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FIRST RESULTS OF A SEARCH FOR NEUTRINOS FROM COLLAPSING STARS WITH THE LVD AT GRAN SASSO

The LVD Collaboration

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INFN - Laboratori Nazionali del Gran Sasso

**First Results of a Search for Neutrinos
from Collapsing Stars with the LVD at Gran Sasso**

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Abstract

The Large Volume Detector (LVD) in the Gran Sasso underground Laboratory is a multipurpose detector consisting of a large volume of liquid scintillator interleaved with limited streamer tubes. In this paper we discuss its power to study low energy cosmic neutrinos.

The results show that the first LVD tower (368 tons of liquid scintillator) is well suited to detect neutrinos from gravitational stellar collapses within all of our Galaxy over a wide range of burst duration (up to a few hundred seconds).

No burst candidates have been observed in the first two months of data taking.

Sommario

Il Large Volume Detector (LVD) dei Laboratori Nazionali del Gran Sasso è un esperimento a multiscopi, consistente di un grande volume di scintillatore liquido interconnesso con tubi a streamer limitato. In questo lavoro si discutono le potenzialità di LVD per lo studio di neutrini cosmici di bassa energia.

I risultati mostrano che la prima torre (368 ton di scintillatore liquido) di LVD è molto adatta alla rivelazione di neutrini da collassi gravitazionali stellari che avvengano entro l'intera nostra Galassia e con un ampio intervallo di durata temporale del fenomeno (fino ad alcune centinaia di secondi).

Nessun candidato è stato osservato nei primi due mesi di presa dati.

1 - Introduction

The Large Volume Detector (LVD) [1,2] in the Gran Sasso underground Laboratory is a multipurpose detector consisting of a large volume of liquid scintillator interleaved with limited streamer tubes in a compact 3-dimensional geometry. A major purpose of the LVD neutrino observatory is to search for stellar collapses.

The detector has a modular structure composed of 190 modules arranged in 5 towers. Each module has 8 scintillator counters surrounded by an L-shaped tracking system. The total mass is 1840 tons of scintillator and the dimensions are 40m x 12m x 13m. Presently the first tower is taking data and the second is under construction.

The first quarter tower (>90 tons of liquid scintillator) became operational in October 1991 and the whole tower (368 tons) was turned on in June 1992. This mass of liquid scintillator makes the first LVD tower one of the largest supernovae neutrino observatories in the world and the largest one based on liquid scintillator.

In this paper the power of LVD to study low energy cosmic neutrinos is discussed, and the result of a search for stellar collapse signals during this initial period of operation is presented.

2 - Supernovae neutrino detection in the LVD

For a burst of 3×10^{53} erg emitted in neutrinos of all flavors at the galactic center (8.5 kpc), the expected numbers of interactions in the LVD have been estimated[1-3]. These estimates assume equipartition of energy, the Fermi-Dirac neutrino energy spectra and temperatures of the ν_e , $\bar{\nu}_e$ and $\nu_{\mu\tau}$, $\bar{\nu}_{\mu\tau}$ neutrinospheres to be in the ranges 3 to 5 MeV and 6 to 10 MeV, respectively. The predicted numbers of observed events in the LVD above the energy threshold of 7MeV are listed in Table I.

Different temperatures T of the neutrinospheres, particularly of the electron neutrinosphere, result in different energy spectra and consequently different numbers of interactions. The energy spectrum of the expected neutrino interactions with protons and ^{12}C nuclei is shown in Fig.1 for $T_{\nu_e} = 3$ MeV and $T_{\nu_{\mu\tau}} = 6$ MeV.

The burst's duration depends on the neutrino emission in the cooling stage of the stellar collapse. According to most theoretical models, this emission has a duration of the order of 10 seconds.

To keep the following considerations independent from the models' parameters, we have used, for LVD 1st tower, the conservative value of 100 interactions due to a SN at the Galactic Center and burst duration up to 100 sec.

Each counter is self-triggered by the three fold coincidence of the photomultiplier signals after discrimination. This high energy threshold (HET) allows the detection of single interactions occurring in a scintillation counter (*singles*) and can be set in the range 2 to 10 MeV.

The sum of the charges from the three photomultipliers is measured and recorded by the C-176. Its ADC has a dynamic range of 12 bits, a conversion time of 800 nsec (total dead time per counter) and an accuracy of about 100 keV/ch.

During the 1 msec period after the trigger a low energy threshold (LET) is enabled, which allows the detection of the 2.2 MeV photons from (n,p) capture. Both the time and amplitude of the signals from these photons are measured.

The time of each event relative to the UT time (given by the laboratory atomic clock) is measured with an accuracy of 12.5 nsec, and the total information (charge and time) related to each event is stored in a FIFO buffer which is shared by eight counters and can store up to 1024 signals.

The read-out system is triggered by the OR of the HET signals of all scintillator counters. The read out procedure of the C-176 FIFO buffers does not introduce any dead time and it is started with a 1 msec delay after the trigger in order to allow the complete event development.

- 3.3 The background

Cosmic ray muons have a rate of $3 \cdot 10^{-2}$ Hz for the whole tower. They are easily rejected by the combined observation of their high energy release, the time coincidence between counters, and reconstructed tracks from the tracking system.

With the present energy threshold (HET ~ 7 MeV) natural radioactivity, essentially due to gammas and neutrons, gives an event rate of $1.1 \cdot 10^{-1}$ Hz for the whole tower. The integral counting rate vs. the high energy threshold for the whole tower is shown in Fig.2.

In the LVD experiment particular attention was paid to reducing the background due to natural radioactivity. This was achieved by minimizing the total surface exposed to the rock, by choosing materials with low radioactive contamination and by shielding with iron and borax paraffin. The results of the shielding can be seen in Fig.3, where the average counting rate per counter at $E > 1.5$ MeV and $E > 7$ MeV is plotted as a function of the counter position. The tower has been divided into the 8 levels from the floor to the top. A 2 cm layer of iron and a 10 cm layer of borax paraffin are set beneath the counters on the floor, while the top level counters have 20% of their surface directly exposed to the rock radioactivity.

The average rate per counter, for energy release greater than 1.5 MeV, is about $2 \cdot 10^2$ Hz when averaged over all 304 counters in the full tower, and only 40 Hz when averaged over the 88 counters at the core of the tower.

Table I

Predicted numbers of events detected in the LVD from a stellar collapse at the galactic center ($E_{th} = 7 \text{ Mev}$)

	LVD (1840 tons)	LVD 1 tower (368 tons)
(1) c.c. $\bar{\nu}_e + p \rightarrow n + e^+$ $n + p \rightarrow D + \gamma$	503 $\div$ 984	100 $\div$ 197
(2) n.c. $\bar{\nu}_{e\mu\tau} + {}^{12}_6\text{C} \rightarrow {}^{12}_6\text{C} + \bar{\nu}_{e\mu\tau} + \gamma$	28 $\div$ 82	5 $\div$ 16
(3) e.s. $\nu_x + e^- \rightarrow \nu_x + e^-$	7 $\div$ 10	1 $\div$ 2
(4) c.c. $\bar{\nu}_e + {}^{12}_6\text{C} \rightarrow {}^{12}_5\text{B} + e^+$	2 $\div$ 15	0 $\div$ 3
(5) c.c. $\nu_e + {}^{12}_6\text{C} \rightarrow {}^{12}_7\text{N} + e^-$	1 $\div$ 10	0 $\div$ 2

3 - The LVD experiment

- 3.1 The scintillator

The LVD consists of 190 modules arranged in five towers. Each module contains eight scintillation counters with an active volume of 1m x 1.5m x 1m each. The internal walls of all counters are lined with aluminized mylar foil for light reflection. The scintillator is observed by three photomultipliers (15 cm diameter) placed on the top of the counter. Each module contains 9.6 tons of liquid scintillator and 6.7 tons of steel.

The liquid scintillator (C_nH_{2n} $\langle n \rangle = 9.6$) has the same properties as that used at the Baksan^[4], Artemovsk^[5] and Mont Blanc^[6] underground laboratories. The density is 0.8 g/cm³, the decay time is 5 nsec, and the attenuation length is >15 m ($\lambda = 420\text{nm}$).

The light output for an energy loss of 1 MeV is approximately 15 photoelectrons on the three photomultipliers of a counter. The energy resolution is about 15% for a 10 MeV energy release, where it begins to be dominated by leakage effects in the counter^[7].

- 3.2 The scintillator electronics

The design of the gravitational collapse electronics was based on the experience gained in the LSD Mont Blanc experiment^[6] incorporating new devices and technology. The electronics is constructed in modular form to accommodate the 4500 channels of the LVD experiment. Two electronic modules^[8], C-175 (discriminator) and C-176 (ADC,TDC), were specifically designed for the detection of the e^+ signals, and the delayed n-capture, from the $\bar{\nu}_e$ interaction with free protons (reaction 1 of Table I).

4 - Detector energy calibration and n-capture detection efficiency

Cosmic ray muons crossing the detector at a rate of $1 \text{ m}^{-2} \text{ hour}^{-1}$ provide the first reference point for the energy calibration of each scintillation counter. The most probable energy loss of vertical muons in the counter is $\sim 165 \text{ MeV}$.

A low activity ^{252}Cf source and a semiconductor detector, both contained in a thin stainless steel cylindrical box^[5,6], can be placed in several positions inside the liquid scintillation counter through an L shaped rigid pipe. This source provides a second reference point for energy calibration. It emits on the average 3.7 neutrons per fission. These are captured by the scintillator protons with the emission of 2.23 MeV gamma rays.

When the spontaneous fission occurs, the counter is triggered by the detection of the prompt gamma pulses with energies above the HET. These simulate the positron signals in the $\bar{\nu}_e + p$ interaction. Triggering is also initiated by the signal produced by the fission fragments in the semiconductor detector contained in the source envelope.

During the 1 msec interval after the trigger measurements are made of: i) the charge distribution of pulses (for the energy calibration of the counter); ii) the time delay among them (to check the event identification); iii) the pulse multiplicity (to evaluate the efficiency of the neutron detection).

The background is directly measured in the absence of the source by using a random trigger. It is also estimated from the time delay distribution of secondary pulses by making a fit with an exponential, due to n-capture, plus a flat distribution, due to background. Because of the low activity of the source ($\sim 10 \text{ fissions min}^{-1}$) pile up is practically absent.

The 2.2 MeV photon energy spectrum resulting from the calibration of a counter and the normalized background spectrum are shown in Fig.4. The energy resolution (σ_E / E) for 2.2 MeV γ 's emitted in the center of the counter is better than 40%. The mean life time for neutron capture inside the liquid scintillator is $205 \pm 5 \text{ } \mu\text{sec}$ in agreement with other measurements^[6] (see Fig.5).

The LET multiplicity distribution inside the 1 msec window with the neutron source is compared with that for pure background in Fig.6. From these measurements and the number of neutrons emitted per fission, the neutron detection efficiency for the counter central volume is found to be $\sim 80\%$. A complete set of measurements with the ^{252}Cf source in different positions inside the scintillator counter, compared with a Monte Carlo simulation, shows that the average counter efficiency for n-capture detection is $\sim 60\%$ ^[9].

5 - Analysis methods

In the search for neutrino bursts from gravitational stellar collapses, two main features must be considered: fast event recognition and precise absolute timing of the burst.

The neutrino burst emitted by a collapsing core is expected to occur very much earlier than the increase of the optical emission. The fast recognition of the burst by an international neutrino detector network could alert astronomical observatories and permit a detailed study of the first stages of the supernova evolution.

In the LVD experiment the liquid scintillator counting rate, after muon subtraction, is continuously monitored by the Supernova On-line Monitor (SOM), a high priority task which examines all the events. This on-line burst selection is based on pure statistical analysis of HET triggers: the SOM analyzes the clustering characteristics of the time sequence of single pulses; time coincidences between different counters are assumed to be muons and are rejected. A cluster of multiplicity m and duration Δt is defined as a sequence of m events within a time interval $\Delta t \leq 100$ sec. Each such cluster is compared with the corresponding Poisson probability computed on the basis of the current trigger rate. If the probability of observing such a cluster is lower than a preset value, (e.g. 0.1 year^{-1}) the cluster is flagged and the corresponding data copied into the Burst Candidate Data File. A large value has been chosen for the maximum time interval Δt in order to keep this preliminary automatic selection model-independent.

After the candidate selection has been made on a purely statistical basis, a complete analysis of the cluster selected by the SOM will test its consistency with a neutrino burst. This will be done on the basis of the topological distribution of pulses inside the entire detector, their energy distribution, and the presence of delayed low energy pulses from n -capture which characterize $\bar{\nu}_e$ interactions.

As we have seen (§ 3) the average background LET counting rate is ~ 200 Hz. The expected LET multiplicity in a $600 \mu\text{sec}$ window (~ 3 n -capture lifetimes) is therefore 0.12 from background and 0.60 for a $\bar{\nu}_e$ interaction identified by neutron capture. If we consider for example $100 \bar{\nu}_e$ interactions, we expect 12 ± 4 LET pulses from background and 60 ± 8 from n -capture, thus showing the real statistical possibility of identifying $\bar{\nu}_e$ interactions even with this first "tower".

Precise knowledge of the universal time of the ν burst from a supernova collapse is obviously of primary importance in order to establish, without uncertainties, time coincidences among events detected by different neutrino observatories. The universal time for the LVD is provided by the Gran Sasso Laboratory rubidium atomic clock, which serves all the experiments. The present accuracy of the absolute time is $100 \mu\text{sec}$ and it is expected to be improved to $1 \mu\text{sec}$ in the near future. The relative time accuracy between scintillation counter events is 12.5 nsec .

6 - Results

Since June 1991 the LVD experiment has been sensitive to ν bursts from gravitational stellar collapses. The liquid scintillator mass has increased from 20 in June 1991 to 368 tons at present. In June 1992 the first full LVD tower was completely instrumented and turned on. Automatic supernova search software has been activated only recently due to the on-going construction, debugging and calibration of the detector.

From 11-June to 25-August 1992, 570134 "singles" were detected in 57.62 days of running time (running time efficiency = 76%). The average rate of singles in the whole tower for energy release greater than 7 MeV is 0.115 Hz (413 events/hr). The scintillator trigger stability for the whole period is shown in Fig.7.

Fig.8 shows the comparison between the expected (assuming Poisson background) and measured numbers of clusters versus their time duration for different cluster multiplicities. The agreement between the full data set and the curves justifies using the Poisson distribution to describe the background behavior.

An $(m, \Delta t)$ scatter plot of clusters is presented in Fig.9. The curves in this figure represent the limit above which the probability to have at least one cluster per year due to Poisson fluctuations is 10^{-1} and 10^{-5} .

As we have discussed in section 2 for an energy threshold of 7 MeV, the expected number of pulses from $(\bar{\nu}_e + p)$ interactions in our detector due to a supernova explosion at the galactic center is $m \geq 100$. A cluster of events with these characteristics is far from the curves of Fig.9, even for a burst duration of the order of 100 seconds. This means that the probability to have one of these clusters due to background fluctuation in 1 year is much lower than 10^{-10} .

The maximum distance of a detectable collapse is a function of the burst duration: as the distance to the collapsing star increases, the number of interactions decreases and therefore the detectable burst duration also decreases. For example, at the distance of 20 kpc, which includes more than 95% of the stars in our galaxy, the expected number of neutrino interactions from a collapsing star ranges from 18 to 36. For this case, for a running time of 1 year, the probability to have one of these clusters due to Poisson fluctuations remains less than 10^{-5} for a burst duration up to 10 seconds.

Notice that all "singles" with energy release greater than the HET level of 7 MeV we are now using in hardware, have been taken into account in the present analysis; the corresponding tower frequency being 0.115 Hz. Clearly, lower is the HET level and fainter is the detectable burst, but for a standard collapse an energy cut introduced in software in the event selection increases the signal to noise ratio. For example a cut at $E \geq 10$ MeV reduces the tower counting rate to 0.019 Hz (as shown in Fig. 2) but the expected number of detectable interactions is almost unchanged: $85 \div 190$ for a collapse at the galactic center, and $15 \div 34$ at 20 kpc.

The advantages of this technique ($E \geq 10$ MeV off-line) are shown in Fig.10, where the previous analysis is repeated with the energy cut. In this case, for a running time of one year, the probability to have one cluster with $m > 15$ pulses due to background fluctuations remains less than 10^{-5} for a burst duration up to 1 minute. On the other hand, for a fixed burst duration of 10 sec, the improvement of the signal to noise ratio is better than 10^5 .

From these considerations we are allowed to conclude that the present LVD first tower is very well suited to monitoring gravitational stellar collapses in the whole galaxy for a wide range of neutrino burst durations.

7 - Discussion and conclusions

The LVD experiment has been operational since June 1992 as a detector for neutrino bursts from collapsing stars. The liquid scintillator mass instrumented is one fifth of the final designed mass. Even in the present configuration, the LVD is the most sensitive liquid scintillator supernova detector currently operational. In this paper we have studied the LVD capability to monitor the entire galaxy in searching for gravitational stellar collapses over a wide range of burst durations.

No evidence for neutrino bursts from collapsing stars has been found in this first period of data taking.

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FIGURE CAPTIONS

- Fig.1 - Expected energy spectrum of neutrino interactions from a supernova collapse.
- Fig.2 - Full tower “singles” integral counting rate versus the high energy threshold.
- Fig.3 - Average counting rate at $E > 1.5$ MeV and $E > 7$ MeV for counters located at different levels from the floor (level 1) to the top (level 8).
- Fig.4 - Energy spectrum of 2.2 MeV photons produced by neutron capture in the scintillator compared with the normalized background spectrum (dashed). Notice that the background is so low that we have to amplify the vertical scale by a factor of 10 in order to have it's shape visible when compared with the measured spectrum.
- Fig.5 - Time delay distribution of LET signals from the ^{252}Cf fission.
- Fig.6 - Multiplicity distribution of LET signals for fission events (circles) compared with background multiplicity (triangles).
- Fig.7 - Scintillator trigger rate [events per hour] during the whole period.
- Fig.8 - Comparison between expected and measured number of clusters with multiplicity = m and duration Δt .
- Fig.9 - Clusters scatter plot. Solid lines represent the limit above which the probability to have one or more clusters due to Poisson fluctuation in one year is $10^{-1}, 10^{-5}$. The dashed line represent the limit above which we expect 1 false Supernova alarm for the actual data set duration.
- Fig.10 - Same of Fig.9 with $E \geq 10$ MeV. Notice the remarkable reduction in the background level. For example the signal to noise ratio for a burst duration of 10 sec is improved by a factor of 10^5 with respect to the analysis done without the energy cut.

Fig 1

Fig. 9

Fig. 3

Fig. 4

Fig. 5

Fig 6

Fig. 4

Fig. 9

Fig. 10