A search for neutrino bursts in the Galaxy at the Baksan Underground Scintillation Telescope

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Abstract. The experiment on recording neutrino bursts operates since the mid-1980. As the target, we use two parts of the facility with the total mass of 240 tons. Over the period of June 30, 1980 to December 31, 2017, the actual observational time is 32.1 years. No candidate for the stellar core collapse has been detected during the observation period. An upper bound of the mean frequency of core collapse supernovae in our Galaxy is 0.072 year$^{-1}$ (90% CL).

1. Introduction
The detection of neutrinos from the supernova SN1987A experimentally proved the critical role of neutrinos in the explosion of massive stars, as it was suggested more than 50 years ago [1, 2, 3].

Due to their high penetration power, neutrinos deliver information on physical conditions in the core of the star during the gravitational collapse. SN1987A has become the nearest supernova in the past several hundred years, which allowed the SN formation process to be observed in unprecedented detail beginning with the earliest time of radiation. It was the first time that a possibility arose for comparing the main parameters of the existing theory – total radiated energy, neutrino temperature, and neutrino burst duration – with the experimentally measured values [4, 5].

Since light (and electromagnetic radiation in general) can be partially or completely absorbed by dust in the galactic plane, the most appropriate tool for finding supernovae with core collapse is a large neutrino detector. In the past decades (since 1980), the search for neutrino bursts was carried out with such detectors as the Baksan Scintillation Telescope [6, 7], Super-Kamiokande [8], MACRO [9], LVD [10], AMANDA [11] and SNO [12]. Over the years, our understanding of how massive stars explode and how the neutrino interacts with hot and dense matter has considerably increased. At present the scale and sensitivity of the detectors capable of identifying neutrinos from a Galactic supernova have grown considerably so that current generation detectors [13, 14, 15] are capable of detecting of order ten thousand neutrinos for a supernova at the Galactic Center.

The Baksan Underground Scintillation Telescope (BUST) [16] is the multipurpose detector intended for wide range of investigations in cosmic rays and particle physics. One of the current tasks is the search for neutrino bursts. The facility has been uninterruptedly used for this
purpose since the middle of 1980. The total galaxy observation time amounts to 90% of the calender time.

2. The method of neutrino burst detection

The BUST consists of 3184 standard autonomous counters arranged in four horizontal and four vertical planes. Each counter is $0.7 \times 0.7 \times 0.3$ m$^3$ in size, filled with an organic scintillator $C_nH_{2n+2}$ ($n \approx 9$), and viewed by one photomultiplier with a photocathode diameter of 15 cm [16]. A counter pulse channel has an operation threshold $8$ MeV and $10$ MeV for the horizontal and vertical planes, respectively (the most probable energy deposition of a muon in a counter is $50$ MeV is a relativistic particle). The total scintillator mass is $330$ t, and the mass enclosed in three lower horizontal layers (1200 standard counters) is $130$ tons. The majority of the events recorded with the Baksan telescope from a supernova explosion will be produced in inverse beta decay (IBD) reactions

$$\bar{\nu}_e + p \rightarrow n + e^+ \tag{1}$$

If the mean antineutrino energy is $E_{\nu_e} = 12 - 15$ MeV [17, 18] the path of $e^+$ (produced in reaction (1)) will be confined, as a rule, in the volume of one counter. In such case the signal from a supernova explosion will appear as a series of events from singly triggered counters (one and only one counter from 3184 operates; below we call such event "the single event") during the neutrino burst. The search for a neutrino burst consists in recording of single events cluster within time interval of $\tau = 20$ s (according to the modern collapse models the burst duration does not exceed $20$ s).

The expected number of neutrino interactions detected during an interval of duration $\Delta t$ from the beginning of the collapse can be expressed as:

$$N_{\nu e}^H = N_H \int_0^{\Delta t} dt \int_0^\infty dE F(E, t) \cdot \sigma(E) \eta(E), \tag{2}$$

here $N_H$ is the number of free protons, $F(E, t)$ is the flux of electron antineutrinos, $\sigma(E)$ - the IBD cross section, and $\eta(E)$ is the detection efficiency. The symbol "H" in left side indicates that the hydrogen of scintillator is the target.

If one assumes the distance from the SN is $10$ kpc, the total energy irradiated in neutrinos is

$$\varepsilon_{\text{tot}} = 3 \times 10^{53} \text{ erg} \tag{3}$$

and the target mass is $130$ t (three lower horizontal layers) the expected number of single events from reaction (1) (we assume that the antineutrino temperature is $k_B T = 3.5$ MeV) will be

$$N_{e^+}^H \simeq 35 \tag{4}$$

Flavor oscillations are unavoidable of course. However, it was recognized in recent years that the expected neutrino signal depends strongly on the oscillation scenario (see e.g. [19, 20, 21, 22]). In the absence of a quantitatively reliable prediction of the flavor-dependent fluxes and spectra it is difficult to estimate the oscillation impact on $\nu_e$- and $\bar{\nu}_e$ fluxes arriving to the Earth. Therefore we do not discuss the effects of flavor oscillations in this work.

Background events are i) radioactivity (mainly from cosmogeneous isotopes) and ii) cosmic ray muons if only one counter from 3184 hit. The total count rate from background events (averaged over the period of 2001 – 2017 years) is $f_1 = 0.0207$ s$^{-1}$ in internal planes (three lower horizontal layers) and $\simeq 1.5$ s$^{-1}$ in external ones. Therefore three lower horizontal layers are used as a target; below, we will refer to this counter array as the D1 detector (the estimation (4) has been made for the D1 detector).
Background events can imitate the expected signal (k single events within sliding time interval \( \tau \)) with a count rate

\[
p(k) = f_1 \times \exp(-f_1 \tau) \frac{(f_1 \tau)^{k-1}}{(k-1)!}
\]

The treatment of experimental data (single events over a period 2001 - 2017 y; \( T_{\text{actual}} = 14.5 \) years) is shown by squares in figure 1 in comparison with the expected distribution according to the expression (5) calculated at \( f_1 = 0.0207 \text{ s}^{-1} \). Note that there is no normalization in figure 1.

According to the expression (5), background events create clusters with \( k = 8 \) with the rate 0.178 \( \text{y}^{-1} \). The expected number of such clusters during the time interval \( T = 14.5 \) y is 2.58 that we observe (2 events). The formation rate of clusters with \( k = 9 \) background events is \( 9.2 \times 10^{-3} \text{ y}^{-1} \), therefore the cluster with multiplicity \( k \geq k_{th} = 9 \) should be considered as a neutrino burst detection.

3. Two independent detectors
As it follows from the estimation (4) the ”sensitivity radius” of the D1 detector is \( R_s \approx 20 \text{ kpc} \). To increase the sensitivity radius (and to increase the number of detected neutrino events), we use those parts of external scintillator layers that have relatively low count rate of background events. The total number of counters in these parts is 1012, the scintillator mass is 110 tons. We call this array the D2 detector, it has the count rate of single events \( f_2 = 0.12 \text{ s}^{-1} \). The count rates of single events in D1 and D2 detectors and the operating stability have been shown in figure 2.
The joint use of D1 and D2 detectors allows us to decrease the threshold multiplicity in D1 cluster \( k_{th} = 9 \) and, consequently, to increase \( R_s \).

We use the following algorithm: in case of cluster detection with \( k_1 \geq 6 \) in the D1, we check the number of single events \( k_2 \) in the 10-second time frame in the D2 detector. The start of the frame coincides with the start of the cluster in D1. Mass ratio of D2 and D1 detectors 1012/1200 = 0.843 implies that for the mean value of neutrino events \( k_1 = 6 \) in D1, the mean number of neutrino events in D2 will be \( \bar{k}_2 = 6 \times 0.843 \times 0.8 = 4.05 \) (factor 0.8 takes into account that the frame duration in D2 is 10 seconds instead of 20 seconds in D1). Since the background adds \( f_2 \times 10 \text{s} = 1.2 \) events, we obtain finally \( \bar{k}_2( k_1 = 6) = 4.05 + 1.2 = 5.25 \).

The D1 and D2 detectors are independent, therefore the imitation probability of clusters with multiplicities \( k_1 \) in D1 and \( k_2 \) in D2 by background events is the product of appropriate probabilities

\[
P(k_1, k_2) = P_1(k_1) \times P_2(k_2)
\]

and we obtain \( P(6, 5) = 0.23 \text{ y}^{-1}, P(6, 6) = 0.045 \text{ y}^{-1} \) (note \( P_1 \) is determined according to the expression (5) and \( P_2 \) is the Poisson distribution).

Therefore the events with \( k_1 \geq 6, k_2 \geq 6 \) should be considered as candidates for a neutrino burst detection (since mean values of \( k_1 \) and \( k_2 \) are significantly exceeded in two independent detectors simultaneously and the imitation probability of such events by background is very small). Thus we decrease the threshold value of \( k_1 \) from 9 to 6 and increase the sensitivity radius up to \( R_s \simeq 23 \text{ kpc} \).

4. Conclusion

The Baksan Underground Scintillation Telescope operates under the program of search for neutrino bursts since June 30, 1980. As the target, we use two parts of the BUST (the D1 and D2 detectors) with the total mass of 240 tons. The "sensitivity radius" of the BUST (for a recording of neutrino bursts from supernovae) is \( R_s \simeq 23 \text{ kpc} \).
Background events are 1) decays of cosmogeneous isotopes (which are produced in inelastic interaction of muons with the scintillator carbon and nuclei of surrounding matter) and 2) cosmic ray muons if only one counter from 3184 hit.

Over the period of June 30, 1980 to December 31, 2017, the actual observation time was 32.1 years. This is the longest observation time of our Galaxy with neutrinos at the same facility. No candidate for the core collapse has been detected during the observation period. This leads to an upper bound of the mean frequency of gravitational collapses in the Galaxy

$$f_{col} < 0.072 \text{ y}^{-1}$$

at 90% CL. Recent estimations of the Galactic core-collapse SN rate give roughly the value \(\simeq 2 - 5\) events per century (see e.g. [23]).

Acknowledgments
The work has been carried out at a unique scientific facility the Baksan Underground Scintillation Telescope (Common-Use Center Baksan Neutrino Observatory INR RAS) and was supported by the Program for Fundamental Scientific Research of RAS Presidium "Fundamental Interactions Physics and Nuclear Technologies”.

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