Prospects of detecting the QCD phase transition in the Galactic supernova neutrino burst with 20-kton scale liquid scintillation detectors

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Abstract. The supernova explosion in the Galaxy is a rare event; that is why the comprehensive study of the next one has absolute priority for the low-energy neutrino astronomy. Because the detailed explosion mechanism has not been unambiguously identified yet and the surrounding matter envelope is opaque for photons, the neutrinos only can give information about physical conditions, dynamics of the collapse, and the SN mechanism. Furthermore, neutrinos could potentially reveal new physics (e.g. QCD phase transition) operating deep in the stellar core.

Keywords: Supernova, Neutrino Bursts

1. Introduction

Observing a high-statistics neutrino signal from supernova explosions in the Galaxy is the major goal of the low-energy neutrino astronomy. The prospects for detecting all flavors of neutrinos and antineutrinos from a core-collapse supernova (ccSN) in operating and forthcoming large liquid scintillation detectors (LLSDs) are widely discussed now. The new-generation large liquid scintillation detectors must have the capability to distinguish the various detection channels. Large statistics must be collected to study spectra and time profiles of all neutrino flavors, thereto the new detectors should have enough large target mass. The peculiarities in the neutrino signal from the ccSNe can also be detected in the forthcoming LLSD.

The QCD phase transition during the postbounce evolution of core-collapse supernovae can be observable as the second peak in a neutrino signal that is accompanied by significant changes in energy of emitted neutrinos [1]. In contrast to the first neutronization burst, this second neutrino burst is dominated by emission of antineutrinos. This circumstance is useful for detection of this peak due to the high cross section of inverse beta decay reaction [2].

2. Next-generation detectors

2.1. The proposed LLSD

The large liquid scintillation neutrino detectors, such as JUNO [3, 4], RENO-50 [5] and LENA [6], are under consideration now. The proposed LLSDs are being planned for a variety of physics reasons. These include determination of the neutrino mass hierarchy, precision measurement of neutrino parameters, detection of supernova neutrinos, solar neutrinos, geoneutrinos, sterile neutrinos, atmospheric neutrinos, nucleon decay, and many other exotic searches.

JUNO will have an inner volume of 20 kton and RENO-50 is being designed to have an inner volume of 18 kton. LENA will have a much larger target mass of liquid scintillator, 50 kton. At low energies, the variety of detection channels available in liquid scintillator will allow us making the energy- and flavor-resolved analysis of a neutrino burst emitted by a galactic supernova. Due to target mass and background conditions, LENA will also be sensitive to the faint signal of the Diffuse Supernova Neutrino Background.

2.2. Baksan Large Volume Scintillation Detector (BLVSD)

One of the proposed LLSDs is the Baksan Large Volume Scintillation Detector (BLVSD). This detector will be installed at the Baksan Neutrino Observatory (BNO) of the Institute for Nuclear Research, Russian Academy of Sciences, at a depth of 4800 m.w.e. (Fig. 1).

A large volume detector filled with liquid scintillator at the Baksan Neutrino Observatory has been discussed for a long time [7], [8], [9], [10], [11]. The main research activities of BLVSD are neutrino geophysics and neutrino astrophysics. At present R&D work aimed at creation of a new-generation detector using an extra-pure scintillator of 5 – 20 kiloton mass is performed [12], [13], [14], [15], [16], [17].

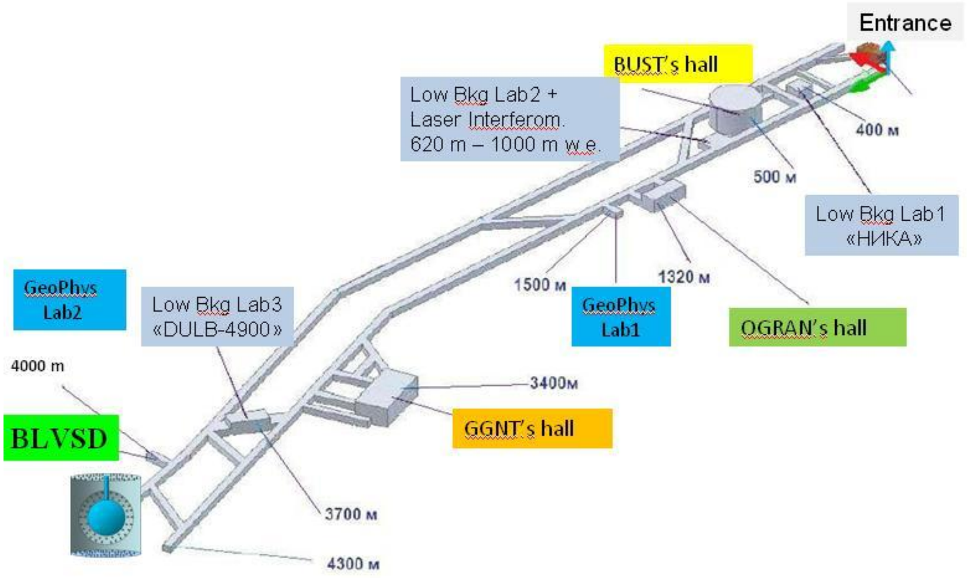

Fig1. *Schematic view of the underground laboratories of the Baksan Neutrino Observatory of INR RAS.*

The recent development of new experimental techniques has opened up an opportunity for a new kind of large-scale detectors capable both to detect all flavors of neutrinos and to reconstruct the supernova location. The approach exploiting the glowing track of a charged particle is under development now in INR RAS [16], [17]. A charged particle traversing a liquid scintillator induces scintillation along its track. At each point of the track the produced light is emitted isotropically. The use of suitable multi-pixel photodetectors (such as CCD or SiPM matrices) with appropriate optical collector gives, in principle, a possibility to do a snapshot of this glowing track. This technique has obvious advantages. Firstly, the snapshot of glowing track of a particle gives a possibility in principle to determine the direction of the particle. Secondly, there is a possibility to measure the energy release along the particle track. But there are some challenges with this method. One of them is that, as opposed to PMTs, each photodetector has a large number of channels. Moreover, for the precise study of detected events the target mass of the new detector should not be too large [16]. On the other hand, large target mass of the detector is needed for obtaining large statistics of neutrino events. Nevertheless, this apparent contradiction can be resolved by creating a network of identical LLSDs, with the target mass of LLSD in the range of 2 – 5 kilotons. The Baksan Neutrino Observatory is one of the optimal sites for location of a detector of the network.

3. Detecting the QCD phase transition in the ccSN neutrino burst

Simulations of the stellar core-collapse with the QCD phase transition predict a sharp burst of electron antineutrinos several hundred milliseconds after the prompt electron neutrinos neutronization burst [1]. Observational signatures of such electron antineutrinos burst at current neutrino detectors – IceCube and Super-Kamiokande – were studied in paper [2]. It was found that signatures of the QCD phase transition can be detected for a Galactic ccSN, regardless of the neutrino oscillation scenario.

Super-Kamiokande is an imaging water Cherenkov detector containing 50.0 kilotons of pure water; but the usual fiducial mass for neutrino measurements is 22.5 kton, with the approximately 1.5×10^{33} free protons [18]. Figure 2 (taken from paper [2]) shows the reconstructed antineutrino event rates expected in Super-Kamiokande for the normal mass hierarchy in square points (blue) with statistical error bars. The range of allowed rates for other possible oscillation scenarios is shown by the shaded band (red). One can see that the QCD burst would produce approximately 60 excess events in two relevant bins. The statistics of antineutrino events allows us identifying the QCD burst even at a ccSN distance of 20 kpc. It is very important because within this distance more than 95% of expected Galactic ccSNs are contained [19].

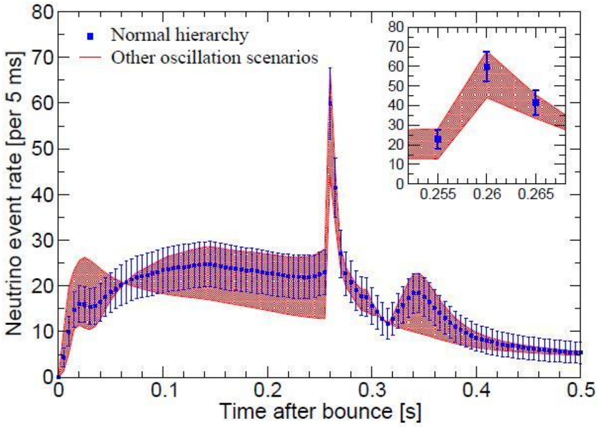

Fig2. Reconstructed antineutrino event rates at Super-Kamiokande (the inset shows the enlarged second burst). This figure is taken from paper [2] (arXiv:0912.2568v2).

The LLSD with fiducial mass of 20 kton and linear-alkyl-benzene (LAB) as a solvent contains approximately 1.49×10^{33} free protons. This means that such LLSD can recognize the QCD burst from a Galactic ccSN in the same fashion as the Super-Kamiokande detector.

4. Conclusion

The proposed large liquid scintillation neutrino detectors are acceptable to detect all flavors of neutrinos from the Galactic core-collapse supernova and to measure the total and average energy in each. Possible detection strategies to measure the total and average energy of all supernova neutrino flavors with appropriate precision are being developed [20]. The QCD phase transition during the postbounce evolution of core-collapse supernovae can be observable by LLSD with a target mass of 20 kton or more. Such LLSD can recognize the QCD burst from almost any Galactic ccSN.

Acknowledgements

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