RESULTS OF THE LVD EXPERIMENT 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 (at present 562 tons are active) interleaved with limited streamer tubes. In this paper we discuss the results on cosmic neutrinos and cosmic ray muons obtained with the first of five towers of LVD, operational since June 1992.

The results show that LVD is well suited to detect neutrinos from collapsing stars within all our Galaxy, over a wide range of burst duration (up to a few hundreds seconds). No evidence for burst candidates has been found in this period of data taking. The muon intensity as a function of slant depth is presented. An interesting result is that this flux is independent of slant depth beyond a depth of about 14,000 kg/cm² of standard rock, and corresponds to near horizontal muons. This is direct evidence that this flux is due to atmospheric neutrinos interacting in the rock surrounding LVD.

1. The LVD detector

The Large Volume Detector (LVD)\textsuperscript{[1]} 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 geometry. The detector, described in detail in ref.\textsuperscript{[2,3]}, has a modular structure made of 190 identical modules arranged in 5 towers. Each module has 8 scintillation counters surrounded by an L-shaped tracking system. The total mass is 1840 tons of liquid scintillator and the dimensions are 40m x 13m x 12m. The complete first tower is taking data since June 1992, and the second one since June 1994 with the full tracking system and one half of the scintillator counters. The total scintillator mass in data taking at present (562 tons) makes LVD 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 and atmospheric muons is discussed, and the results obtained during this initial period of operation is presented.

The LVD scintillator counters have an active volume of 1m x 1.5m x 1m each. The internal walls are lined with aluminized mylar foil for light reflection. The scintillator is viewed by 3 photomultipliers (15 cm diameter) placed on the top of the counter. Each module contains 8 scintillation counters, with about 9.6 tons of liquid scintillator and 7.5 tons of steel.

A double energy threshold (a High Energy Threshold HET, for positron detection; and a Low Energy Threshold LET, for neutron detection active only during a 1 ms wide gate opened by the main trigger) allows us to
detect both products of the inverse $\beta$ decay, furnishing the signature of $\bar{\nu}_e$ interactions with the protons of the scintillator. Photons emitted by $n$-captures are detected with an average efficiency of $\approx 60\%$. The liquid scintillator properties and the electronics capabilities are described in ref.[4].

The rate of cosmic ray muons, at the LVD depth underground, is about 1 muon per m$^2$ per hour. Muons are easily recognized by the combined observation of their high energy release in the scintillator, the time coincidence between counters, and the reconstructed tracks from the tracking system.

At a HET of $\approx 7$ MeV natural radioactivity, essentially due to gammas and neutrons, gives an event rate of $8 \cdot 10^{-2}$ Hz in one tower. In the LVD, particular attention was paid to reduce 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 covering the floor with iron and borax paraffin. The average counting rate per counter, for energy release greater than 1.5 MeV, is about $2 \cdot 10^2$ Hz when averaged over all 304 counters of one tower, and only 40 Hz when averaged over the 88 counters at the core of the tower.

Each element of an L-shaped tracking detector contains two staggered layers of 6.3 m long limited streamer tubes. The tube has 8 cells with 9x9 mm$^2$ active cross sectional area for each cell. Below and parallel to, and above and perpendicular to, the streamer tubes wires, are 4 cm wide pickup strips ($x$ and $y$ strips) to provide bidimensional information about an ionizing particle’s impact point. The staggered double layer of streamer tubes and their orthogonal readout strips yield an effective strip width of 2 cm with no dead space, high overall tracking efficiency, and an angular resolution better than 4 milliradians. The geometric acceptance of one tower is about 1700 m$^2$sr.

2. Neutrinos from stellar collapses

For a burst of $3 \cdot 10^{53}$ erg emitted in neutrinos of all flavours at the galactic center (8.5 kpc), the expected numbers of interactions in the LVD have been estimated[4]. These estimates assume equipartition of energy, Fermi-Dirac neutrino energy spectra and temperatures of the $\nu_e$, $\bar{\nu}_e$ and $\nu_{\mu\tau}$, $\bar{\nu}_{\mu\tau}$ neutrinospheres to be in the ranges 3 to 5 MeV and 6 to 10 MeV, respectively. For the full experiment (5 towers), the expected number of interactions above an energy threshold of 7 MeV ranges from 500 to 1000, being the difference due to the different theoretical predictions on the neutrino emission from the source. Most of the interactions are due to the inverse $\beta$ decay: $\bar{\nu}_e + p \rightarrow n + e^+$.

The burst 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 present
considerations independent from the parameters of the different models, we have used, for the first LVD tower, the conservative value of 100 interactions due to a supernova at the Galactic Center, and burst duration up to 100 seconds.

The neutrino burst emitted by a collapsing core is expected to occur several hours or days 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 all signals: the SOM analyzes the clustering characteristics of the time sequence of single pulses; time coincidences (\( \Delta t \leq 250 \text{ ns} \)) between contiguous counters are assumed to be muons and are rejected. A cluster of multiplicity \( m \) and duration \( \Delta t \) is defined as a sequence of \( m \) events within a time interval \( \Delta t \leq 100 \text{ seconds} \). 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.

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:

a) topological distribution of pulses. A real burst should have pulses almost uniformly distributed over the entire detector, while background pulses are more frequent in the surface than in the core counters.

b) energy distribution. A real burst should have a Fermi-Dirac spectrum, while the background spectrum drops very strongly with energy.

c) presence of delayed low energy pulses in the gate, i.e. the signature of \( \bar{\nu}_e \) interactions in the scintillator.

Point c requires a short explanation. Since the average background counting rate at \( E > 1.5 \text{ MeV} \) is \( \sim 200 \text{ Hz per counter in the tower, the expected multiplicity in a 600 \mu s wide time window (about 3 n-capture lifetimes) is therefore 0.12 from background and 0.6 for a \( \bar{\nu}_e \) interaction, identified by the delayed \( \gamma \) from neutron capture. If we consider for example a burst of 100 \( \bar{\nu}_e \) interactions, we expect \( 12 \pm 4 \text{ NET} \) pulses from background and \( 60 \pm 8 \) from neutron capture (i.e. \( 72 \pm 9 \) in total). This shows the real statistical possibility of identifying \( \bar{\nu}_e \) interactions in LVD.

Precise knowledge of the universal time of the \( \bar{\nu}_e \) burst from a supernova collapse is 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 atomic rubidium clock, which
serves all the experiments. The present accuracy of the absolute time is 1 μs. The least count of the scintillation counter TDC is 12.5 ns.

Since June 1991 the LVD experiment has been sensitive to neutrino bursts from stellar collapses in our Galaxy. The active mass of liquid scintillator has increased from 20 tons in June 1991 to 368 tons in June 1992, and to 562 tons in June 1994.

We have already published\(^{4,5}\) the results of the off-line analysis of the data from the first LVD tower for the period from 11 June 1992 to 31 May 1993, during which 2,208,574 single events (after muons rejection) were detected in 285.1 days of running time (average running time efficiency = 79%). The average rate of single pulses in the full tower for energy release greater than 7 MeV was 0.09 Hz (324 events/hr). The total exposure in this period was about 244 tons-year. Recently, we have reduced the HET, and extended the analysis from June 1993 to January 1995. In this analysis also the data from the second tower, running since June 1994, have been included.

![Cluster scatter plot](image)

**Fig. 1** - Cluster scatter plot. Solid lines represent the limit above which the probability to have one or more clusters due to Poisson fluctuation of the background in one year is \(10^{-1}, 10^{-5}\). The dashed line represents the limit above which we expect 1 false supernova alarm for the actual data set duration. The expected signal would be far above this curves.
An example of the multiplicity of pulses versus the time duration of the burst, i.e. a $(m,\Delta t)$ scatter plot of clusters from the raw data, taken from ref.[4], is reported in Fig.1. The curves in this figure represent the limit above which, at the average HET of about 7 MeV (corresponding to the threshold of the runs to which the data of fig.1 refer), the expected number of pulses from $(\nu_e + p)$ interactions in our detector due to a supernova explosion at the galactic center is $m > 100$. A cluster of events with these characteristics is far from the curves of fig.1, even for a burst duration of 100 seconds. This means that the probability to observe one of these clusters in LVD due to background fluctuation in 1 year is much lower than $10^{-5}$.

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 in the detector decreases and 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 in one LVD tower with HET ~7 MeV. For this multiplicity, the probability to have one of these clusters due to Poisson fluctuations remains less than $10^{-5}$ for a burst duration up to about 20 to 30 seconds.

From these considerations we are allowed to conclude that the present LVD is already very well suited to monitoring gravitational stellar collapses in the whole Galaxy for a wide range of neutrino burst durations. In this period of data taking no evidence for burst candidates has been found.

3. Cosmic ray muons

The muons reaching LVD are of three types:

a) muons that are the decay products of pions and kaons produced by the interaction of cosmic rays with the earth's atmosphere,
b) muons that are the decay products of short lived particles such as charm mesons, also produced by interactions of cosmic rays with the earth's atmosphere,
c) muons that are produced by the charged currents interactions of muon neutrinos that interact in the rock near the LVD detector. The $\nu_\mu$ are the products of particles that decay in the earth's atmosphere.

At slant depths less than about 14,000 hg/cm$^2$ of standard rock, the major contribution to the muon intensity is muons of type a cited above. Muons of type b above, so called prompt muons, certainly contribute to the muon intensity at slant depths less than 12,000 hg/cm$^2$ of standard rock, but they constitute a much less frequent source of muons than the pions and kaons. The muons of type c are dominant at slant depth greater than about 14,000 hg/cm$^2$ of standard rock.

In this report, which is a summary of ref.[6], we will discuss the results of LVD in studying muons of type a and c; the study of muons of

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type b with LVD is in progress. In particular, we will present our analysis and measurement of the flux of muons produced by neutrinos in the rock close to LVD at a zenithal angle close to 90° and energy above 1 GeV.

The selection of the data sample required that at least one scintillation counter was triggered in the event, and there was a minimum of three space points available for track reconstruction. A complete description of our data selection criteria, as well as the detector acceptance correction for the single muon events, can be found in reference[3]. In total, 978,074 single muon events were selected during 11,366 hours of live time. Note that our study is an inclusive one, namely the data include only events containing single muons, and that they have been acceptance corrected.

![Graph](image)

Fig.2 - Muon vertical intensity as a function of slant depth in standard rock. Note that the size of the circles do not represent the statistical errors, they represent the bin width. The horizontal bars also represent the bin width.

Fig.2 displays the vertical muon intensity as a function of slant depth. The main features of this plot are roughly the exponential shape up to a slant depth of about 14,000 hg/cm² of standard rock and the roughly
constant behaviour beyond that point. These data, which cover over five decades of vertical intensity, can be fit with three parameters over the full range, from 3,000 hg/cm$^2$ to 20,000 hg/cm$^2$ (details of this study are discussed in reference[6]). The function we fit is:

$$I_v(h) = A \cdot e^{-\frac{h}{h_0}}(\frac{h}{h_0})^2 + K$$

Our best fit to these 3 parameters are: $A = (1.77 \pm 0.02) \times 10^{-6}$ cm$^{-2}$s$^{-1}$sr$^{-1}$, $h_0 = (1211 \pm 3)$ hg/cm$^2$ of s.r., $K = (2.98 \pm 1.15) \times 10^{-13}$ cm$^{-2}$s$^{-1}$sr$^{-1}$ (all quoted errors are statistical).

The vertical intensity of the data from our experiment between 3,000 hg/cm$^2$ and 9,000 hg/cm$^2$ have been compared with the results of Nusex, Frejus and Macro. All experiments are in reasonable agreement, taking into account that our work is an exclusive study (only single muons are included in our data set with appropriate corrections), while the other are inclusive ones (muons from all multiplicities are included in their data sets). Our points in the intensity plot should therefore be ~10% lower than the other three experiments.

A direct way to establish the existence of atmospheric muon neutrinos interacting in the rock near an underground detector is to show that for a fixed zenithal angle close to 90° the muon flux is independent of slant depth for depths greater than about 14,000 hg/cm$^2$ of standard rock. The unique topology of the Gran Sasso Laboratory allows us to explore slant depths from 14,000 to 20,000 hg/cm$^2$ of standard rock at a fixed zenithal angle close to 90°. In our data sample there are 17 single muon events beyond a slant depth of 14,000 hg/cm$^2$ of standard rock; of which 14 have a zenithal angle greater than 82.5°. Hence, we have establish that for the fixed zenithal angle of about 90° and for slant depths greater than 14,000 hg/cm$^2$ the muon flux is independent of slant depth. We measure the value of this flux near 90° to be:

$$l(90°) = (8.3 \pm 2.6) \times 10^{-13}$$ cm$^{-2}$s$^{-1}$sr$^{-1}$

As stated above, this is direct evidence of the existence of a muon flux induced by neutrinos in the rock surrounding LVD.

References

DISCUSSION

J. HORVATH: In the occasion of SN 1987 A explosion there was a lack of synchronization between detectors that allowed considerable freedom in the t = 0 respect to each other. How good is the LVD synchronization among everybody this time?

P. GALEOTTI: At the time of SN 1987 A, INB and Mont Blanc had good timing (few ms), but not Kamioka and Baksan (~ 1 min). Now the Gran Sasso laboratory has an UT clock with precision ± 1 µs to which any experiment (including LVD) is connected.

Hence, there is not a timing problem, at least for the Gran Sasso and Mont Blanc experiments. I am sure that also Kamiokande experiment has a good timing, now.

L.W. JONES: Could you estimate when all 5 towers will be operable?

P. GALEOTTI: Several institutions participate in the LVD collaboration from Italy, USA, Russia, Brazil, China and Japan.

It is responsibility of the Russian collaborators to provide the LVD scintillator and they have now some internal difficulty, as anyone knows. In any case, we hope to install 3-full towers at Gran Sasso by the end of 1995. For the other two towers I cannot give any prediction.

A.D. ERLYKIN: Have you derived the spectrum of energies released by cascades in your tower, induced by high energy muons?

P. GALEOTTI: Not yet. We plan to do that.