A search for neutrino bursts signal from supernovae at the Baksan Underground Scintillation Telescope

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Abstract The current status of the experiment on recording neutrino bursts from core collapse stars is presented. The actual observational time is 29.76 years. The upper bound of the mean frequency of core collapse supernovae in our Galaxy is $f_{col} < 0.077$ year^{-1} (90% CL).

Keywords: Supernova, Neutrino Bursts

1. Introduction

The detection of neutrinos from the supernova SN1987A [1] – [4] experimentally proved the critical role of neutrinos in the explosion of massive stars, as was suggested more than 50 years ago [5] – [7].

Neutrinos are especially important, because they reveal physical conditions in the star core at the instant of collapse. The SN1987A event helped to establish some aspects of the theory, namely the total energy radiated, the neutrinos temperatures and the duration of neutrino burst [8], [9].

At present, the standard paradigm of SN explosion mechanism is the “delayed explosion scenario” or “neutrino mechanism”, which was suggested first by Wilson [10] and Bethe [11]. In this scenario, one of the key parameters is a neutrino energy deposition behind the stalled shock. This energy deposition can revive the shock energy (which the shock wave lost during propagation through the outer iron core) and leads finally to the SN explosion.

In recent years a substantial progress has been achieved in two-dimensional (2D) and three-dimensional (3D) hydrodynamic simulations of SN progenitor evolution. These simulations found out considerable deviations from spherical symmetry [12] – [14]. In particular, the lepton-number emission self-sustained asymmetry (LESA) phenomenon is identified [15]. It means that the observed neutrino flux depends on the observer position.

On the other hand, results obtained in 3D simulations pointed out that energy of the shock wave is insufficient for a successful SN explosion. However in the recent work by T. Melson et al. [16] it has been shown that strangeness contributions to neutrino-nucleon scattering with an axial-vector coupling of $g_a^s = -0.2$ are sufficient to turn a non-exploding 3D simulation (in which g_a = 1.26 was used for the standard isovector form factor) to a successful explosion. This result indicates that an accurate knowledge of neutrino-nucleon interaction rates, in particular also for neutral current scattering, is of crucial importance for assessing the viability of the neutrino driven explosion mechanism.

The supernova neutrino detection will be crucial to test the explosion mechanism and thus to compare current supernova models with experimental data.

Several neutrino detectors have been observing the Galaxy in the last decades to search for stellar collapses, namely Super-Kamiokande [17], Baksan [18], [19], MACRO [20], LVD [21], [22], AMANDA [23], SNO [24]. At present, the new generation detectors, which are capable to record effectively the neutrino burst from the next SN, are added to the facilities listed above: IceCube [25], Borexino [26], [27], KamLAND [28] and some others.

The Baksan Underground Scintillation Telescope operates under the program of search for neutrino bursts since the mid-1980. In this paper we present the current status of the experiment and some results related to investigation of background events and stability of the facility operation. Section 2 is a brief description of the facility. Section 3 is devoted to the method of neutrino burst detection. Discussion and Conclusion are presented in Section 4.

2. The facility

The Baksan Underground Scintillation Telescope (BUST) is located in the Northern Caucasus (Russia) in an underground laboratory at the effective depth $8.5 \cdot 10^4$ g·cm^{-2} (850 m of w.e.) [29]. The facility has the size $17\times17\times11$ m^3 and consists of four horizontal scintillation planes and four vertical ones (Fig.1).

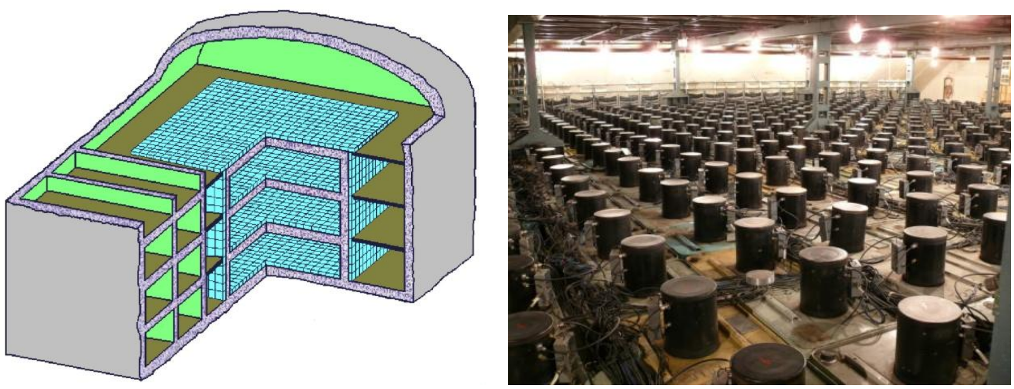

Fig1. *The Baksan Underground Scintillation Telescope, Right –the upper plane of the BUST*

Five planes of them are external planes and three lower horizontal planes are internal ones. The upper horizontal plane consists of 576 (24×24) liquid scintillator counters of the standard type, three lower planes have 400 (20×20) counters each. The vertical planes have (15×24) and (15×22) counters. Each counter is $0.7\times0.7\times0.3$ m^3 in size, filled with an organic C_nH_{2n+2} ($n \approx 9$) scintillator, and viewed by one photomultiplier with a photocathode diameter of 15 cm. The distance between neighboring horizontal scintillation layers is 3.6 m. The angular resolution of the facility is 2^o, time resolution is 5 ns.

Information from each counter is transmitted over three channels: an anode channel (which serves to trigger formation and amplitude measurements up to 2.5 GeV), a pulse channel with the operation threshold 8 MeV and 10 MeV for the horizontal and vertical planes, respectively (at first this threshold was equal to 12.5 MeV; the most probable energy deposition of a muon in a counter is 50 MeV ≡ 1 relativistic particle) and a logarithmic channel with the threshold s_0 = 0.5 GeV. The signal from the fifth dynode of PM tube FEU-49 goes to a logarithmic channel (LC) where it is converted into a pulse whose length *t* is proportional to logarithm of the signal amplitude [30].

The BUST is a multipurpose detector. The physical experiments began in 1978. Since that time, the parameters of scintillation counters and data acquisition system were permanently improved. One of the current tasks is the search for neutrino bursts. The facility has been operating almost continuously under the program of search for neutrino bursts since the mid-1980. The total time of Galactic observation accounts for 90% of the calendar time.

3. The method of neutrino burst detection

The BUST consists of 3184 standard autonomous counters. 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 reactions

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

If the mean antineutrino energy $E_{\bar{\nu}_e} = 12 - 15\ MeV$ [31], [32], the pass of e^+ (produced in reaction (1)) will be included, as a rule, in the volume of one counter. In such a case the signal from a supernova (SN) explosion will appear as a series of events from singly triggered counters (one and only one counter from 3184 operates; below we call such an event “a single event” or “1 from 3200” event) during the neutrino burst.

The search for a neutrino burst consists in the recording of single events bunch within a time interval of τ = 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 δt from the beginning of the collapse can be expressed as:

$$N_{ev}^{H} = N_H \int_0^{\delta t} dt \int_0^{\infty} dE \times F(E,t) \times \sigma(E)\eta_1(E), \tag{2}$$

here N_H is the number of free protons, $F(E,t)$ is the flux of electron antineutrinos, σ (E) is the IBD cross section and η_1 (E) is the detection efficiency of e^+ in reaction (1) ($\eta_1 \approx 0.7$ if the positron energy E_e = 10 MeV and η_1 = 0.9, if E_e = 20 MeV). The symbol “H” in the left side indicates that the hydrogen is the target.

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

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

the expected number of single events from reaction (1) (we assume the total energy of the $\bar{\nu}_e$ flux is equal to ($1/6\varepsilon_{tot}$)) will be

$$N_{ev}^{H} \cong 35 \tag{4}$$

Flavor oscillations are unavoidable, of course. However, in recent years it was recognized that the expected neutrino signal depends strongly on the oscillation scenario (see e.g. [33] - [36]). In the absence of a quantitatively reliable prediction of the flavor-dependent fluxes and spectra it is difficult to estimate the oscillation impact on ν_e– and $\bar{\nu}_e$ fluxes arriving to the Earth.

Therefore we do not discuss the effects of flavor oscillations in this paper.

Background events are radioactivity and cosmic ray muons if only one counter from 3184 hit. The total count rate from background events is f = 0.02 s^{-1} in internal planes (three lower horizontal layers) and ≈ 1.5 s^{-1} in external ones. Therefore three lower horizontal layers are used as a target (the estimation (4) has been calculated for three internal planes). The trigger is the operation of any counter pulse channel (with the threshold 8 MeV).

In Fig.2 we show how the counter operation threshold changed with time (12.5→ 10→ 8 MeV) and the corresponding total count rate of single events in the three internal planes (1200 counters, the target mass is 130t).

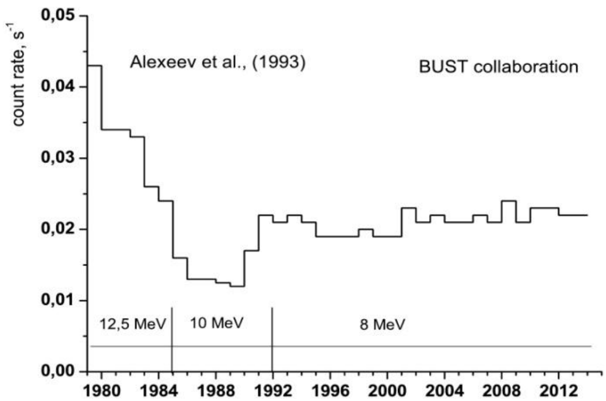

Fig2. *The mean count rate of single events in the three telescope internal planes (1200 counters) vs the counter operation threshold*

The energy spectra of single events (i.e. background events) in three lower horizontal planes are presented in Fig.3. The planes have the numbers 6, 7 and 8 (the numeration is from the bottom upwards). The exposure time is 322 days in 2014 year. The spectra have been measured by linear amplitude channels which have the threshold of 6 MeV and the energy resolution of 60 KeV.

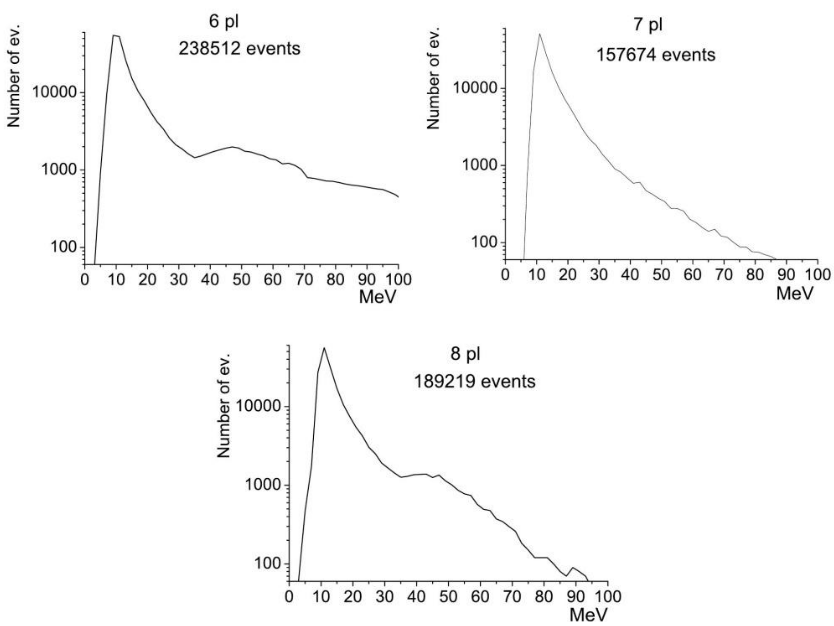

Fig3. *Energy spectra of events "1 from 3200" in the 6-th, 7-th and 8-th planes. The exposure time is 322 days (2014 y). The energy bin width is 2 MeV. The total numbers of events are shown in each panel.*

The peak in the region of 10 - 15 MeV is due to decays of cosmogenic isotopes (^{12}B, ^{12}N, ^{8}B, ^{8}Li etc.), which are generated in inelastic interactions of muons with nuclei of ^{12}C into scintillator and nuclei of surrounding matter. We estimate the rate of cosmogenic isotopes generation on the base of results obtained in [37]. In reality, we observe the summary decay curve from all isotopes which is truncated at the left side with the operation threshold of counters (8 MeV). The rest single events are muons which pass the external planes without recording (through a slit between counters or brushing counters so that energy deposition is less than 8 MeV).

The expected number of background events during the exposure time is ≈ 190 000. This value should be compared with the experimental events number.

Background events can imitate the expected signal (k single events within the sliding time interval τ) with a count rate

$$p(k) = f \times \exp(-f\tau)\frac{(f\tau)^{k-1}}{(k-1)!} \tag{5}$$

The treatment of experimental data (background events over a period 2001 - 2014 y; $T_{actual} = 11.98$ years) is shown by squares in Fig.4 in comparison with the expected distribution according to the expression (5) calculated at f = 0.02 s^{-1}. Note there is no normalization in Fig.4.

Background events are to create clusters with k = 8 with the rate 0.138 y^{-1} (and $6.9 \cdot 10^{-3} y^{-1}$ if k = 9). The expected number of clusters with k = 8 during the time interval $T_{actual} = 11.98$ y is 1.65 that we observe in the experiment (2 events). Clusters with $k \geq 9$ should be considered as a neutrino burst signal.

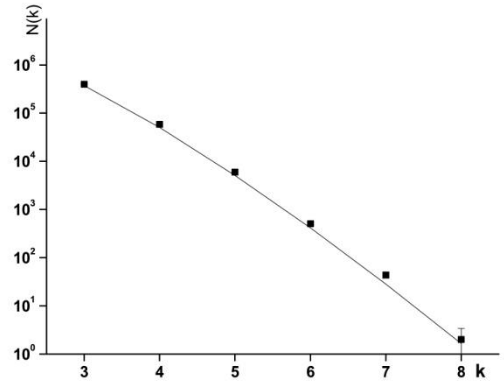

***Fig4**. Number of bunches with k single events within time interval of τ = 20s. Squares are experimental data, the curve is the expected number according to expression (5).*

3.1. Reactions on Carbon nuclei

There are models which predict the mean neutrino energy from SN is $\overline{E_\nu}$= 30 - 40 MeV [38], [39]. In such case the reactions on Carbon nuclei of the scintillator become effective and neutrinos can be detected in the BUST through interactions:

$$\nu_i + {}^{12}C \rightarrow 12C^* + \nu_i, \qquad E_{th} = 15.1\, MeV$$

$$\text{i=e,}\mu,\tau, \tag{6}$$

$$12C^* \rightarrow {}^{12}C + \gamma, \quad E_\gamma = 15.1\, MeV$$

and $$\nu_e + {}^{12}C \rightarrow {}^{12}N + e^-, \quad E_{th} = 17.34\, MeV$$

$$^{12}N \rightarrow {}^{12}C + e^+ + \nu_e, \quad \tau({}^{12}N) = 15.9\, ms \tag{7}$$

τ is a lifetime of the nucleus ^{12}N.

Reaction (6) allows us measuring the total neutrino flux with the energy $E_\nu > 15.1\ MeV$.

If the mean energy $\overline{E_\nu} = 30\ MeV$ the expected number of events for reactions (6) and (7) can be estimated (under conditions (3) by the formulae

$$N^C_{ev2} = 16 \times \eta_2 \quad (E_\gamma = 15\ MeV) \tag{8}$$

$$N^C_{ev3} = 30 \times \eta_3 \quad (E_\nu = 30\ MeV) \tag{9}$$

The radiation length for our scintillator is 47 g/cm^2 therefore $\eta_2 \approx 0.3$. In reaction (7) BUST can detect both e^- with energy $(E_\nu - 17\ MeV)$ and e^+, if the energy deposition from these particles is greater than 8 MeV. In the latter case, reaction (7) will have the distinctive signature: two signals separated by the 1 - 45 ms time interval (dead time of the BUST is 1 ms).

In reaction (7) the sum of energies $(E_{e+} + E_\nu)$ is 17.3 MeV therefore $\eta_3 \approx 0.7$.

The low part of the overlap between horizontal scintillation planes is the 8 mm iron layer. This can be used as the target in the reaction

$$\nu_e + {}^{56}Fe \rightarrow {}^{56}\mathrm{Co}^* + \mathrm{e}^-, \quad \mathrm{E_{th}} = 10\ MeV \tag{10}$$

(cobalt emerges in the excited state).

Under conditions (3) the expected number of events from reaction (10) (neutrinos arrive from above) is

$$\mathrm{N^{Fe}_{ev}} = 6.3 \times \eta_{\mathrm{Fe}} \quad (20\ \mathrm{MeV}) \tag{11}$$

η_{Fe}(20MeV) ≈ 0.3 is the detection efficiency of e^- with the energy 20 MeV produced into the 8 mm iron layer.

It should be noticed, if $\overline{E}_{\mathrm{ve}}$ = 30 - 40 MeV a noticeable percentage of neutrino reactions will cause triggering two adjacent counters.

4. Discussion and Conclusion

The Baksan Underground Scintillation Telescope operates under the program of search for neutrino bursts since June 30, 1980. The counting rate of single events was stable over the period of observation and its behavior is Poissonian.

One can see from expression (4) that the “radius of sensitivity” of the Baksan telescope is ≈ 20 kpc. This region includes ≈ 95% stars of our Galaxy. For more distant SNe, the cluster-signal will have the number of recorded neutrino events k < 9 (if we do not hope for an exotic mechanism with large neutrino energies). In this case, one should investigate the correlations with others detectors.

Over the period of June 30, 1980 to December 31, 2014, the actual observation time was 29.76 years [18], [40]. This is the longest observation time of our Galaxy with neutrino at the same facility.

No candidate for the core collapse has been detected during the observation period. This leads to an upper bound on the mean frequency of gravitational collapses in the Galaxy

$$f_{col} < 0.077\ y^{-1},\ 90\%\ CL \tag{12}$$

Recent estimations of the Galactic core-collapse SN rate give roughly the value ≈ 2-5 events per century (see e.g. [41]).

The results of two-dimensional (2D) [42] – [44] and 3D [12], [13], [45], [14] hydrodynamical simulations of SN progenitors evolution found out considerable deviations from spherical symmetry and imply that SN explosions are multi-dimensional.

In particular, the lepton-number emission self-sustained asymmetry (LESA) phenomenon is identified in 3D simulations [36], [15], i.e. the observed neutrino flux depends on the observer position. The dependence ν_e– and $\overline{\nu}_e$ fluxes arriving to the Earth according the oscillation scenario only complicates the interpretation.

The result obtained in [16] can be an important step on a path leading to conversion of the “delayed explosion scenario” from a standard paradigm to the generally used one.

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