Search for Neutrino Radiation from the Collapse of Stellar Cores Using LVD Detector

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Abstract—The article presents the latest results with the experiment of the Large Volume Detector located in the Gran Sasso Laboratory at the depth of 3650 m.w.e. LVD has been in operation since 1992 on the program a search for neutrino bursts from stellar core collapses, variations of the cosmic ray muon flux, and investigations of background sources at detecting rare events. According to the data of the LVD neutrino telescope for 29 years of operation (1992–2021), an experimental limitation on the frequency of neutrino bursts from gravitational collapses of stars in the Galaxy was obtained: less than 1 event in 12.6 years \((f = 0.08 \text{ year}^{-1})\) at a 90% confidence level.

Keywords: neutrino, gravitational collapse, underground physics

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1. INTRODUCTION

The emergence of powerful neutrino fluxes in the Galaxy is associated with the formation of neutron stars and black holes—during the gravitational collapse of stars at the last stage of their evolution. According to the standard model of gravitational collapse, during a supernova explosion, neutrinos of all types with energies \((10–20)\) MeV are emitted. The energy going into neutrino radiation is about 10% of the mass of the core of the collapsed star and is divided between six types of neutrinos. For experiments on the detection and emission of neutrino radiation from a collapsing star, the following characteristics are essential: the energy that is carried away by neutrinos of various types; flash duration; the energy spectrum of each type of neutrino; time course of the energy spectrum.

For the detection of electron neutrinos and antineutrinos, experiments with large masses of the working substance have been created. Water (Super-Kamiokande [1], IceCube [2], Baikal-GVD [3]) and scintillators (BUST [4], LVD [5] and no longer working Borexino [6] and ASD [7]) are usually used as working substances. To detect \(\pi_e\), the reaction of inverse beta decay (IBD) is used, which makes the main contribution.

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2. DETECTOR DESCRIPTION

The Large Volume Detector (LVD) is located underground at an average depth 3650 m w.e. (minimal depth 3000 m w.e.), in the Gran Sasso National Laboratory, Istituto Nazionale Fisica Nucleare (Italy). The experiment consists of an array of 840 scintillator counters, 1.5 m³ each, viewed from the top by three photomultipliers. Counters filled with liquid scintillator \((C_nH_{2n}, n = 9.6)\). Sets of eight such containers are placed within steel modules (porthanks) grouped into five columns that have seven horizontal layers. Thirty five modules form a tower. The detector has three towers. The modularity allows LVD to achieve a very high duty cycle. The detector maintenance can be done during data acquisition by stopping only the part that needs to be maintained, even a single counter. This peculiarity allows a dynamic active mass \(M_{\text{act}}\) and a high duty cycle. The experiment has been in operation since June 9, 1992 after a short commissioning phase, its mass increasing from 300 t to its final one, 1000 t, at time of building phase completion in January 2001. The detector has two energy thresholds: trigger (upper) \(E_{\text{HET}} = 4\) MeV, and lower \(E_{\text{LET}} = 0.5\) MeV. The lower one is in turn active only in a 1 ms time-window following the trigger, allowing the detection of \((n,p)\)-captures.
Table 1. Characteristics of clusters with significance \( F_{im} < 1 \text{ year}^{-1} \)

| Cluster date and time | Cluster multiplicity | Duration \( \Delta t_i, s \) | Energy, MeV | Frequency \( 1/F, \text{ year}^{-1} \) |
|----------------------|---------------------|--------------------------|------------|--------------------------|
| 16.04.1994 10:40:49.263 | 7                   | 18.88                    | 26.5       | 1.06                     |
| 27.08.1995 16:18:10.478 | 7                   | 5.49                     | 36.2       | 11.16                    |
| 07.10.1998 15:41:41.775 | 12                  | 90.05                    | 32.2       | 1.76                     |
| 18.07.2009 07:39:20.510 | 12                  | 42.71                    | 14.6       | 4.02                     |
| 25.05.2014 03:54:14.555 | 14                  | 61.56                    | 22.6       | 1.49                     |
| 18.12.2014 20:21:28.787 | 8                   | 9.98                     | 18.8       | 3.22                     |

3. BASIC PRINCIPLE OF NEUTRINO DETECTION

Neutrinos from gravitational collapse can be detected in LVD through charged current and neutral current interactions on proton, carbon nuclei and electrons of the liquid scintillator. The scintillator detector is supported by an iron structure, whose total mass is about 850 t. This can also act as a target for neutrinos and antineutrinos, as the product of interactions in iron can reach the scintillator and be detected [8]. The total target thus consists of \( 8.3 \times 10^{31} \) free protons, \( 4.3 \times 10^{31} \) C nuclei and \( 3.39 \times 10^{32} \) electrons in the scintillator and of \( 9.7 \times 10^{30} \) Fe nuclei in the support structure.

The main reaction of antineutrino interaction is IBD reaction, which creates two detectable signals: the first signal is caused by a positron, followed by neutron capture (\( E_\gamma = 2.2 \) MeV, the average capture time is about 150 \( \mu s \)).

The search for neutrino bursts is based on the identification of event clusters with a low probability of event imitation due to background fluctuations.

To search for supernova neutrino bursts, we analyze the time series of the selected events and look for clusters. While to provide the SNEWS, the on-line network of running neutrino detectors [11], with a prompt alert we use in the burst search method (online mode) a fixed time window (20 s) [9].

SNEWS is SuperNova Early Warning System. Its goal is to provide the astronomical community with early warning of a supernova explosion in our Galaxy so that experimenters can observe the astronomical consequences of a star’s gravitational collapse. SNEWS increases the reliability of events detected simultaneously by several detectors at their threshold of sensitivity.

In this analysis (off-line mode) we consider different burst durations up to 100 s as discussed in detail in [10].

In both cases the selection is essentially a two-step process.

In the first step, we analyze the entire time series to search for clusters of events.

The second step of the process consists in determining if one or more among the detected clusters are neutrino bursts candidates. To this aim, we associate to each of them (characterized by multiplicity \( m_i \) and duration \( \Delta t_i \)) the imitation frequency \( F_{im} \).

This quantity represents the frequency with which background fluctuations can produce, by chance, clusters with multiplicity \( m \geq m_i \) and duration \( \Delta t_i \).

As shown in [12], this quantity, which depends on \((m_i, \Delta t_i)\), on the instantaneous background frequency, \( f_{bk} \) and on the maximum cluster duration chosen for the analysis, \( \Delta t_{max} \) (100 s), can be written as:

\[
F_{im} = f_{bk}^2 \Delta t_{max} \sum_{k>m_i-2} P(k; f_{bk}^i \Delta t_i), \tag{1}
\]

where \( P(k; f_{bk}^i \Delta t_i) \) is the Poisson probability to have \( k \) events in the time window \( \Delta t_i \) and being \( f_{bk}^i \) the background frequency.

Given the long duration of the LVD data set, we choose 1/100 year\(^{-1}\) as imitation-frequency threshold, \( F_{im}^{th} \). This means that a cluster \((m_i, \Delta t_i)\) is considered a neutrino burst candidate if:

\[
\sum_{k>m_i-2} P(k; f_{bk}^i \Delta t_i) < F_{im}^{th}/f_{bk}^2 \Delta t_{max}. \tag{2}
\]

From the viewpoint of the search for neutrino bursts, the introduction of the imitation frequency allows us to define a priori the statistical significance of each cluster in terms of the background frequency, in general not constant but actually changing with the detector active mass.
4. RESULTS FOR OFF-LINE MODE: FOUND CLUSTERS

All found clusters with $F_{\text{im}} < 1/\text{year}$ have been checked in terms of energy spectra and low energy signals that may be the signature of the IBD interactions. They are fully compatible with chance coincidence among background signals. The Table I shows all found 6 clusters with significance $F_{\text{im}} < 1\ \text{year}^{-1}$. Besides the date, we show multiplicity, duration, average energy of events and imitation frequency.

5. CONCLUSIONS

In this paper, we have summarized the results of the search for neutrino bursts from gravitational collapses of stars. Off-line analysis was performed using LVD data collected from 1992 to 2021.

Neutrino burst candidates are selected as clusters of events, with duration up to 100 s, statistically selected by having an imitation frequency less than $1/100\ \text{year}^{-1}$. This makes our search model-independent, as the duration of a neutrino burst due to a supernova explosion is unknown.

During the observation period, none of the detected clusters has a simulation frequency of less than $1/100\ \text{year}^{-1}$. Thus, it can be concluded that no signals from supernova explosions were recorded at a distance of up to 25 kpc during the observation period.

According to the LVD data for 29 years of work, an experimental limitation on the frequency of neutrino bursts from gravitational collapses of stars in the Galaxy has been obtained: less than 1 event in 12.6 at a 90% confidence level.

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CONFLICT OF INTEREST

The author declares that they have no conflicts of interest.

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