38 years of galactic observations in searching for neutrino bursts from core collapse supernovae with the Baksan Underground Scintillation Telescope

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Abstract. The core collapse of a massive star in the Milky Way will produce a neutrino burst, which will be detected by the Baksan Underground Scintillation Telescope (BUST). The stable and enough low background at the BUST is a clear asset for searching for neutrino bursts. Now two parts of the facility (with the total mass of 242 tons) are used as independent coinciding detectors. Such approach allows us to increase dependability detection of the neutrino signal and the radius of sensitivity of the BUST. The facility has the potential to see a supernova in the Galaxy independently from other detectors.

No burst candidate for the core collapse has been detected during the observation period of June 30, 1980, to June 30, 2019. The actual observation time is 33.477 years. This is the longest observation time of our Galaxy with neutrinos at the same facility. An upper bound on the mean frequency of gravitational collapses in the Galaxy is 6.88 per century (at 90% C.L.).

1. Introduction
Neutrino emission is very important for the stellar evolution, especially for the final stage of massive stars evolution. Standard stellar evolution theory predicts that life of massive stars ends by core collapse, with possible Supernova explosion [1]. Core-collapse supernovae (SN) are among the most powerful sources of neutrinos in the Universe. 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 [2], [3], [4]. Due to their high penetration power, neutrinos deliver information on physical conditions in the core of the star during the gravitational collapse.

But no core-collapse supernovae has been observed in the Galaxy since the invention of the optical telescope, instruments for other wavelengths, neutrino detectors, or gravitational wave observatories. Supernova explosions in the Galaxy are rare events: the expected rate is 1 – 3 per century [5], [6]. The detection of the neutrino burst from SN is also very important from the point of view of astronomers because an alert could be given for following optical/near-IR observations.
2. The Baksan Underground Scintillation Telescope

The BUST is located in Baksan Valley (North Caucasus, Russia) within an underground laboratory at an effective depth of 850 m of water equivalent. It is a multi-purpose instrument designed for a wide range of studies into physics of cosmic rays and elementary particles, and neutrino astrophysics [7, 8]. The telescope of dimensions $17 \times 17 \times 11$ m$^3$ consists of 4 horizontal and 4 vertical planes with scintillation counters, the total number of which in the BUST being equal to 3184. The standard scintillation counter is an aluminum container with dimensions $0.7 \times 0.7 \times 0.3$ m$^3$ filled with organic liquid scintillator using white spirit as a solvent $C_nH_{2n+2}$ ($n \approx 9$). Each scintillation counter is viewed by a single PM tube FEU-49 with a photocathode diameter of 15 cm. The most probable energy release of muons in the counter is 50 MeV. Each counter has four output signals. The PM anode signal is used for fixing the time of a plane triggering and for measuring its energy release up to 2.5 GeV. The current output (anode signal coming through an integrating circuit) is used for adjustment and control of PM gains. Signals from the $12^{th}$ dynodes feed the inputs of pulse shape discriminators (the so called pulse channel) with threshold amplitudes 8 and 10 MeV for the inner and outer planes, respectively. The signal from the $5^{th}$ dynode comes to the input of a logarithmic converter, where it is transformed into a pulse whose duration is proportional to logarithm of signal amplitude. The logarithmic channel allows one to measure the energy release in each detector within the energy range 0.5 – 800 GeV.

The data acquisition system is triggered by actuation of the pulse channel of any BUST counter. The count rate of such trigger is $17 \text{s}^{-1}$. When a trigger appears all data about a given event come to the on-line computer where pre-processing of events is performed in order to get information about the current state of recording devices. GPS signals with a synchronization accuracy of 0.2 ms are used in order to reference events with the universal time.

One of the main tasks of the BUST is the search for neutrino supernova explosions with core collapse in the Galaxy. The experiment on recording neutrino bursts operates since the mid 1980. The duty cycle of the BUST over a last 18-year period is $\simeq 90\%$. The reasons for non-operation are:

i) We have a regular repair-day once a week (it lasts $\simeq 8$ hours). This is $\simeq 4\%$ of the calendar time. Data collection continues during repair time. These data can be used in the analysis.

ii) The Baksan Observatory is located within a mountain gorge. The power supply of the Observatory depends on natural disasters - snowslides, mudflows, floods. Power outage due to these reasons takes $\simeq 1\%$ of the time.

iii) Failure of registration system elements $\simeq 5\%$.

3. The method of neutrino burst detection

The BUST consists of 3184 standard autonomous counters. The total scintillator mass is 345 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

$$\bar{\nu}_e + p \rightarrow n + e^+ \quad (1)$$

If the mean antineutrino energy is $E_{\nu_e} = 12 - 15$ MeV [9, 10] 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 a 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:

$$N_{\text{ev}}^{H} = N_{H} \int_{0}^{\Delta t} dt \int_{0}^{\infty} dE \ F(E, t) \cdot \sigma(E) \eta(E),$$

(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. In calculating (2), we used the Fermi-Dirac spectrum for the $\bar{\nu}_e$ energy spectrum integrated over time (with the antineutrino temperature $k_B T = 4.5$ MeV) and the IBD cross section, $\sigma(E)$, from [11].

For an SN at a “standard” distance of 10 kpc, a total energy radiated into neutrinos of $\varepsilon_{\text{tot}} = 3 \times 10^{53}$ erg, and a target mass of 130 t (the three lower horizontal planes), we obtain (we assume the $\bar{\nu}_e$ flux is equal to $1/6 \times \varepsilon_{\text{tot}}$)

$$N_{\text{ev}}^{H} \simeq 35 \quad (\text{no oscillations})$$

(3)

The reactions on the scintillator carbon give a small contribution ($\simeq 2\%$) due to high energy threshold. The contribution from interactions in the container walls or in the concrete is $\simeq 1\%$.

Background events are i) radioactivity (mainly from cosmogenetic 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 – 2018 years) is $f_1 = 0.0207 \text{ s}^{-1}$ in internal planes (three lower horizontal layers) and $\simeq 1.5 \text{ s}^{-1}$ 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 (3) has been made for the D1 detector).

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 $T = 15.48 \text{ y}$ is 2.75 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 $k \geq k_{\text{th}} = 9$ should be considered as a neutrino burst detection.

4. Two independent detectors

To increase the number of detected neutrino events and to increase the ”sensitivity radius” of the BUST, we use those parts of external scintillator layers which have relatively low count rate of background events. The total number of counters in these parts is 1030, the scintillator mass is 112 tons. We call this array the D2 detector, it has the count rate of single events $f_2 = 0.12 \text{ s}^{-1}$. The joint use of D1 and D2 detectors allows us to increase the number of detected neutrino events and the detection reliability of a neutrino burst.

We use the following algorithm: in case of a 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 1030/1200 = 0.858 implies that for the mean value of neutrino events $k_1 = 6$ in D1, the mean number of neutrino events in D2 will be $\overline{k_2} = 6 \times 0.858 \times 0.8 = 4.12$ (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 $f_2 \times 10 = 1.2$ events, we obtain finally $\overline{k_2} = 4.12 + 1.2 = 5.32$.

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 and 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).
5. The SN neutrino burst warning
Because the joint use of D1 and D2 detectors allows us to increase the detection reliability of a neutrino burst, since early 2017 the information about researching for neutrino bursts is analyzed in the online mode (we obtain the result within 20 minutes). When the process finds the event ($k_1 \geq 6$, $k_2 \geq 6$), it generates a SN warning which initiates automated SMS message and emails sent to experts in the BUST collaboration. The experts make a decision to make a world-wide announcement or not within one hour.

6. Conclusion
There is a long-term stability of operation of the Baksan Underground Scintillation Telescope for searching of neutrino bursts. Using all set of the BUSTs data allow us to know background in great depth.

Two independent detectors the D1 (the inside, 130 t) and the D2 (the outside, 112 t) increase dependability of neutrino signal and the radius of sensitivity of the BUST. The registration of fake SN neutrino burst is practically excluded.

No burst candidate for the core collapse has been detected during the observation period of June 30, 1980, to June 30, 2019. The actual observation time is 33.477 years. This is the longest observation time of our Galaxy with neutrinos at the same facility. An upper bound on the mean frequency of gravitational collapses in the Galaxy is 6.88 per century (at 90% C.L.).

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References
[1] Georg Raffelt 2012 Neutrinos and the Stars. Preprint arXiv:1201.1637
[2] Gamow G and Shoenberg M 1940 Phys. Rev. 58 1117
[3] Zeldovich Ya B and Guseinov O Kh 1965 Dokl. Akad. Nauk SSSR 162 791
[4] Colgate S A and White R H 1966 Astrophys. J. 143 626
[5] John N Bahcall and Tsvi Piran 1983 Astrophys. J. 267 L77
[6] Scott M Adams et al 2013 Astrophys. J. 778 164
[7] Alekseev E N et al 1979 Proceedings of 16th International Cosmic Ray Conference (Kyoto, Japan, August 6 - 18) 10 276
[8] Alekseev E N et al 1998 Phys. Part. Nucl. 29 254
[9] Imshennik V S, Nadezhin D K 1982 Itogi Nauki i Tehniki, ser. Astronomy 21 63
[10] Hillebrandt W, Hoffish P 1989 Rep. Prog. Phys. 52 1421
[11] Strumia A and Vissani F 2003 Phys. Lett. B 564 42 (Preprint astro-ph/0302055)