RED-100 detector for the first observation of the elastic coherent neutrino scattering off xenon nuclei

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Abstract. The RED-100 (Russian Emission Detector) is being constructed for the experiment to search for elastic coherent neutrino scattering off atomic nuclei. This fundamental process was theoretically predicted several decades ago [1]. This is a neutral current process with a cross-section approximately proportional to N^2 (where N is the number of neutrons in the nucleus) due to the coherence enhancement factor. In order to carry out the experiment the RED-100 is a two-phase emission xenon detector containing ~200 kg of the liquid Xe (~ 100 kg of that is in a fiducial volume). One of the possible sites to study neutrino properties. The energy spectrum of neutrinos produced at the SNS extends up to ~ 50 MeV and satisfies coherence condition. These neutrinos give kinetic energies of Xe recoils up to a few tens of keV where the response of nuclear recoils is well-known from neutron calibrations of dark matter detectors. The detector will be deployed 30 meters from the SNS target. The expected signal and background are estimated for this specific location. The detector details, current status and future plans are provided.

1. Introduction

Coherent elastic neutrino-nucleus scattering (CENNS) was theoretically predicted more than 40 years ago [1]. This is a neutral current process with a cross-section approximately proportional to N^2 (where N is the number of neutrons in the nucleus) due to the coherence enhancement factor. In order to...
satisfy the coherence condition, neutrinos with energies less than 50 MeV are mostly preferred. The clear understanding of coherent neutrino scattering behavior can be employed for explaining several fundamental physics models. For example, CENNS reaction plays important role in supernova core-collapse processes [2]. As a probe of the Standard Model, any measured deviation from prediction could be an indication of new physics [3]. Moreover, the precise knowledge of coherent neutrino scattering cross-sections in the energy range of solar and atmospheric neutrinos is vitally important for the sensitivity of the next generation direct dark matter detection experiments where neutrinos are an irreducible background [4].

The international collaboration COHERENT has recently been established with the main goal to discover coherent neutrino scattering at SNS (Spallation Neutron Source), Oak Ridge National Laboratory, USA. SNS is a proton accelerator that provides the most intense pulsed neutron beams in the world. Although SNS primarily is constructed for the neutron production, neutrinos with energies up to 50 MeV are created as by-products of stopped pions decaying in the spallation liquid mercury target. The pulsed structure of the beam, high neutrino flux and appropriate energy spectrum make SNS the most attractive site for the first CENNS observation. Although the rate of events for medium-A nuclei is relatively high compared to the conventional neutrino detection processes like elastic neutrino-electron scattering or inverse beta decay reactions, CENNS still remains unobserved due to low energy of nuclear recoils resulted from the neutrino interaction. The energy of the recoils lies in the range of a few keVs or less. Modern low-background detectors for dark matter search have quite well-known response in this energy region that hopefully allows to apply a similar technique for coherent neutrino scattering detection.

It was decided that the best way to unambiguously discover CENNS and investigate $N^2$ dependence is to use three detector systems (CsI[Na] scintillation crystals, p-type point-contact germanium detectors, and a two-phase liquid xenon time projection chamber (TPC)). In the framework of this joint effort, we propose to use the RED-100 detector as one of suggested technologies. The RED100 is a two-phase liquid xenon time projection chamber that now is fully assembled and commissioning at NRNU MEPhI. It is supposed that the detector will be shipped to USA for installation at the experimental site at SNS in the short-term future.

2. Two-phase emission detector technology

The two-phase principle of particle detection was invented about 40 years ago [5]. Particles interacting with dense noble liquefied gas medium produce excitation and ionization. The excitation creates prompt scintillation ($S_1$ signal). Under the influence of the applied electric field ionization electrons drift along the field towards the surface and then enter the gas phase where produce proportional scintillation or electroluminescense ($S_2$ signal). The time difference between $S_1$ and $S_2$ signals defines the $Z$ position of the event, while the $X$-$Y$ position is determined from the pattern of $S_2$ light in the photodetecting system. The 3D event reconstruction allows to define a fiducial volume eliminating potential background events originated in the vicinity of the detector walls. Measurement of the ratio of $S_2$ to $S_1$ signals gives an ability to discriminate between electron recoils and nuclear recoils providing an efficient background rejection.

3. RED-100 detector design

In addition to the TPC enclosed in a vacuum cryostat, the RED-100 experimental setup (photo is shown in figure 1b) consists of several ancillary systems. These systems are cryogenics; xenon purification; light collection, electronics and data acquisition; interface breakout-out-box.

3.1. Cryostat and internal structure

The RED-100 cryostat consists of two cylindrical vessels made of VT1-00 titanium. The outer vessel (168 cm in height and 64 cm in diameter) is utilized to hold a vacuum to insulate the inner cold vessel (108 cm in height and 50 in diameter) from external heat load. The cold vessel upper flange is attached to the outer vessel upper dome flange via three hangers thermally isolated in plastic and three flexible
bellows. The flanges of both cans are designed for Helicoflex sealing. The detector drawing is shown in figure 1. The inner vessel contains a field cage and ~200 kg of liquid xenon. The field cage is a dodecagonal structure formed by PTFE light reflection panels and enclosing the detector active volume viewed from above and below by two arrays of 19 PMTs each.

Five electrodes: cathode, anode, gate and two shield grids define an electric field inside the detector and are embedded in the PTFE structure. There are 20 copper field-shaping rings between the cathode and anode grids. The field-shaping rings are connected to each other with a 1 GΩ resistor ensuring a uniform electric field. All grids are fabricated in the form of two stainless steel rings pressing a stainless steel mesh (90% open area) with screws. The distance between the cathode and anode grids is 43 cm. The liquid level is set halfway between the anode and gate grids, which are separated by 2 cm. The top (6 cm to the anode) and bottom (5 cm to the cathode) shield grids prevent the high electric field influence from the adjacent electrodes at the PMT photocathode. The field cage is joined to both PMT arrays with six Ti straps. Every PMT is placed inside a Cu holder that is inserted in a copper 10 cm thick PMT support disc. All copper details are M1 OFHC grade. Gaps between PMT windows in the array are covered with PTFE reflectors for improving light collection.

Figure 1. a) Rendering of RED-100 detector: 1) Outer Ti vessel 2) Inner Ti vessel 3)Top PMT array 4) Drift cage with PTFE reflectors 5) Bottom PMT array; b) RED-100 detector at NRNU MEPhI during technical run

3.2. Break-Out-Box

In order to provide a compact detector location inside a passive shielding and minimize amount of radioactive materials near the detector, so called Break-Out-Box (BOB) was constructed. BOB is placed on a mobile platform and connected to the detector inner vessel through three flexible 4 m in length stainless steel bellows. The first bellow is packed with PMT high voltage/signal and instrumentation cables. The other conduit contains three grid high voltage cables. The last comprises a xenon heat exchanger designed in the form of two flexible bellow hoses (for incoming and outcoming flow) passed inside each other. Decoupler boxes for PMT cables, HV bandwidth filters and a commercial ceramic vacuum feedthrough for the cathode HV (up to 50 kV) are instrumented in the BOB structure. The BOB is connected to a gas purification system with two 4 m long flexible hoses.
3.3. Cryogenics
To keep the RED-100 detector at LXe temperatures we developed a cryogenic system based on thermosyphon technology [6]. This system is economical, possesses high cooling power and is capable of maintaining stable temperature throughout the detector operation. A thermosyphon (gravity assisted heat pipe) is a closed tube filled with gaseous nitrogen and consists of three sections: 1) at the top, condenser immersed in a LN$_2$ Dewar; 2) at the bottom, evaporator attached to the detector inner vessel and 3) passive adiabatic copper pipe, connecting two active sections. In RED-100 we use four thermosyphons (adiabatic section length varies from 2 to 3.5 m) with total cooling power up to 400 W. The most powerful thermosyphon (16 mm in diameter tube) through evaporator section is attached to a massive copper disc inside the detector inner vessel. This disc plays a role of a cold head serving as a heat sink for cables and providing cooling power for xenon condensation. Other thermosyphons (12 mm in diameter tube) are attached to the bottom and copper thermal shield surrounding the detector inner vessel to maintain a temperature gradient along the vertical direction. The temperature is monitored with ADAM 6015 module utilizing the signal from Pt-100 temperature sensors. This thermosyphon configuration showed stable performance with temperature accuracy better than 1 K. The thermosyphons operate in a dynamic regime by adjusting amount of N$_2$ in the tube. The bottom thermosyphon cold head is equipped with three 100 W heaters assisting LXe recovery.

3.4. Xenon purification system
The operation of LXe emission detectors requires a very low level of electronegative and molecular impurities. In order to achieve reasonable electron lifetime (several meter drift lengths) we constructed a purification system. The purification is accomplished by continuously circulating xenon gas with a double-diaphragm pump through a SAES MonoTorr hot getter. To evaporate LXe (getter works only with gas), liquid is sucked out through a thin tube from the detector bottom by the circulation pump. The heat exchanger is used to mitigate heat load from the condensation of returning gas. Gaseous xenon is stored in 50 liter Luxfer aluminum cylinders placed on weigh scales.

3.5. Light collection, electronics and data acquisition
Since our detector is a light detection device we use a low radioactive 3-inch Hamamatsu R11410-20 photomultiplier tube specially designed for LXe low-background experiments. All PMTs were characterized in terms of single photoelectron response and dark count rate before the implementation in the internal structure. The voltage divider boards are made of Cirlex and supply a positive bias voltage to the PMT with a total resistance of 18.5 MΩ. The performed tests demonstrated that these PMTs satisfy the detector requirements, however, an unusual behavior was noticed for several PMT units [7]. All PMTs were installed in top and bottom arrays according to their quantum efficiency and noise characteristics. To exclude PMT performance deterioration from a bright light, a special circuit was designed to switch off the tubes in case of a cosmic muon crossing the TPC [8]. The electronic system amplifies signals from PMTs and sends it to registration without shaping. We use CAEN V1730 FlashADC fast digitizers with 500 MSmps speed and 14-bit resolution to record waveforms of signals. Waveforms are stored in computer for offline processing. The trigger system is based on specific digital module built on CAEN V1495 board and allows to use a flexible selection criteria with a threshold as low as a single ionization electron [9]. Testing of DAQ system is underway now.

4. Prospects for CENNS observation with RED-100 at SNS
A 1 GeV proton beam hits the liquid mercury target in 700 ns wide bursts with a 60 Hz frequency. The proton interaction produces π$^-$-mesons which are stopped in the target and decay at rest. These pion decays yield a 30 MeV monochromatic $\nu_\mu$ flux (prompt neutrinos), followed within 2.2 $\mu$s interval by $\bar{\nu}_e$ and $\nu_e$ with a few tens of MeV energy from $\mu^+$ decays (delayed neutrinos). During a background measurement campaign several possible deployment sites at SNS were studied. The background measurements indicated that the beam-related neutron count in the basement
hallway is four orders of magnitude lower than that in the experimental floor. Moreover, the basement location is protected from cosmic rays by 8 m.w.e. of overburden. The RED-100 response has been simulated taking into consideration the expected neutrino flux at this particular site. The computational model is based on Geant4 and NEST package, describing interactions of charged particles in noble gas based detectors. According to this model, an optimal passive shielding configuration is 10-15 cm of lead and 15 cm of water. Backgrounds from the radioactivity of internal components, external gammas and neutrons from the SNS and induced by cosmic muons were all considered. Approximately 1,700 CENNS events per year are expected for delayed neutrinos under the condition $S_1 \geq 2$ ph.e. This allows to apply 1 $\mu$s timing cut to eliminate beam-coincident fast neutron backgrounds. The background simulation shows that the expected background is an order of magnitude less than the signal from coherent neutrino scattering. A 5$\sigma$ measurement of CENNS is expected within a few months of operation.

5. Conclusion
The process of coherent elastic neutrino-nucleus scattering can be discovered with the two-phase liquid xenon RED-100 detector. During a background measurement campaign, it was found out that the best site for deploying the detector is the basement of SNS. For this particular place the detector expected signal and background simulations were performed, showing that RED-100 has a great potential for the first CENNS observation. The detector design and details are described. The RED-100 is under commissioning now at NRNU MEPhI and then will be transferred to SNS.

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