SN neutrinos in LVD

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The Large Volume Detector (LVD) in the INFN Gran Sasso National Laboratory (LNGS), Italy, is a ν observatory mainly designed to study low energy neutrinos from the gravitational collapse of galactic objects. The experiment has been monitoring the Galaxy since June 1992, under increasing larger configurations: in January 2001 it has reached its final active mass $M = 1$ kt. Next year it will celebrate twenty years of operation. No burst candidate has been found over 6314 days of live-time, since $June\ 6^{th}$ 1992 to $March\ 27^{th}$ 2011, resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy ($D \leq 20$ kpc) is 0.13 y^{-1}.
Since July 2005 LVD participates to the Supernovae Early Warning System (SNEWS), the network of SN neutrino observatories whose main goal is to provide the astronomical community with a prompt alert for the next galactic core collapse supernova explosion.
Since 2006 acts as a far beam monitor for the Cern Neutrinos to Gran Sasso (CNGS) project, the high energy, wide band ν_μ beam, set up at Cern and sent towards the LNGS. Possible upgrade of the experiment have been studied and discussed in the last years.

1 The LVD Detector

The Large Volume Detector (LVD), located in the hall A of the INFN Gran Sasso National Laboratory, Italy, consists of 1000 tons of liquid scintillator arranged in a modular geometry. The major purpose of LVD is the search for neutrinos from Gravitational Stellar Collapses (GSC) in our Galaxy [1].
The detector consists of an array of 840 scintillator counters, 1.5 m^3 each. The whole array is divided in three identical "towers" consisting of 35 "modules" hosting a cluster of 8 counters. Each counter is viewed from the top by three photomultipliers (PMTs). The main neutrino reaction in LVD is $\bar{\nu}_\text{e}\text{p} \to \text{e}^+\text{n}$, which gives two detectable signals: the prompt one, due to the e^+, followed by the signal from the (n,p) capture ($E_\gamma = 2.2$ MeV) with a mean delay of $\simeq 185$ μs.
The trigger logic is optimized for the detection of both products of the inverse beta decay and is based on the three-fold coincidence of the PMTs of a single counter. Each PMT is discriminated at two different thresholds resulting in two possible levels of coincidence between a counter's PMTs: H and L, corresponding to $\mathcal{E}_H \simeq 4$ MeV and $\mathcal{E}_L \simeq 500$ KeV.
The iron support structure of the detector can also act as a target for neutrinos and antineutrinos. The products of the interaction can exit iron and be detected in the liquid scintillator. The signal observable in LVD, in different reactions and due to different kinds of neutrinos, besides providing astrophysical informations on the nature of the collapse, is sensitive to intrin-

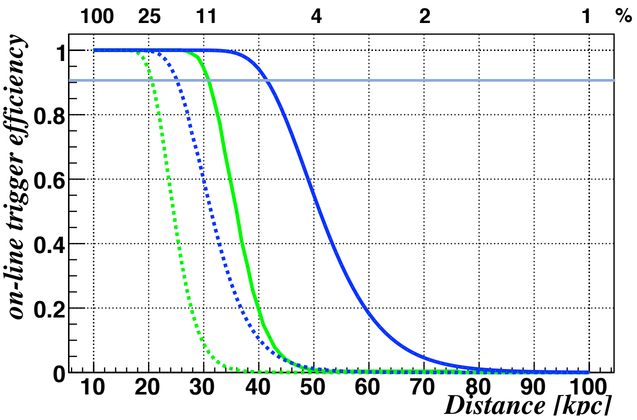

Figure 1: (color online) Trigger efficiency versus distance (lower scale) and percentage of SN1987A signal at 10 kpc (upper scale) for E_{cut}=7-10MeV (light green and dark blue lines, respectively) and M=300t (dotted) and 1000t (continuous) for LVD stand alone.

sic ν properties, as oscillation of massive neutrinos and can give an important contribution to define some of the neutrino oscillation properties still missing. We have studied [2] how neutrino oscillations affect the signal detected by LVD and also evaluated the impact on the signal of the astrophysical parameters of the supernova explosion mechanism, such as the total energy emitted in neutrinos, the star distance, the neutrino–sphere temperatures and the partition of the energy among neutrino flavors.

However, being aware of the fact that the astrophysical parameters of the supernova mechanism are up to now not well defined, to compute the detector sensitivity expressed in terms of source distance or emitted neutrino flux we adopted the following conservative values for the astrophysical parameters [3],[4]: average $\bar{\nu}_e$ energy $\langle E_{\bar{\nu}_e}\rangle$=14 MeV; total radiated energy $E_b = 2.4{\cdot}10^{53}$ erg and average non-electron neutrino energy 20% higher than $\bar{\nu}_e$. Concerning neutrino oscillations we conservatively considered normal mass hierarchy and non-adiabaticity. Taking into account Poisson fluctuations in the cluster multiplicity, we derived the trigger efficiency shown in figure 1 as a function of the distance for LVD working stand-alone [5].

2 Results

LVD has been taking data since June 1992 with increasing mass configurations (sensitive mass being always greater than 300 t), enough to monitor the whole Galaxy ($D \leq 20$ kpc)[1]. In fig. 2 we show sensitive mass and duty cycle of the experiment since $June\ 6^{th}$ 1992 to $March\ 27^{th}$ 2011. The search for ν burst candidates is performed by studying the temporal sequence of triggers and looking for clusters. Preliminary cuts are applied to reject muons and events with an energy release lower than 7 MeV to avoid threshold effects. The neutrino burst candidate selection, widely discussed in [5], requires that the bulk of the events in the

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[1] The results of this search have been periodically updated and published in the ICRC and Neutrino Conference Proceedings, since 1993 till 2011. [6].

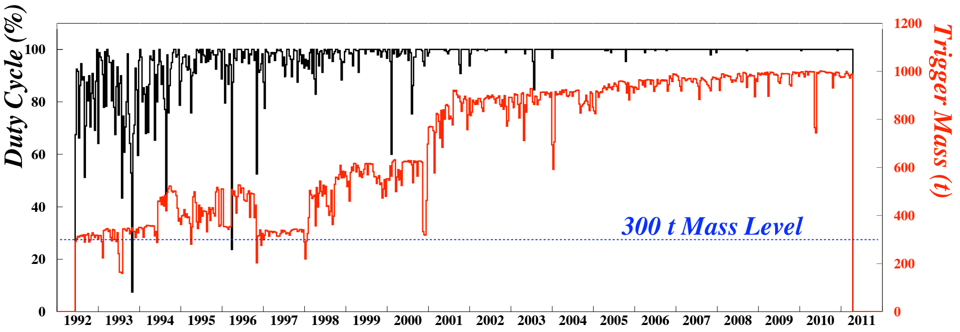

Figure 2: (color online) LVD sensitive mass and duty cycle during 1992-2011.

cluster is contained in a time window of duration 10 sec (relaxed to 100 sec in the off-line analysis) and that events are uniformly distributed inside the array. The candidate is simply characterized by its multiplicity m, i.e. the number of pulses detected in Δt. All the other characteristics of the cluster are left to a subsequent independent analysis. The search for burst candidates is performed, on-line, simultaneously for two values of the energy cut: $\mathrm{E}_{cut} = 7$ MeV ($f_{bk} = 0.2$ Hz) and $\mathrm{E}_{cut} = 10$ MeV ($f_{bk} = 0.03$ Hz). The chosen imitation frequencies, F_{im}, below which the detected cluster will be a candidate supernova event, is 1 per 100 year working stand-alone while it is relaxed to 1 per month working in coincidence with other detectors (SNEWS),[2] and 1 per day for monitoring task. After this pure statistical selection a complete analysis of each detected cluster with $F_{im} \leq 1$/day is performed, to test its consistency with a ν burst through the study of the topological distribution of events inside the array, energy spectrum and time distribution of events in the cluster and time distribution of delayed low energy pulses, signature of $\bar{\nu}_e$ interactions.

No candidates have been found since 1992, see detail in table 1. Since the LVD sensitivity is higher than expected from GSC models (even if the source is at a distance of 20 kpc and for soft neutrino energy spectra), the resulting 90% c.l. upper limit to the rate of gravitational stellar collapses in the Galaxy ($D \leq 20$ kpc) is 0.13 y^{-1}.

3 Possible upgrades

During the last years we have investigated possible upgrades of the detector. In particular we studied the possibility to improve the detector capability in distinguish different neutrino interactions by adding Gd to the liquid scintillator and the possibility of LVD to act as an active shielding and veto with respect to an internal volume.

Doping the liquid scintillator with a small ($\sim 0.15\%$ in weight) quantity of Gd definitely improves the performance of the LVD tank in the neutron detection, because Gd has a huge cross

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[2] The SNEWS (SuperNova Early Warning System) [7] project is an international collaboration including several experiments sensitive to a core-collapse supernova neutrino signal in the Galaxy and neighbourhood.

Table 1: LVD run.

RUN	SINCE	TO	LIVE TIME	DUTY CYCLE	MASS
1	6-6-1992	5-31-1993	285 days	60 %	310 t
2	8-4-1993	3-11-1995	397 days	74 %	390 t
3	3-11-1995	4-30-1997	627 days	90 %	400 t
4	4-30-1997	3-15-1999	685 days	94 %	415 t
5	3-16-1999	12-11-2000	592 days	95 %	580 t
6	12-12-2000	3-24-2003	821 days	98 %	842 t
7	3-25-2003	2-4-2005	666 days	> 99 %	881 t
8	2-4-2005	5-31-2007	846 days	> 99 %	936 t
9	5-31-2007	4-30-2009	669 days	> 99 %	967 t
10	5-1-2009	3-27-2011	696 days	> 99 %	981 t
Σ	6-6-1992	3-27-2011	6314 days		

section for n-capture due, essentially, to the two isotopes ^{155}Gd and ^{157}Gd. In particular the mean n-capture time results highly shortened and the gamma cascade generated in n-captures on Gd has a total energy of about 8 MeV to be compared with 2.2 MeV of gamma quanta from (n,p) captures [8]. Accordingly, doping with Gd the LVD liquid scintillator, we could increase the signal to noise ratio of a factor of several hundreds maintaining the present neutron capture detection efficiency, simply increasing the energy threshold for neutron detection and shortening the time window for the coincidence.

The improvements that LVD could obtain if all its active scintillator mass was doped with this small amount of Gadolinium has been evaluated in [9]. It results that the detection probability of a neutrino burst from a core collapse in the Large Magellanic Cloud would be as high as 90%, while it is currently around 50%. The sensitivity that is achieved when Gd doping the whole detector is comparable to that which we would obtain doubling the mass of LVD.

It is well known that the muon-induced high energy neutrons limit the possibility of searches for rare events, like neutrinoless double beta decay or WIMP dark matter interactions. Underground laboratories provide the overburden necessary to reduce this background, by attenuating cosmic-ray muons and their progenies. If the depth of the underground laboratory is not enough to reach the necessary background reduction, the high energy neutron flux can be shielded and/or actively vetoed. An inner region inside the LVD structure with a volume of about 30 m^3 could be realized causing a negligible impact on LVD operation and sensitive mass and could be effectively exploited by a compact experiment for the search of rare events [10].

We have evaluated the shielding power of LVD working both as an active veto for muons that generate high energy neutrons, and as a passive shield and moderator for the low energy gamma and neutron background. From the results of a dedicated simulation [11] it appears that, with LVD behaving as a muon veto, the flux of high energy un-vetoed neutrons at the surface of the inner region is reduced by a factor 50, that is equivalent to the muon-induced neutron flux at the equivalent vertical depth of 6 km w.e (i.e. the Sudbury mine).

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