ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2016. Т. 47. ВЫП. 6

THE SEARCH FOR NEUTRINO BURSTS FROM SUPERNOVAE WITH BAKSAN UNDERGROUND SCINTILLATION TELESCOPE

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

PACS: 97.60.Bw

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 the 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 the neutrino burst [8, 9].

Since light can be partially or totally absorbed by dust in the Galactic plane (see e.g., [10]), while neutrinos are not, large long-term neutrino detectors are the most suited ones to observe the Galaxy and search for core-collapse supernovae explosions. Several neutrino detectors have been observing the Galaxy in the last decades to search for stellar collapses, namely, Super-Kamiokande [11], Baksan [12, 13], MACRO [14], LVD [15, 16], AMANDA [17], SNO [18]. 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 [19], Borexino [20, 21], KamLAND [22], and some others.

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The Baksan Underground Scintillation Telescope operates under the program of search for neutrino bursts since the mid-1980s. In this paper, we present the current status of the experiment and some results related to the investigation of background events and the stability of the facility work. Section 1 is the brief description of the facility. Section 2 is devoted to the method of neutrino burst detection. In Sec. 3, we present the results of the study of afterpulses associated with the passage of muon-induced cascades. Discussion and Conclusion are presented in Sec. 4.

1. THE FACILITY

The Baksan Underground Scintillation Telescope (BUST) is located in the Northern Caucasus (Russia) in the underground laboratory at the effective depth of $8.5{\cdot}10^4$ g$\cdot$cm^{-2} (850 m of w.e.) [23]. The facility has dimensions pf $17{\times}17{\times}11$ m and consists of four horizontal scintillation planes and four vertical ones (Fig. 1). Five 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 $0.7 \times 0.7 \times 0.3$ m in size, filled with an organic C_nH_{2n+2} ($n \simeq 9$) 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 $2°$, time resolution is 5 ns.

The information from each counter is transmitted over three channels: an anode channel (which serves for trigger formation and amplitude measurements up to 2.5 GeV), a pulse channel with operation threshold of 8 and 10 MeV for the horizontal and vertical planes, respectively, (at first this threshold was equal

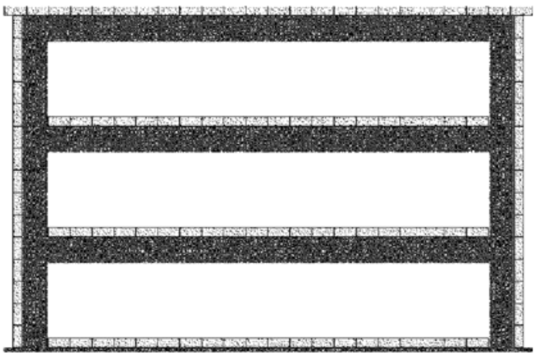

Fig. 1. The Baksan Underground Scintillation Telescope (side view)

to 12.5 MeV; the most probable energy deposition of a muon in a counter is 50 MeV $\equiv$ 1 relativistic particle), and a logarithmic channel with a 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 is proportional to the logarithm of the amplitude of the signal [24].

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-1980s. The total time of Galactic observation accounts for 90% of the calender time.

Since 2001, all events are collected by the facility. Earlier only the events selected by physics programs (by means of corresponding electronic systems) were recorded. All events recording allows us to observe any events before and after single events.

2. 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 t. The majority of the events recorded with the Baksan Telescope from a supernova explosion will be produced in inverse beta decay reactions

$$\bar{\nu}_e + p \to n + e^+. \tag{2.1}$$

If the mean antineutrino energy is $E_{\nu_e} = 12{-}15$ MeV [25, 26], the pass of e^+ (produced in reaction (2.1)) 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 “the single event”) during the neutrino burst. The search for a neutrino burst consists in recording single events bunch within time interval of $\tau = 20$ s (according to modern collapse models, the burst duration does not exceed 20 s).

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

$$\varepsilon_{\rm tot} = 3 \cdot 10^{53}\ \text{erg}, \tag{2.2}$$

the expected number of single events from reaction (2.1) (we assume the total energy of the $\bar{\nu}_e$ flux equals to $1/6\varepsilon_{\rm tot}$) will be

$$N_{\rm ev}^{\rm H} \simeq 38\eta_1, \tag{2.3}$$

where η_1 denotes the detection efficiency of e^+ in reaction (2.1) and the symbol "H" indicates that the hydrogen is the target. $\eta_1 \approx 0.7$ if the electron energy $E_e = 10$ MeV, and $\eta_1 = 0.9$ if $E_e = 20$ MeV.

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., [27–30]). 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, ghost signals from counters and cosmic ray muons if only one counter from 3184 hit. The total count rate from background events is $f = 0.02\ \mathrm{s}^{-1}$ in internal planes (three lower horizontal layers) and $\simeq 1.5\ \mathrm{s}^{-1}$ in external ones. Therefore, three lower horizontal layers are used as a target (the estimation (2.3) has been calculated for three internal planes). In Fig. 2, we show how the counter operation threshold changed with time ($12.5 \to 10 \to 8$ MeV) and corresponding the total count rate of single events in the three internal planes (1200 counters, the target mass is 130 t).

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

$$p(k) = f \exp\left(-f\tau\right) \frac{(f\tau)^{k-1}}{(k-1)!}. \tag{2.4}$$

The treatment of experimental data (background events over a period 2001–2014; $T_{\mathrm{actual}} = 11.98$ yr) is shown by squares in Fig. 3 in comparison with the expected

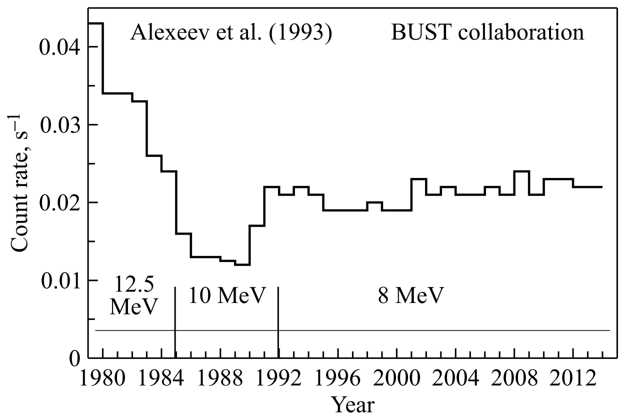

Fig. 2. The mean count rate of single events in three telescope internal planes (1200 counters) vs. the counter operation threshold

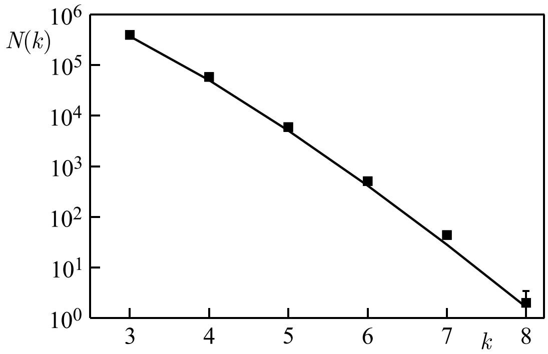

Fig. 3. The number of bunches with k single events within time interval of $\tau = 20$ s. Squares are experimental data, the curve is the expected number according to the expression (2.4)

distribution according to the expression (2.4) calculated at $f = 0.02$ s^{-1}. Note there is no normalization in Fig. 3.

Reactions on Carbon Nuclei. There are models which predict the mean neutrino energy from SN, $\bar{E}_{\nu_e} = 30{-}40$ MeV [31,32]. In this case, the reactions on Carbon nuclei of the scintillator become effective and neutrinos can be detected in the BUST through interactions

$$\begin{gathered} \nu_i + {}^{12}\mathrm{C} \to {}^{12}\mathrm{C}^* + \nu_i, \quad E_{\mathrm{th}} = 15.1 \text{ MeV}, \quad i = e, \mu, \tau, \\ {}^{12}\mathrm{C}^* \to {}^{12}\mathrm{C} + \gamma, \quad E_\gamma = 15.1 \text{ MeV}, \end{gathered} \tag{2.5}$$

and

$$\begin{gathered} \nu_e + {}^{12}\mathrm{C} \to {}^{12}\mathrm{N} + e^-, \quad E_{\mathrm{th}} = 17.34 \text{ MeV}, \\ {}^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e, \quad \tau({}^{12}\mathrm{N}) = 15.9 \text{ ms}, \end{gathered} \tag{2.6}$$

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

Reaction (2.5) allows measurement of the total neutrino flux with the energy $E_\nu > 15.1$ MeV.

If the mean energy $\bar{E}_\nu = 30$ MeV, the expected number of events for reactions (2.5) and (2.6) can be estimated (under conditions (2.2)) by the formulae

$$N^{\mathrm{C}}_{\mathrm{ev2}} = 16\eta_2 \ (E_\gamma = 15 \text{ MeV}), \tag{2.7}$$

$$N^{\mathrm{C}}_{\mathrm{ev3}} = 30\eta_3 \ (E_\nu = 30 \text{ MeV}). \tag{2.8}$$

The radiation length for our scintillator is 47 g/cm^2, therefore $\eta_2 \approx 0.2$. In reaction (2.6) BUST can detect both e^- with energy $E_\nu = 17$ MeV and e^+ if the energy deposition from these particles is greater 8 MeV. In the latter case, reaction (2.6) will have the distinctive signature: two signals separated with 1–45 ms time interval (dead time of the BUST is $\simeq 1$ ms).

In reaction (2.6) the sum of energies $E_{e^+} + E_\nu$ is 17.3 MeV, therefore $\eta_3 \approx 0.5{-}0.7$.

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

$$\nu_e + {}^{56}\text{Fe} \to {}^{56}\text{Co}^* + e^-, \quad E_{\text{th}} = 10 \text{ MeV}, \tag{2.9}$$

(cobalt emerges in excited state).

Under conditions (2.2) the expected number of events from reaction (2.9) (neutrinos arrive from above) is

$$N_{\text{ev}}^{\text{Fe}} = 6.3\eta_{\text{Fe}} \text{ (20 MeV)}, \tag{2.10}$$

η_{Fe} (20 MeV) ≈ 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 $\bar{E}_{\nu_e} = 30{-}40$ MeV a noticeable percentage of neutrino reactions (2.9) will cause triggering two adjacent counters.

3. SINGLE EVENTS ASSOCIATED WITH THE PASSAGE OF CASCADES

Part of the single events could be due to the inelastic interaction of CR muons with the matter of the detector, resulting in the generation of unstable nuclei. Their decay can lead to the response of only one counter in the facility. The afterpulses after a large energy release ($\geqslant$ 500 MeV) in the counter were studied in order to select such events.

Those events were selected in which the internal planes of the facility (6th, 7th, and 8th) had the response of logarithmic converters (LCs) with a threshold of 500 MeV (event “a”), and the same counter then recorded the single event (event “b”) after a time of Δt.

The recording time was 6664 h. During this time, 2 201 500 events happened in which at least one LC responded on the internal BUST planes (when several LC responded on the plane, the single event (event “b”) was traced only in the counter with the largest energy release).

Figure 4 shows the distribution of such events within $\Delta t = t_b - t_a$ for the interval $\Delta t \leqslant 1$ s. The distribution is well fitted by the decay exponent

$$\exp\left(-\Delta t/\tau\right) \quad \text{at} \quad \tau = (29.7 \pm 0.9) \text{ ms},$$

which is close to the lifetime of ^{12}B and ^{12}N isotopes ($\tau(^{12}\text{B}) = 29.3$ ms, $\tau(^{12}\text{N}) = 15.9$ ms).

It should be mentioned that 1-s interval is too wide for determination of isotope lifetime, if this time is 20–30 ms (the lifetime is shifted to the larger

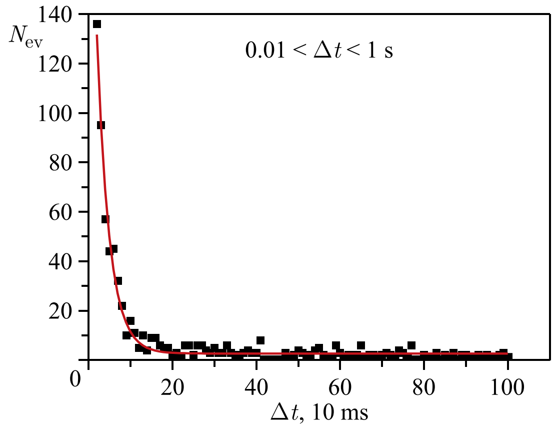

Fig. 4. Distribution of type “b” events vs. Δt

values by uniformly distributed background events). Therefore, we used the interval $0 < \Delta t < 200$ ms to determine the lifetime of decaying isotopes more precisely. This makes $\tau = (21.8 \pm 1.0)$ ms.

We interpret the events of type “b” as electrons and positrons from decays of ^{12}B and ^{12}N isotopes which can appear in the reactions (with π mesons produced in muon-initiated cascades)

$$^{12}\mathrm{C} + \pi^- \to {}^{12}\mathrm{B} + \pi^0, \tag{3.1}$$

$$^{12}\mathrm{C} + \pi^+ \to {}^{12}\mathrm{N} + \pi^0 \tag{3.2}$$

and then decay

$$^{12}\mathrm{B} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e, \quad \tau = 29.3 \text{ ms},$$
$$^{12}\mathrm{N} \to {}^{12}\mathrm{C} + e^+ + \nu_e, \quad \tau = 15.9 \text{ ms}.$$

During the observation time $T = 6664$ h, $N_{a-b} = 683$ events were recorded with $\Delta t \leqslant 0.2$. The total number of background events (with $f = 0.021$ s^{-1}) within this period was $N_{\rm tot} = 510\,000$.

It should be also mentioned that the generation of ^{12}B and ^{12}N isotopes can proceed at an energy release less than the LC operation threshold ($s_0 =$ 500 MeV). Assuming that number N_{a-b} is approximately $\simeq 10\%$ of the total number of reactions (3.1) and (3.2) we can estimate the fraction of the single events associated with the decays of ^{12}B and ^{12}N: $10N_{a-b}/N_{\rm tot} = 0.013$.

Thus, the discrimination of such events cannot lead to an appreciable reduction of the background.

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.

We have studied the afterpulses associated with the decays of ^{12}B and ^{12}N isotopes which can appear in muon-initiated cascades. The contribution of such single events in the total background count rate is $\simeq 1.3\%$. The discrimination of such events cannot lead to an appreciable reduction of the background.

One can see from the expression (2.3) that the "radius of sensitivity" of the Baksan Telescope is $\simeq 20$ kpc. This region includes $\simeq 95\%$ stars of our Galaxy. Over the period of June 30, 1980 to December 31, 2014, the actual observation time was 29.76 yr [12, 33]. 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.

Let $f_{\rm col}$ be the mean frequency of collapses. The probability of collapse absence during the time interval T is (according to the Poisson law) $\exp{(-f_{\rm col}T)}$. An upper bound on the mean frequency of gravitational collapses in the Galaxy at 90% C.L. can be obtained with the help of the expression

$$\exp{(-f_{\rm col}T)} = 0.1. \tag{4.1}$$

Thus,

$$f_{\rm col} < 0.077\ \text{yr}^{-1}, \quad 90\%\ \text{C.L.} \tag{4.2}$$

Recent estimations of the Galactic core-collapse SN rate give roughly the value $\simeq 2{-}5$ events per century (see, e.g., [10]).

It is noteworthy that recently developed two-dimensional (2D) [34–36] and 3D [37–40] 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 [30, 41], i.e., the observed neutrino flux depends on the observer position. The dependence of ν_e- and $\bar{\nu}_e$ fluxes arriving to the Earth on the oscillation scenario only complicates the interpretation.

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