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Search for neutrino bursts at the Baksan Underground Scintillation Telescope

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The Baksan Underground Scintillation Telescope (BUST) has been operating under the neutrino burst search program since the mid-1980s. As a target, we use two parts of the facility with a total mass of 240 tons. The current status of the experiment is presented. The possibilities of the BUST in detecting neutrino bursts from nearby supernovae are shown. For the period from June 30, 1980 to December 31, 2021, the observation time was 35.8 years. No candidate for the stellar core collapse has been detected during the observation period. This leads to the value of the upper limit of the average frequency of gravitational collapses of stars in the Galaxy 0.064 year^{-1} at the 90% confidence level.

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1. Introduction

It has been 35 years since supernova 1987A. This event became an experimental confirmation of the ideas about the extremely important role of neutrinos in the process of explosion of massive stars (the birth of supernovae), put forward more than 50 years ago [1–3]. This has made a significant impact on both theoretical studies of the supernova (SN) phenomenon and the development of experimental facilities.

Due to their high penetration power, neutrinos deliver information on physical conditions in the core of the star during the gravitational collapse. The neutrino burst carries the most important experimental information about the SN phenomenon, which should be a test to verify our ideas about the mechanism of the SN explosion.

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 are large neutrino detectors. In the past decades (since 1980), the search for neutrino bursts was carried out with such detectors as the Baksan Scintillation Telescope [4, 5], Kamiokande [6] and Super-Kamiokande [7], MACRO [8], LVD [9], AMANDA [10] and SNO [11]. Over the years, our understanding of how massive stars explode and how the neutrino interacts with hot and dense matter has increased by a tremendous degree. 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 [12–15] are capable of detecting of order ten thousand neutrinos for a supernova at the distance of 10 kpc.

The Baksan Underground Scintillation Telescope (BUST) [16] is a multipurpose detector intended for wide range of investigations in cosmic-ray and particle physics. One of the tasks is the search for neutrino bursts. The facility has been uninterruptedly used for this purpose since the middle of 1980. In 2001, a significant modernization of the data acquisition system was carried out. This system operate since March 6, 2001. The data processing system until 2001 is described in [4]. The total observation time of the Galaxy amounts to 90% of the calendar time.

2. The method of neutrino burst detection

The BUST consists of 3180 standard autonomous counters. The standard counter is an aluminum tank $0.7 \times 0.7 \times 0.3$ m^3 in size, filled with an organic C_nH_{2n+2} ($n \simeq 9$) scintillator. The total scintillator mass is 330 t, and the mass enclosed in three lower horizontal layers (1200 counters) is 130 tons. The counter pulse channel has a trigger threshold of 8 and 10 MeV for the horizontal and vertical planes, respectively (the most probable energy deposition of a muon in a counter is 50 MeV $\equiv$ 1 relativistic particle).

The trigger is an operation of any counter pulse channel of the BUST (its count rate is 17 s^{-1}). When a trigger appears, the entire information on this event is fed to an online computer, in which the events are preprocessed and rendered as a "frame". The frame duration is 300 ns (i.e., all the counters that have hit within 300 ns since the trigger moment fall into one frame). The average frame processing time ("dead time" of the BUST) is $\simeq$ 1 ms.

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The majority of the events recorded with the Baksan telescope from a supernova explosion will be produced in inverse beta decay (IBD) reactions

$$\overline{\nu}_e + p \to n + e^+ \tag{1}$$

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 3180 operates; below we call a such event a "single event") during the neutrino burst. The search for a neutrino burst consists in searching for cluster of single events within a time interval of $\tau = 20$ s (according to modern collapse models the burst duration does not exceed 20 s).

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

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

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 $\eta(E)$ the detection efficiency. The symbol "H" at the left side indicates that the hydrogen of the scintillator is the target. In calculating (2), we used the Fermi-Dirac spectrum for the $\overline{\nu}_e$ energy spectrum integrated over time (with the antineutrino temperature $T_{\overline{\nu}_e} = 4.5$ MeV) and the IBD cross section, $\sigma(E)$, from [19].

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

$$N_{ev}^{H} \simeq 35 \quad (no\ oscillations) \tag{3}$$

The reactions on the scintillator carbon

$$\overline{\nu}_e +^{12} C \to^{12} B + e^+, \quad E_{\overline{\nu}_e} > 14.4\ MeV \tag{4}$$

$$\nu_e +^{12} C \to^{12} N + e^-, \quad E_{\nu_e} > 17.34\ MeV \tag{5}$$

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

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. [20–23]). The oscillation effects depend on many unknown or poorly known factors . These are the self-induced flavor conversions, the matter suppression of self-induced effects, specific flavor conversions at the shock-fronts, stochastic matter flows fluctuations.

The measurement of a "large" value of θ_{13} ($\sin^2\theta_{13} = 0.023$) [24, 25] has siginifcantly reduced the uncertainty in the predictions of possible transformations of the initial SN neutrino fluxes on the way to the Earth.

For the simplest scenario, in which the transformation of neutrino fluxes is determined only by the MSW effect [26, 27], we get (we assume that the temperature of non-electronic neutrinos is $T_x = 6$ MeV)

$$N_{ev}^{H}(NH) \simeq 39 \qquad for\ normal\ hierarchy, \tag{6}$$

$$N_{ev}^{H}(IH) \simeq 48 \qquad for\ inverted\ hierarchy. \tag{7}$$

3. Background events

Background events are i) radioactivity (mainly from cosmogeneous isotopes) and ii) cosmic ray muons if only one counter from 3180 is hit. The total count rate from background events (averaged over the period of 2001 – 2021 years) is $f_1 = 0.0207\ s^{-1}$ in the internal planes (three lower horizontal layers) and $\simeq 1.5\ s^{-1}$ in the external ones. Therefore, the 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 can imitate the expected signal (k single events within sliding time interval τ) with a count rate

$$p(k) = f_1 \times exp(-f_1\tau)\frac{(f_1\tau)^{k-1}}{(k-1)!} \tag{8}$$

The treatment of experimental data (single events over a period 2001 - 2021 y; T_{actual} = 18.1 years) is shown by squares in Fig. 1 in comparison with the expected distribution according to the expression (8) calculated with $f_1 = 0.0207\ s^{-1}$. Note that there is no normalization in Fig. 1.

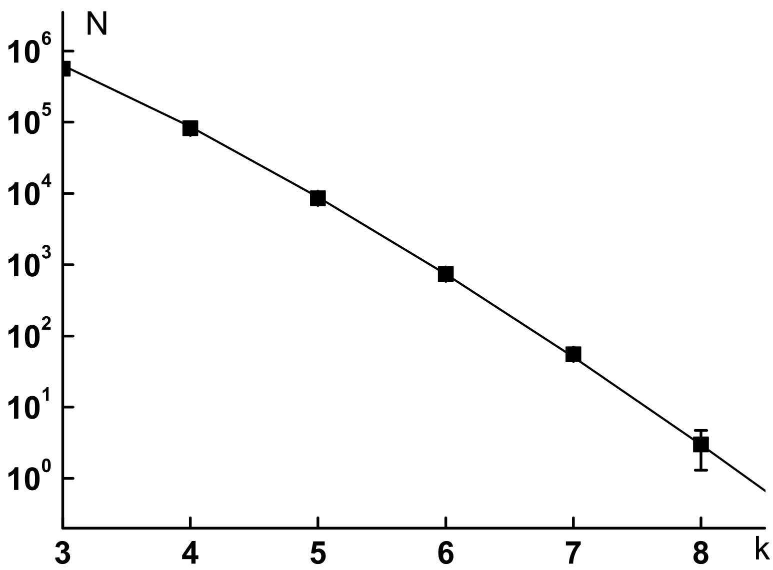

Figure 1: The number of clusters with k single events within time interval of τ = 20 s. Squares are experimental data, the curve is the expected number according to the expression (8).

According to the expression (8), background events create clusters with k = 8 with a rate 0.178 y^{-1}. The expected number of such clusters during the time interval T = 18.1 y is 3.22 that we observe (3 events). The formation rate of clusters with k = 9 background events is $9.2 \times 10^{-3}\ y^{-1}$, therefore a cluster with multiplicity $k \geq 9$ should be considered as a candidate for neutrino burst detection.

4. Two independent detectors

To increase the number of detected neutrino events and the reliability of neutrino burst detection, we use those parts of the outer scintillation layers that have a relatively low count rate of background events. The total number of counters in these parts is 1030, the scintillator mass is 110 tons. We call this array the D2 detector, it has a count rate of single events $f_2 = 0.12$ s^{-1}.

We use the following algorithm: in case of a cluster detection with $k1 \geq 6$ in the D1, we check the number of single events, $k2$, in the 10-second time frame in the D2 detector. The start of the frame coincides with the start of the cluster in D1. The mass ratio of D2 and D1 detectors 1030/1200 = 0.858 implies that (in the case of a real neutrino burst) for the mean value of neutrino events $k1 = 6$ in D1, the mean number of neutrino events in D2 will be $\overline{k2} = 6 \times 0.858 \times 0.8 = 4.12$ (the 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 $f_2 \times 10$ s = 1.2 events, we obtain finally $\overline{k2}(\ \overline{k1} = 6) = 4.12 + 1.2 = 5.32$.

According to the exp. (2), the expected average number of detected neutrino events in the D2 detector is $N^H_{ev}(D2) \simeq 28$ (under the same conditions and assumptions as in (3)). So the expected total number of detected neutrino events (in IBD reactions (1)) reads

$$N^H_{ev} = N^H_{ev}(D1) + N^H_{ev}(D2) \simeq 63 \quad (no\ oscillations) \tag{9}$$

For oscillation hypotheses with normal hierarchy (NH) and inverted hierarchy (IH), we get (T_x = 6 MeV)

$$N^H_{ev}(NH) \simeq 71 \tag{10}$$

$$N^H_{ev}(IH) \simeq 88 \tag{11}$$

The D1 and D2 detectors are independent, therefore the imitation probability of clusters with multiplicities $k1$ in D1 and $k2$ in D2 by background events is the product of appropriate probabilities

$$P(k1, k2) = P1(k1) \times P2(k2) \tag{12}$$

and we obtain $P(6, 5) = 0.23$ y^{-1}, $P(6, 6) = 0.045$ y^{-1} (note that $P1$ is determined according to the expression (8) and $P2$ is the Poisson distribution for the 10-second time frame).

Therefore the events with $k1 \geq 6$, $k2 \geq 6$ should be considered as candidates for a neutrino burst detection (since mean values of $k1$ and $k2$ 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

The BUST data collected by the data acquisition system are sent to the on-line computer operative memory. Every 15 minutes (0, 15, 30 and 45 minutes of every hour) this information is written in a file whichs number is in a one-to-one correspondence with the calendar time. We call it a RUN-file. In 20 seconds the RUN-file is sent to the off-line computer where in 4 minutes the off-line data processing begins (among others things, the search for neutrino burst according to the algorithm described in Section 4). This process takes about 1 minute, thus we obtain the result within 20 minutes (if the neutrino burst has occured in the beginning of the 15-minutes time interval). When the process finds an event with $k1 \geq 6$, $k2 \geq 6$ (see Section 4), it generates a SN warning which initiates phone-callings 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.

It should be noted that in the case of a very close SN, for example at the distance of 0.2 kpc, the total number of events from IBD reactions, according to the estimate (9), will be $\simeq$ 250,000. In the first seconds (after a core bounce), we should expect $\simeq$ 30,000 events per second. Against this count rate, the count rate of muon events (17 s^{-1}) is negligible. So all events recorded by the BUST (with all 3180 counters, the scintillator mass is 330 ton) during this time period will be neutrino events. The frame duration of the BUST is 300 ns, the frame processing time is $\simeq$ 1 ms, therefore we will record $\simeq$ 1000 events per second, with the overwhelming majority of events being frames with one counter. The fraction of frames in which two counters hit (i.e. two neutrino events fell in the time frame of 300 ns) is less than 0.5%. Thus, in the case of a very close SN, some part of the events (which depends on the distance to the SN) will be lost.

6. Conclusion

The Baksan Underground Scintillation Telescope operates as a monitor for neutrino bursts since June 30, 1980. As a target, we use two parts of the BUST (the D1 and D2 detectors) with a total mass of 240 tons. The estimation (9) allows us to expect $\simeq$ 10 neutrino interactions from a most distant SN ($\simeq$ 25 kpc) of our Galaxy. In the opposite case, of a very close SN, some part of the events (which depends on the distance to the SN) will be lost (see Section 5).

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 3180 hit.

Over the period of June 30, 1980 to December 31, 2021, the actual observation time was 35.8 years. This is the longest observation time of our Galaxy with neutrinos at the same facility. No candidate for a core collapse has been detected during the observation period. This leads to an upper bound on the mean frequency of star gravitational collapses in the Galaxy

$$f_{col} < 0.064 \ y^{-1} \tag{13}$$

at 90% CL. Estimations of the Galactic core-collapse SN rate give roughly the value $\simeq 2-5$ events per century (see e.g. [28]).

The high stability of BUST parameters, noise immunity, background understanding and practically continuous operation of the facility provide an opportunity to study rare processes and phenomena over a long period of time. Archival registration data from the BUST is available from April 1981.

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