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Abstract. The iron-scintillation detector LVD is designed to detect various types of neutrinos from collapsing stars in our Galaxy and in Magellanic Clouds. The report will present the results for 28 years of the experiment's existence. New limit has been set on the frequency of supernova detection in our Galaxy. The results of the correlation analysis between detectors LVD and BUST are presented. The results obtained during event registration from the CERN neutrino beam are discussed.

1. Introduction

The major purpose of Large Volume Detector (LVD) is monitoring the Galaxy and its satellites to study neutrino bursts from gravitational stellar collapses.

Supernova explosion in our Galaxy is a very rare phenomenon. Appearing in 1604, Kepler's Supernova is the most recent supernova in our Galaxy to have been unquestionably observed with the naked eye. It is estimated, around 1667, light from type II supernova explosion in the constellation Cassiopeia in our Galaxy reached Earth. At the moment, neutrino burst has been detected only once, 23 February 1987. It was a type II supernova (SN1987A) in the Large Magellanic Cloud, a dwarf satellite galaxy of the Milky Way.

That's why experiments in this field must be long-term, work without interruption, have a low background and estimate it correctly, have a low energy threshold.

In this article, we'll present the main results in neutrino physics that were obtained by LVD Collaboration over the 28 years of the experiment's existence.

2. Large Volume Detector (LVD)

LVD is the largest iron-scintillation telescope in the world with a total mass of 2 kt (1 kt of liquid scintillator and 1 kt of iron in the detector structure). It is located in the Gran Sasso National Laboratory (LNGS), Italy, at the average depth of 3650 m w. e. [1]. It has started operation in 1992. The final upgrade took place in 2001, when LVD became fully operational. Active mass increased from 300t up to 1 kt. Since July 2005 LVD has taken part to the Supernovae Early Warning System (SNEWS), the network of supernova neutrino observatories which designed to give early warning to astronomers if supernova explosion happens in the our or satellite galaxies. Since 2006 and up to 2012 it has been acting as a far-monitor of the CNGS (CERN Neutrinos to Gran Sasso) beam [2, 3].

LVD is a three-dimensional array of 840 independent scintillator counters with a volume of 1.5 m^3 each (1.5 m $\times$ 1 m $\times$ 1m). Any counter contains 1.2 t of liquid scintillator (C_nH_{2n}, n=9.6), for a total mass 1 kt [4]. Each counter is viewed by three photomultipliers (PMTs). The PMTs have different high voltage values, so the background from PMT after-pulses is minimized. Mean energy threshold of LVD detector is 4 MeV. Trigger opens time gate for a period of 1 ms with an energy threshold of 1 MeV.

LVD consists of 3 towers. Every tower has 5 columns and 7 levels, any column includes 8 counters per level situated in iron portatanks. The modular structure of the detector is presented in Figure 1. The modularity is a key feature of LVD, since it allows to achieve a very high live time, which is essential in the search for unpredictable sporadic events. LVD can be serviced during data taking by stopping only the part of the detector that needs maintenance. Duty cycle and active mass along the experiment life, up to 2016, May 27th are shown in Figure 2 [5].

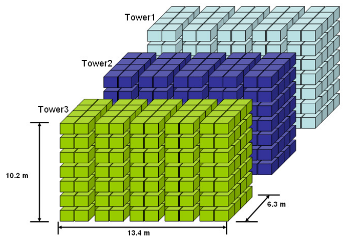


Figure 1. The modular structure of the LVD detector.

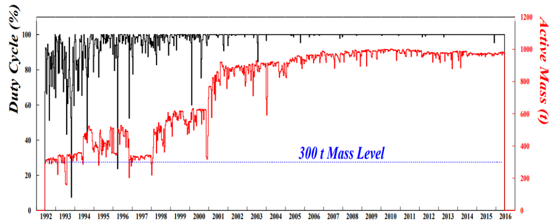


Figure 2. Duty cycle (in black) and active mass (in red) as a function of time.

3. SuperNova signal detection

In the frames of Standard Collapse Model average energies of electron antineutrinos should be about 12 MeV, electron neutrinos should be about 10 MeV, other types of neutrinos should be about 20-25 MeV.

The trigger logic of LVD is optimized for the detection of both products of the inverse beta decay (IBD) $\overline{\nu}_e p \to e^+ n$, the main neutrino interaction channel. LVD is possible to detect not only electron antineutrino via the IBD reaction but also electron neutrinos due to their interaction with iron and other types of neutrinos via interaction on carbon nuclei and electrons of the liquid scintillator. All neutrino interaction channels in LVD are presented in Table 1 [6].

Table 1. The ν interaction channels in LVD.

	ν interaction channel	E_ν threshold	%
1	$\overline{\nu}_e + p \to e^+ + n$	1.8 MeV	88
2	$\nu_e +^{12} C \to^{12} N + e^-$	17.3 MeV	1.5
3	$\overline{\nu}_e +^{12} C \to^{12} B + e^+$	14.4 MeV	1.0
4	$\nu_i +^{12} C \to^{\nu}_{i} +12C^* + \gamma$	15.1 MeV	2.0
5	$\nu_i + e^- \to^{\nu}_{i} +e^-$	-	3.0
6	$\nu_e +^{56} Fe \to^{56} Co^* + e^-$	10.0 MeV	3.0
7	$\overline{\nu}_e +^{56} Fe \to^{56} Mn + e^+$	12.5 MeV	0.5
8	$\nu_i +^{56} Fe \to^{\nu}_{i} +56Fe^* + \gamma$	15.0 MeV	2.0

To search for supernova neutrino bursts, we followed the next scheme of event selection in the detector data. At the first stage, events caused by muon interactions in the detector are excluded. Such events are characterized by the response of two or more counters in a time window less than 175 ns. Also external counters are excluded from the analysis, i.e. counters bordering on the surrounding volume of the LVD detector. After that we analyzed the time series of the selected events by two different ways.

First analysis was done for all clusters with multiplicity more than 30 and with duration less than 100 seconds. Energy threshold was 5 MeV. For each cluster, average time of its detecting and duration was calculated. The counting rate in the LVD detector was about 0.04 events per second during 2006-2017 yy. Clusters of events from collapsing stars have not been detected [7].

For another analysis events were selected in the [10-100] MeV energy range with burst durations up to 100 s. The counting rate in the detector was about 0.03 events per second [5]. Only 6 clusters were obtained with a signal imitation frequency $F_{im} < 1$ year^{-1} during 25 years of the LVD operation. They are fully compatible with chance coincidence among background signal. No evidence of neutrino burst signal is found. The upper limit of the rate of gravitational stellar collapses out to 25 kpc is 0.1 per year at 90% c.l.

We wait 500 events only due to IBD reaction and 77 due to other interactions in the case of explosion in the center of our Galaxy. While we set the limit on the rate of gravitational stellar collapses in our Galaxy. It is 0.082 events$\cdot$ year^{-1} at 90% c.l. for 28 years of the experiment's operation.

4. Background estimation

Background events are always random events. It means that time between them has an exponential distribution. The event time distributions in the LVD detector are presented in [7]. Pseudorandom number generator is used for the calculations. Time between events is distributed exponentially and experimental results do not contradict the calculations.

Neutrino bursts from SN1987A have been recorded by four underground detectors (LSD, BUST, Kamiokande II, and IMB), that were operating at that time. LSD (Large Scintillation Detector) experiment, prototype of LVD, smaller LVD in 7 times, detected 5 events at 02:52 UT within 7 seconds. It was a significant increase from the previously observed background level. BUST(Baksan Underground Scintillation Telescope), Kamiokande II, IMB (Irvine–Michigan–Brookhaven) detectors registered 6, 8 and 12 events respectively at 07:35 UT in a burst lasting less than 16 seconds. It was a very incomprehensible result. Before it was assumed that stellar collapse should be accompanied by the one neutrino burst [8].

For this reason, it was decided to check the coincidences within one second between the setups for background estimation. As a result, a statistically significant increase was found in the number of matches between single pulses in the LSD and BUST detectors and in the LSD and Kamiokande detectors around 02:52 UT [9]. Due to LSD-BUST coincidence analysis 13 events within 2 hours were obtained.

4.1. LVD and BUST coincidences

The same coincidence analysis have been made between LVD and BUST in 2011-2014 yy [10]. Results are presented in the Table 2.

As can be seen, 5 coincidences per day recorded only twice during the 4 years of readout experimental data. This fact gives the importance of the experimental result obtained in 1987. On the average, the counting rate of random coincidences is approximately 1 coincidence per day.

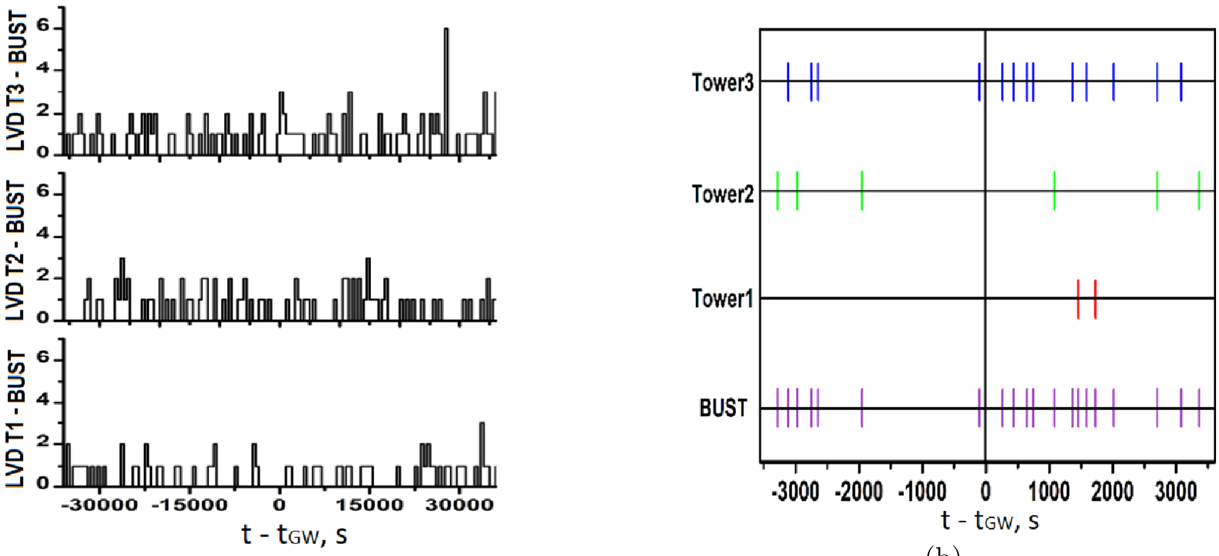
4.2. GW170817

Next interesting event happened at 17 August of 2017 year. Gravitational wave signal, which was produced by merging of two neutron stars, originating from the shell elliptical galaxy NGC 4993, was observed by LIGO and Virgo detectors [11]. We have analyzed LVD and BUST data for 1 second coincidence in the time range 10 days before and after of this data [12].

Table 2. Number of coincidences per day for 2011-2014 yy.

N_{coin}	2011	2012	2013	2014
1	143	121	116	130
2	51	51	54	46
3	11	9	11	16
4	4	3	8	5
5	0	0	1	1

Figure 3 (a) shows the coincidence in 1 second of single pulses in LVD (for each tower separately) and BUST in the period of 10 hours before and after the signal GW170817 (bin with a duration of 500 s). The number of matches of single pulses do not have significant deviations from the average values. Figure 3 (b) shows a time diagram of the coincidence of single pulses in LVD and BUST in the hourly neighborhood of registration GW170817. A dash in the time diagram corresponds to one pulse in the detector. The figure shows which tower of the LVD detector recorded a single pulse.



(a) (b)

Figure 3. (a) The number of matches of single pulses in 500 s in LVD and BUST; (b) Timing diagram of pulse coincidence in LVD and BUST detectors.

Most coincident single pulses are observed in the third LVD tower. Within 1000 s after the registration of the gravitational wave, cluster of 5 coincident pulses was observed in the BUST and in the third LVD tower. The cluster duration is 477 s; the first coincidence in the cluster was found 266 s later than the registration of the gravitational wave. Its average background formation time is 26.5 hours. Nevertheless, results seems like background events.

5. Neutrino velocity measurement

A stringent limit for electron anti-neutrino energies about 10 MeV, $|v_\nu - c|/c < 2 \times 10^{-9}$, has been obtained from the observation of SN1987A [13]. Nevertheless, the task of neutrino speed measurement in the CNGS project framework was a very interesting, but very difficult from a technical point of view.

Muon neutrino beam started from the SPS accelerator from CERN, gone 731 km underground and come to Gran Sasso detectors. Average energy of this beam was 17 GeV. Only during two weeks special for accurate measurement of the neutrino velocity the next beam structure was made. Proton waveform had 4 batch mode. Time between modes was 300 ns, time inside one mode between signals was 100 ns. Signal width was about 3 ns.

The resulting 48 events have been used to determine the time-of-flight of ν_μ. On the Figure 4 proton waveform in the CERN has light grey colour, events in LVD marked as black lines.

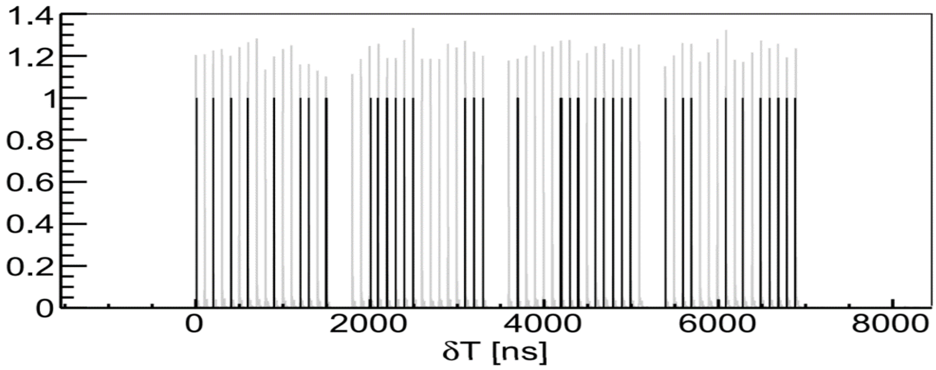


Figure 4. Comparison of the δT values of the 48 selected events (black lines) with the summed waveforms of proton extraction (grey lines).

The beam structure is clearly identifiable, and every LVD event can be associated to the closest beam-waveform peak. For each event the time difference with respect to the maximum intensity of the peak were calculated. The deviation from the time expected from propagation at the speed of light has been found to be: $\delta t = -0.3 \pm 0.6_{stat} \pm 3.2_{sys}$. The corresponding 99% confidence limit on the speed of neutrino is: $-3.3 \times 10^{-6} < (v_\nu - c)/c < 3.5 \times 10^{-6}$ [14].

6. Conclusion

The main results in neutrino physics obtained by LVD Collaboration over the 28 years of the experiment's existence were presented. New limit has been set on the frequency of Supernova detection in our Galaxy: 0.082 events$\cdot$ year^{-1} at 90% c.l. The results of the correlation analysis between detectors LVD and BUST are presented. 5 coincidences per day recorded only twice during the 4 years of readout experimental data. This fact gives the importance of the experimental result obtained in 1987. Results for GW170817 seems like background events. The corresponding 99% confidence limit on the speed of muon neutrino is: $-3.3 \times 10^{-6} < (v_\nu - c)/c < 3.5 \times 10^{-6}$.

6.1. Acknowledgments

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