceed $10^{-14} \mu_B$ [5, 6, 7]. Therefore, observation of the NMM value higher then $10^{-14} \mu_B$ would be an evidence for New Physics and, in addition, would indicate undoubtedly that the neutrino is a Majorana particle. That is why it is rather important to make laboratory NMM measurements sensitive enough to reach the $\sim 10^{-11} \mu_B$ region.

A laboratory measurement of NMM is based on its contribution to the neutrino-electron scattering. For nonzero NMM neutrino-electron cross section is given by the sum of standard weak interaction cross section $(d\sigma/dT)_{\text{weak}}$ and the electromagnetic one $(d\sigma/dT)_{\text{EM}}$ [8]:

$$\frac{d\sigma_W}{dT} = \frac{G_F^2 m_e}{2\pi} \left[ \left(1 - \frac{T}{E_\nu}\right)^2 (1 + 2 \sin^2 \theta_w)^2 + 4 \sin^2 \theta_w - 2(1 + \sin^2 \theta_w) \sin^2 \theta_w \frac{m_\nu T}{E_\nu^2} \right]$$ \hspace{1cm} (2)

$$\frac{d\sigma_{\text{EM}}}{dT} = \frac{\mu_\nu}{\mu_B} \frac{\pi e^2}{m_e^2} \frac{1 - 1}{T - \frac{1}{E_\nu}} \right]^2$$, \hspace{1cm} (3)

where $E_\nu$ is the incident neutrino energy, $T$ is the electron recoil energy. At low recoil energy ($T < E_\nu$) the value of $(d\sigma/dT)_{\text{weak}}$ becomes almost constant while $(d\sigma/dT)_{\text{EM}}$ increases as $T^{-1}$, so that lowering of the detector threshold leads to considerable increase of $\mu_\nu$ effect with respect to the weak irremovable contribution. Dependence of differential cross sections of antineutrino-electron scattering on electron recoil energy is shown in figure 1.
3. Experiments GEMMA I and GEMMA II
Our group was the first to propose a germanium detector for the search for NMM in order to decrease the detection threshold and thereby increase sensitivity of the measurements. In our GEMMA spectrometer [9], we used a 1.5 kg HPGe detector with the energy threshold as low as 2.8 keV. Various methods are implemented for the background suppression. The detector is placed inside a cup-shaped NaI crystal with 14 cm thick walls and surrounded by 5 cm of electrolytic copper and 15 cm of lead. This active and passive shielding reduces the external γ-background in the region from 11.2 to 55 keV to the level of ~2 counts/keV/kg/day. Being located just under the reactor #2 of KNPP (at the distance of 13.9 m from the reactor core center) the detector is well shielded against the hadronic component of cosmic rays by the reactor body and technologic equipment (overburden ~70 m. w. e.). The muon component is reduced by a factor of 10 at ±20º with respect to vertical line and 3 at 70º÷80º. Nevertheless a part of residual muons is captured in the massive shielding and produce neutrons that scatter elastically in the Ge detector and raise the low energy background. To suppress this effect the spectrometer is covered with additional plastic scintillator plates which produce relatively long μ-veto signals (figure 2). The data set was collected in operating (“on”) and shut down (“off”) states of the reactor during four years. Analysis of the data resulted in the upper limit on the value of NMM $\mu_\nu < 2.9\cdot10^{-11}\mu_B$. Up to now it’s the best result in the world [10].

At present time we prepare experiment GEMMA II. The measurements will be performed at third unit of KNPP. The detector is installed directly under the core of an industrial 3.1 GW reactor. The distance to the core center as small as 10.7 m can be reached by means of a movable platform (figure 3). At that distance the density of the antineutrino flow is $5.2\cdot10^{13}$ cm$^{-2}$c$^{-1}$. Four point-contact HPGe detectors (~400 g each) produced at LNP JINR will be used for antineutrino registration. The energy threshold is 300 – 350 eV. Sensitivity down to $\mu_\nu \leq 1\cdot10^{-11}\mu_B$ is expected to be achieved within 3 years of operation.

4. The DANSS project
The DANSS project is aimed to create a relatively compact neutrino spectrometer for carrying out fundamental and applied experiments. The detector DANSS is based on a cubic meter of plastic scintillator and designed for remote on-line diagnostics of nuclear reactor parameters and search for short range neutrino oscillations. It is located at KNPP under 3.1 GW LWR unit #4, which provides ~50 m w. e. shield against cosmic muons (6-times muon reduction and no cosmic neutrons). The detector
is placed on a movable platform which allows to change the distance to the reactor core center in the
range 10.7–12.7 m. 2500 scintillator strips (10×40×1000 mm³) with thin Gd-containing surface

![Figure 2. Ge detector inside the active and passive (Cu, Pb) shielding](image2)

![Figure 3. The set up GEMMA II at movable platform under 4-th unit of KNPP](image3)

coating are read out individually by SiPMs and in groups of 50 by PMTs. In addition to the overburden by the reactor the detector has multilayer passive shielding and active muon veto. Passive shielding consists of: electrolytic copper frame ~5 cm, borated polyethylene 8 cm, lead 5 cm, borated polyethylene 8 cm. Active muon veto is formed by double layer 3 cm PS plates from 5 sides of the detector (figure 4). Details of the DANSS detector could be found elsewhere [11].

To detect antineutrinos, the reaction of inverse beta decay (IBD) on a free proton of hydrogen in plastic is used:

\[ \bar{\nu}_e + p \rightarrow e^+ + n. \]  

(4)

The reaction is well studied theoretically and has the largest cross section in comparison with other neutrino processes. In this reaction practically all antineutrino energy above the energy threshold 1.806 MeV is transferred to the positron. And the positron kinetic energy \( T \) is equal to \( E_r - 1.806 \) [MeV]. The problem of separating the reaction (4) from the background is significantly simplified by employing the method of delayed coincidences of the positron ("prompt") and neutron ("delayed") signals. The prompt signal is produced immediately and consists of the positron track ionization and Compton scattering of the two \( \gamma \)-quanta, coming from the annihilation of the stopped positron. The neutron undergoes moderation and then it is captured by gadolinium, which is included in the strip coating. This capture produces a flash of \( \gamma \)-rays with the total energy of about 8 MeV. The time difference between the prompt and the delayed signal is in the tens of microsecond’s range, which produces a very good reaction signature. In our experiment separate recording of positron and neutron candidates is carried out, while the building of the delayed coincidence pairs is performed during “off line” data treatment.

5. Measurement of the reactor thermal power

The possibility of the reactor parameters monitoring with an antineutrino detector is based on the unique dependence of antineutrino spectra and flux densities on the condition and characteristics of nuclear reactors. The counting rate of antineutrino detector \( N \), can be explicitly expressed in terms of the reactor power:
\[ N_\nu = \gamma (1 + k) W_{th} \]  \hspace{1cm} (5)

where \( N_\nu \) is the counting rate of the neutrino detector, \( W_{th} \) is the thermal power of a nuclear reactor, \( \gamma \) is a proportionality factor, and \((1+k)\) is the coefficient taking into account the nuclear fuel composition.

**Figure 4.** Composition of the detector shielding.

It follows from (5) that the reactor power determination accuracy depends on the statistical accuracy of \( N_\nu \) measurements, the systematic error in determination of the proportion factor \( \gamma \), while the coefficient \((1+k)\) varies in the course of the operation period. To measure the reactor power, one should know the factor \( \gamma \) to be determined by calibration of the detector. For detector near reactor core the neutrino counting rate of \( \sim 10^4 \) events/day can be achieved. In this case proportionality factor \( \gamma \) can be determined with about 0.3% accuracy during 10 days of the calibration. The coefficient \((1+k(T))\) is known from calculations with similar accuracy \( \sigma_{(1+k)} \sim 0.3% \) [12]. \( W_{th} \) can be determined using calorimetric measurements with the accuracy of about 0.5% [13]. This leads to total systematic error \( \sigma_S = (\sigma_\gamma^2 + \sigma_k^2 + \sigma_{th}^2)^{0.5} \approx 0.6 \% \). DANSs detector currently takes statistics at full speed of about 5000 antineutrino events per day with background \(< 1\% \). Combining this with the statistical error of 1.4% one gets the total error in the \( W_{th} \) determination of about \( \sim 1.5\% \) in one day of measurement (figure 5).

**6. Searching for “sterile” neutrino**

There are several indications in favor of existence of the 4th neutrino flavor – “sterile”, which also can be seen in oscillations [14]. The oscillation parameters (\( \Delta m^2_{new} > 1.5 \) eV\(^2\) and \( \sin^2(2\theta_{new}) = 0.14\pm0.08 \)) proposed by G. Mention et al. [15] assume relatively short oscillation range. The ideal distance for direct search for such oscillations would be around five to twenty meters from the reactor core. Since the detector DANSs is located just below the core of an industrial reactor it possesses a number of significant advantages in searching for “sterile” neutrino. Firstly, the detector position below the reactor provides high neutrino flux and an overburden of about 50 m w. e., protecting from cosmic muons and fast neutrons. Secondly, the lifting gear allows the detector movement by nearly 2 m and gives opportunity to measure neutrino spectrum at various distances with the same detector. Both spectra are measured in the same experiment with the same detector. No dependence on the theory, absolute detector efficiency or other experiments.

The experiment was started in April 2016. 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). Details of the data set and its treatment...
could be found in [16]. In ‘Up’ detector position about 5000 neutrino events/day in fiducial volume of 78% is recorded with the background not exceeding 1%. The ‘Up’, ‘Middle’ and ‘Down’ positron spectra at total statistics 674489 events collected till May 2017 are shown in figure 6. The spectra shows only pure kinetic energy of the positron (annihilation photons not included). In figure 7 Down/Up positron spectrum ratio is shown. As it seen from the plot the ratio does not contradict to a straight line with current statistics.

Figure 5. IBD flux measured by the DANSS perfectly matches the actual reactor power monitor data, reported by the KNPP.

Figure 6. The ‘Up’, ‘Middle’ and ‘Down’ positron spectra with statistics of 674489 events
Figure 7. The ‘Up’/‘Down’ positron spectrum ratio with statistics by May 2017.

The exclusion region for the parameters of “sterile” neutrinos was calculated using Gaussian CLs method [17] which is more conservative than usual Confidence Interval method. A large fraction of allowed parameter space is already excluded by preliminary DANSS results based on the data sample collected before May 2017 (figure 8). The analysis is performed using only ratio of positron spectrum at different distance (independent on $\nu$ spectrum, detector efficiency). Theoretical curves for each $\Delta m^2$ and $\sin^2(2\theta)$ calculated based on: model neutrino spectrum from Huber and Mueller [18], fuel burning profile from NPP, detector size and detector energy resolution. Systematics studies include variations

Figure 8. DANSS preliminary (95% CL) results for exclusion region for parameters of “sterile” neutrinos. Compilation of allowed region was taken from [19].
This summer DANSS took data during 40 days of the scheduled reactor shutdown, which will allow even better background estimates. Further plans include improvements on MC for perfect reflection of detector energy response and elaboration of analysis methods for better sensitivity.

Acknowledgments
The authors are grateful to the directorates of ITEP and JINR for constant support of this work. The authors appreciate the administration of the KNPP and the staff of the KNPP Radiation Safety Department for permanent assistance in the experiment. This work is supported in part by the Russian State Corporation ROSATOM (state contracts H.4x.44.90.13.1119 and H.4x.44.9B.16.1006) and by the Russian Foundation for Basic Research, grant 09-02-00449. Young JINR physicists were supported by JINR grants 14-202-(07,08), 15-203-(02,03,07,10), 16-202-(03,04), 16-203-(02,03) and Czech Ministry of Education, Youth and Sports INGO II-LG14004. DANSS detector operation and data analysis becomes possible due to the valuable support from Russian Science Foundation grant 17-12-01145.

References
[1] Reines F and Cowen C L 1953 Phys. Rev. 92 830
[2] Voloshin M B, Vysotsky M I and Okun L B 1986 Sov. Phys. JETP 64 446
[3] Fukugita M and Yanagida T 1987 Phys. Rev. Lett. 58 1807
[4] Pakvasa S and Valle J 2003 Neutrino properties before and after KamLAND (Preprint hep-ph/0301061)
[5] Bell N F, Cirigliano V, Ramsey-Musolf M J, Vogel P and Wise M B 2005 How magnetic is the Dirac neutrino? Phys. Rev. Lett. 95 151802 (Preprint hep-ph/0504134)
[6] Bell N F, Cirigliano V, Ramsey-Musolf M J, Vogel P and Wise M B 2006 Magnetic moments of Dirac neutrinos AIP Conf. Proc. 842 874-76 (Preprint hep-ph/0601005)
[7] Giunti C and Studenikin A 2010 J. Phys.: Conf. Series 203 012100 (Preprint hep-ph/2010.1502)
[8] Vogel P and Engel J 1989 Phys. Rev. D 39 3378
[9] Beda A et al. 2007 Phys. At. Nucl. 70 1873 (Preprint hep-ex/0705.4576)
[10] Beda A et al. (GEMMA Collaboration) 2012 The results of search for the neutrino magnetic moment in GEMMA experiment Adv. High Energy Phys. 2012 350150
[11] Alekseev I et al. 2016 JINST 11 11011
[12] Klimov Yu et al. 1994 Neutrino method remote measurement of reactor power and power output Atomic Energy 76 123
[13] Djurcic Z et al. 2008 Uncertainties in the antineutrino production of nuclear reactor (Preprint hep-ex/0808.0747)
[14] Abazajian K N et al. 2012 Light Sterile Neutrinos: A White Paper FERMILAB-PUB-12-881-PDD (Preprint hep-ph/1204.5379)
[15] Mention G et al. 2011 Phys. Rev. D 83 073006 (Preprint hep-ex/1101.2755)
[16] Alekseev I et al. 2016 Preprint ins-det/1606.02896
[17] Qian X et al. 2014 Preprint hep-ex/1407.5052
[18] Huber P 2011 Phys. Rev. C 84 024617
Mueller T A et al. 2011 Phys. Rev. C 83 054615
[19] Achenfelter J et al. 2015 Preprint ins-det/1512.02202