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# Search for elastic coherent neutrino scattering off atomic nuclei at the Kalinin Nuclear Power Plant

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**Abstract**

We propose to detect and study neutrino neutral elastic coherent scattering off atomic nuclei with two-phase emission detector with liquid xenon as a target medium. One of the possible experimental site is a Kalinin Nuclear Power Plant (KNPP) situated in the Russian Federation. In this paper we discuss the design of the detector and expected signals and background for this site.
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## 1. Introduction

There are a lot of predicted physical phenomena, which haven't been experimentally discovered yet. For example non-baryonic dark matter, neutrinoless double beta decay. One of the most interesting processes, predicted by Standard Model (SM), is the coherent elastic neutrino nucleus scattering. Discovery of this process would give additional confirmation of SM and also could be used for nuclear reactor monitoring. This search requires development of detectors responsible to distinguish extremely rare events from background caused by natural radioactivity and cosmic rays.

One of the promising technologies for this challenging task is a two-phase emission detector technology. It is well-known technique for direct dark matter searching. Recently, RED (Russian Emission Detectors) collaboration performed large mass liquid Xenon emission detector for neutrino research. This article is focused on the one of the possible site for our detector – Kalinin Nuclear Power Plant, design of the detector and primarily simulations of expected signal in comparison with different background are presented.

## 2. Search for elastic coherent neutrino scattering at KNPP

### *2.1. Coherent scattering*

Coherent elastic neutrino nucleus scattering was predicted by the SM long time ago [1]. The differential cross section of this process can be given by the formula:

$$\frac{d\sigma}{dE_r} = \frac{G_F^2}{4\pi} Q_w^2 M \left(1 - \frac{ME_r}{2E_\nu^2}\right) F^2(Q^2)$$

where $G_F$ is the Fermi constant, $F(Q^2)$ is the form factor at four-momentum $Q$ and $Q_w = N - (1-4\sin^2(\theta_w))Z$ is the weak charge for a nucleus with $N$ neutrons and $Z$ protons, $\theta_w$ is the weak mixing angle. The total cross section is relatively large which is presented as:

$$\sigma \approx 0.4 \cdot 10^{-44} N^2 (E_\nu)^2 cm^2$$

$E_\nu$is measured in MeV [2]. This formula is valid for neutrinos with energies up to 50 MeV, and thus can be applied to reactor, solar and supernova neutrinos. The dependence of the cross section on the neutron number as $N^2$ provides a significant advantage for detectors using heavy nuclei as a target. Consequently, the compact neutrino detectors can be used for observation coherent neutrino scattering and furthermore for reactor monitoring techniques and nonproliferation tasks [3]. Unfortunately, the reaction has not been measured yet, since the energy of recoil nucleus is extremely low. For example, the energy of Xenon recoil nucleus is below 1 keV for neutrinos produced at nuclear power plant. Detectors for this research require large mass, high efficiency for sub-keV signals and low background level. There are several directions of development detectors for searching coherent scattering: low noise Germanium detector [4], low background NaI detectors [5], and noble emission detectors [6,7,8]. We are studying the last one technology since its capability to measure low signals, compactness and good scalability up to several tones in the future.

### *2.2. Emission detector RED-100*

The emission method of particle detection was invented about 40 years ago [9]. It can be used for construction of so called “wall less” detectors, that make them attractive for low background experiments [10]. Also this technique allows detection of single ionization electron, generated in target medium, such as condensed noble gases. Nowadays emission detectors are widely used for cold dark matter searching in assumption that it manifests itself as weakly interacting massive particles (WIMPs). Neutrino coherent scattering off heavy nuclei must have the same signature as a WIMP's signal. Two-phase emission detector operates as follows (Fig. 1):

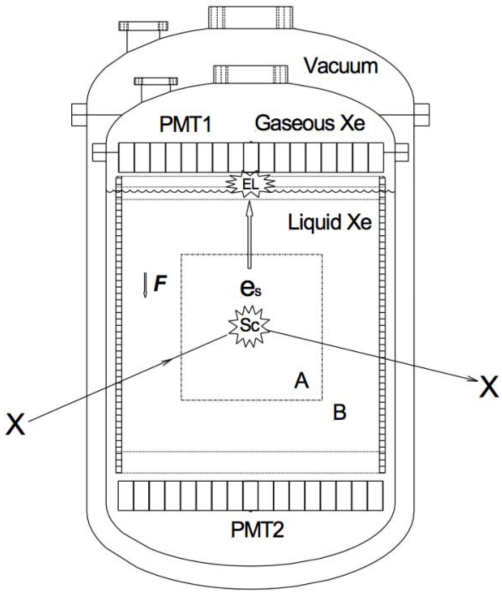


Fig. 1. Operation principle of two-phase «wall less» detector with liquid xenon as a target medium. Sc — scintillation flush generated by interaction of particle X with Xe atoms; EL — electroluminescence flush in the gaseous state generated by electrons extracted from liquid state by electric field F; PMT1 and PMT2 — arrays of PMTs responsible for detection Sc and EL; A — the fiducial volume; B — liquid xenon used as an active shield for fiducial volume. The active volume is surrounded by a highly reflective cylindrical teflon reflector with electrode structure providing uniform electric field F. The detector is enclosed in the vacuum cryostat made from low-background titanium.

1. Radiation interacts with the target (liquid xenon in our case), ionizing and exciting atoms. Excitement of atoms is released by emission of characteristic photon. This scintillation signal can be registered and used as a trigger.
2. Ionization electrons drift under external electric field to the surface of the condensed state where they pass to the gaseous state through the surface potential barrier. In the gas, under strong external electric field, electrons attain enough kinetic energy for exciting atoms of the gas. Thus secondary scintillation (so called electroluminescent) is generated.
3. Both primary and secondary scintillations are measured by photodetectors. With a set of photodetectors one can reconstruct the coordinates of the original event in the plane of the set. Using the time delay between two scintillation signals corresponded to electron drift time the third coordinate can be derived.
4. Fiducial volume (A, Fig. 1) can be determined using three-dimensional reconstruction. Huge amount of target medium with a high stopping power around the fiducial volume suppress background caused by radioactivity of detectors parts. It can be also used as an active shield to reduce background in fiducial volume correlated with interactions in outer volume.
5. Further analysis of scintillation and ionization signals can reject background as well.

The RED-100 is the two-phase emission detector being under construction in correspondence with its schematic computer model showed at the Fig. 2. The detector consist of vacuum cryostat made from titanium for maintenance xenon in liquid state. There is an electrode structure in the cryostat for applying an electric field to the liquid xenon. It consists of grid cathode at the bottom, electrode field-shaping rings and grid electrodes used for making strong electric field in the electroluminescent gap. Target medium included in the electrode system is being watched by PMT R11410-20 developed by Hamamatsu special for low-background emission detectors with liquid xenon as a target medium. These PMTs were made for cryogenic temperatures (-100 °C), quantum efficiency for the 175 nm wavelength is about 30%. RED-100 has two sets with 19 PMT in each, one under the grid cathode and one at the top of target medium. Owing to extended electroluminescent gap to 11 mm thick approximately we expect amplification such as 80 photoelectrons per one ionization electron. This will allow us to distinguish real events from single photoelectrons noise.

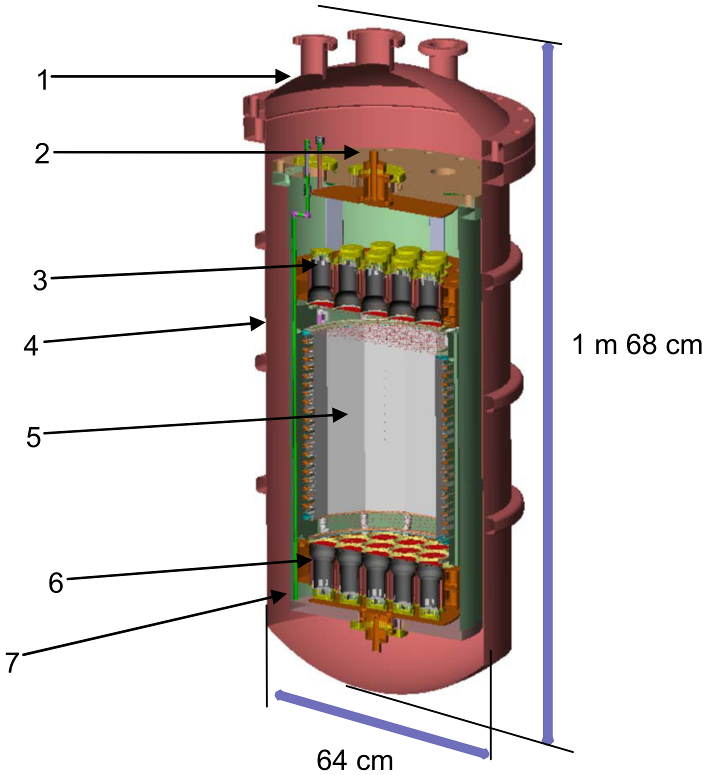


Fig. 2. The computer model of the detector RED-100. 1 — Titanium warm vessel; 2 — Thermosyphone cold head; 3,6 — Arrays of 19 PMTs in each in a copper holders; 4 — Copper termoscreen; 5 — Teflon drift chamber filled with liquid xenon and electrode structure; 7 — Titanium cold vessel.

*2.3. Neutrino elastic coherent scattering experiment at KNPP*

Despite the RED-100 will likely move to SNS at the Oak Ridge National Laboratory of USA for the first observation of neutrino coherent scattering on nuclei, there is a possibility to carry out the experiment at the Kalinin Nuclear Power Plant. The nuclear reactor produces huge amount of electron anti-neutrinos in beta decays of radioactive neutron-rich products of fission. The neutrino flux depends on composition of fuel in the reactor core, therefore, can be used for reactor monitoring. The reaction of coherent neutrino scattering if observed could be used for reactor monitoring as well [3]. So we are looking forward to carry out the experiment at this site.

The Kalinin Nuclear Power Plant is equipped with four WPR-type nuclear reactors with 3 GW power each. The local background was measured by experiments GEMMA [11] and DANSS [12] which are already installed at one of the unit. The possible place for our experiment is in the underground gallery bellow the reactor core in 19 meters from it.

This site is overburden by 70 meters of water equivalent (m.w.e.) in vertical direction (if we take into account the reactor core, its shielding and construction elements) against cosmic rays and provides about 20 m.w.e. at 60-70$^{o}$.

We expect reduction of cosmic muon flux in a factor of 5. The hadron component of cosmic rays will be eliminated [13].

An expected antineutrino flux at the distance of 19 m from reactor core is about $1.35*10^{13}cm^{-2}*s^{-1}$. We expect about 38000 events per day in the fiducial volume of 100 kg of liquid xenon. Since nuclear recoils produce only a few ionization electrons, the single electron noise can be a problem for events registration. Single electron emission is spontaneous process observed in two-phase emission detectors. This noise is associated with thermal electron emission of ionization electrons accumulated under the liquid surface [14]. On the Fig. 3 there is a result of our simulation for antineutrino signal vs single electrons noise. Peaks on the antineutrino scattering curve correspond to detection of one, two and so on ionization electrons. It is seen that huge background caused by single electrons noise can be avoided if we require threshold at the level of three and more electrons per event. In this assumption the rate of antineutrino coherent scattering events per day will be reduced to 433 approximately.

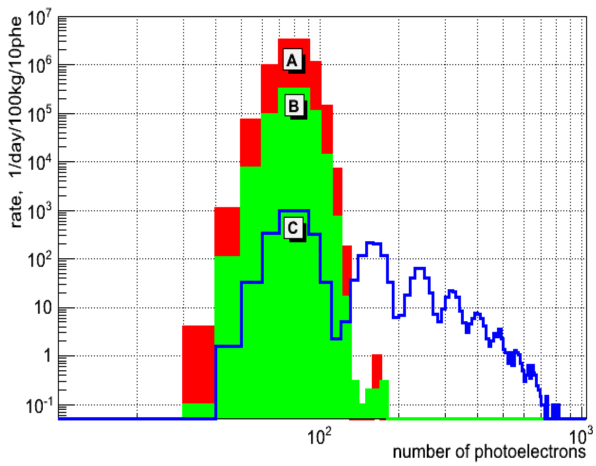


Fig. 3. The simulation of the single emission electron noise in the RED-100 at two rates of 100 Hz (A) and 10 Hz (B) and neutrino coherent scattering (C).

The background estimation is running now on the computer model of the detector and GEANT-4, but we have already had a preliminary results. It includes background from the natural radioactivity of the internal and external components, neutrons generated by cosmic rays, and $^{85}$Kr distributed within Xe volume. It was used only fiducial volume of 100 kg of liquid xenon from 200 kg of total mass for self-shielding.

For estimation background caused by detector components, the data from general database was used. Recently we received data on the radioactivity of exactly our detector components, so new set of calculation is being carried on. Preliminary results, obtained with general dataset can be founded in the Table 1. At the region of interest, the background caused by $^{85}$Kr has rate about 0.5 events per day which is not significant.

Table 1. The natural radioactivity of detector components

| Component (material) | $^{238}$U | $^{232}$Th | $^{40}$K | $^{60}$Co | $^{137}$Cs |
|---|---|---|---|---|---|
| PMT (mBq/unit) | 0.4 | 0.3 | 8.3 | 2.0 | - |
| Cryostat (Titanium) (mBq/kg) | 0.2 | 0.25 | 0.93 | - | - |
| Reflector (Teflon) (mBq/kg) | 2 | 2 | 15 | 5 | 1 |
| PMT support / heat exchanger (Copper) (mBq/kg) | 2 | 1 | 4 | 1 | 0.5 |

The radioactivity from external environment was measured by GEMMA collaboration at the possible location at KNPP [11]. Simulation gave rate 30 events per day in our detector at the energy range of interest (below 1 keV). It is at least 10 times smaller then the background rate from internal components. Also according GEMMA measurements the neutron flux from the reactor core does not depend on the reactor operates or not since the location is well isolated from reactor core. That's mean, we should focus on the cosmic rays as the second main contributor to the total background.

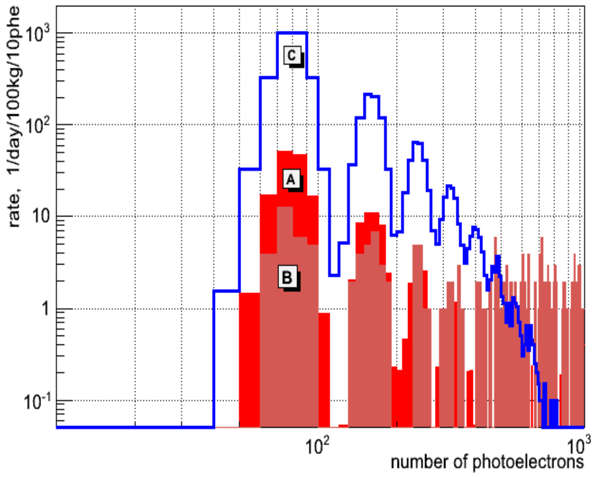


Fig. 4. The simulation of the background caused by detector components (A), by neutrons of cosmic rays (B) in comparison with simulation of coherent neutrino scattering (C).

As it was mentioned before it is muon component which produce the main part of the background associated with cosmic rays at the detectors disposal. Original muons don't contribute much to the low energy rang also they and their products can be vetoed by plastic scintillation «umbrella» covering the RED-100. The most dangerous background generated by muons and cannot be avoided is the neutrons both prompt and cooled down after number of scattering in the shielding. Simulation of this background was done with several assumptions. According to GEMMA measurements the muon flux is reduced with a factor of 5 from Earth surface level. GEMMA is situated one step up from the RED-100 possible site, but we used factor 5 as a pessimistic variant since we haven't got any calculation of muon flux at our disposal. Also we used in our calculations the same energy spectrum of neutrons as it is at the level of Earth surface [15].

The preliminary result on summary of backgrounds from internal detector structure components radioactivity (A), cosmic neutrons (B) together with expected signal (C) is presented on the Fig. 4.

As the expected signal is at a level of several order of magnitude higher then background we propose our detector as a compact tool for different tasks of reactor monitoring. We are carrying on the simulation of several reactor parameters which could be obtained by our neutrino detector. At the Fig. 5 one can find preliminary results of this simulations.

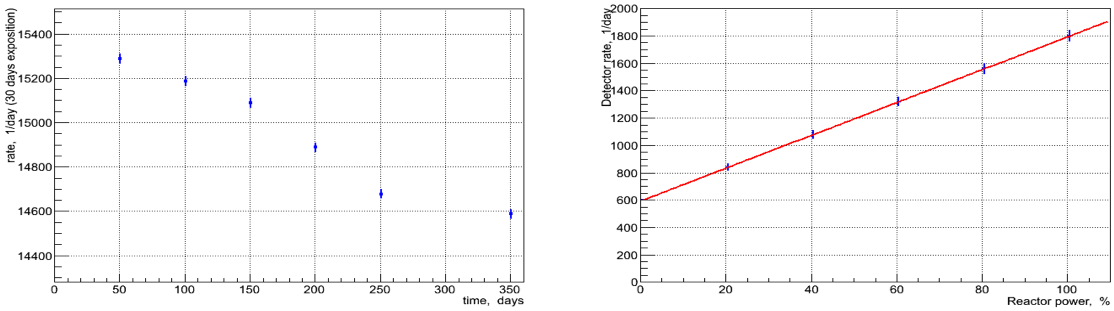


Fig. 5. Preliminary simulation of antineutrino flux evolution (on the left site) during the 350 days of reactor cycle and simulation of reactor power monitoring (on the right site) using the coherent neutrino scattering and RED-100 as a tool.

## 3. Conclusion

We proposed the two-phase xenon detector responsible to detect neutral coherent neutrino scattering on heavy nuclei. We have been studying the environmental conditions at one of the possible detector site, KNPP. Computer model showed possibility of usage our detector for detect and study coherent neutrino scattering at this disposal. Furthermore, it is possible to use this process and our detector as a tool for different reactor monitoring tasks: monitoring of output power; monitoring of burn-up effect; monitoring of critical situations.

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