Measurement of the Characteristics of Neutrino Flux from a Supernova Explosion at the Baksan Underground Scintillation Telescope

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Abstract. The experiment on recording neutrino bursts operates since the mid-1980. As a target, we use two parts of the facility with a total mass of 240 tons. Over the period of June 30, 1980 to June 30, 2020, the actual observational time is 34.4 years. No candidate for the stellar core collapse has been detected during the observation period. The corresponding upper bound of the mean frequency of core collapse supernovae in our Galaxy is 0.067 year^{-1} (90% CL).

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1 The Method of Neutrino Burst Detection

The Baksan Underground Scintillation Telescope (BUST) (Alexeyev et al. 1979) operates under the program for the search for neutrino bursts since the middle of 1980. The total observation time amounts to 90% of the calendar time.

The BUST consists of 3184 standard autonomous counters (Novoseltsev et al. 2020). The total scintillator mass is 330 t, and the mass enclosed in three lower horizontal layers (1200 standard counters) is 130 tons. The standard autonomous 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 scintillator volume is viewed by one FEU-49 photomultiplier (PM) with a photocathode diameter of 15 cm through a 10-cm-thick organic glass window (the thick window serves to reduce the light collection nonuniformity). The majority of the events recorded with the Baksan telescope from a supernova explosion will be produced in inverse beta decay (IBD) reactions

$$\overline{\nu}_e + p \to n + e^+ \qquad (1)$$

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 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.

For a supernova (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; below, we will refer to this counter array as the D1 detector), the expected average number of single events in a cluster will be (assuming the $\overline{\nu}_e$ flux is equal to $1/6 \times \varepsilon_{tot}$ and the temperature $T_{\overline{\nu}_e}$ is 4.5 MeV)

$$N_{ev}(D1) \simeq 35 \quad (\textit{no oscillations}) \tag{2}$$

Background events are i) radioactivity (mainly from cosmogeneous isotopes) and ii) cosmic ray muons if only one counter from 3184 is hit. The total count rate from background events (averaged over the period of 2001 – 2019 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.

2 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 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}. The threshold of counter operation is 8 MeV and 10 MeV in D1 and D2 detectors respectively. The count rates of single events in D1 and D2 detectors and the operating stability are shown in Fig. 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 expected average number of detected neutrino events in the D2 detector is $N_{ev}(D2) \simeq 28$ (under the same conditions and assumptions as in (2)). So the expected total number of detected neutrino events (in IBD reactions (1)) reads

$$N_{ev} = N_{ev}(D1) + N_{ev}(D2) \simeq 63 \quad (\textit{no oscillations}) \tag{3}$$

If the conversion of neutrino fluxes on the way to Earth is due only to the MSW effect (Wolfenstein 1978; Mikheyev & Smirnov 1985), then the number

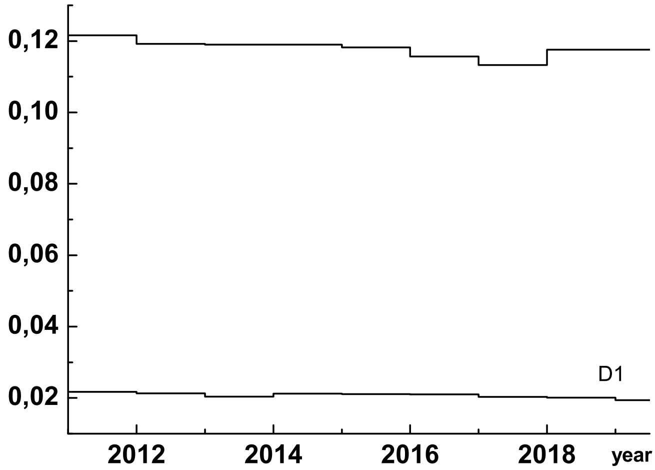

Fig. 1. The count rates of single events in the D1 and the D2 detectors.

of detected events will increase (we have assumed that the temperature of non-electronic neutrinos is $T_x = 6$ MeV):

$$N_{ev}(NH) \simeq 71 \quad (4)$$
$$N_{ev}(IH) \simeq 88 \quad (5)$$

for normal mass hierarchy (NH) and inverted hierarchy (IH) respectively.

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 (3), will be $\simeq$ 250,000. In the first seconds (after a core bounce), we should expect $\simeq (25-30) \times 10^3$ 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 3184 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.

3 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 (3) allows us to expect $\simeq$ 10 neutrino interactions from a most distant SN ($\simeq$ 25 kpc) of our Galaxy.

Over the period of June 30, 1980 to June 30, 2020, the actual observation time was 34.4 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

$$f_{col} < 0.067\ y^{-1} \tag{6}$$

at 90% CL.

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