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The LVD Neutrino Observatory

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Abstract. The Large Volume Detector (LVD) in the INFN Gran Sasso National Laboratory, 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, with increasing larger configurations: in January 2001 it has reached its final active mass $M = 1$ kt. LVD is one of the largest liquid scintillator apparatus for the detection of stellar collapses and, together with SNO and SuperKamiokande, it is part of the SNEWS network.

Key words. Stars: supernovae – Cosmic Rays: neutrinos–

1. Introduction

LVD, located in Hall A of the INFN Gran Sasso National Laboratory, is a multipurpose detector consisting of a large volume of liquid scintillator interleaved with limited streamer tubes in a compact geometry. The main purpose of the LVD experiment is the search for neutrinos from Gravitational Stellar Collapses (GSC) in our Galaxy (Aglietta 1992).

In spite of the lack of a "standard" model of the gravitational collapse of a massive star, the correlated neutrino emission appear to be well established. At the end of its burning phase a massive star ($M > 8M_\odot$) explodes into a supernova (SN), originating a neutron star which cools emitting its binding energy $E_B \sim 3 \cdot 10^{53}$ erg mostly in neutrinos. The largest part of this energy, almost equipartitioned among neutrino and antineutrino species, is emitted in the cooling phase: $E_{\bar{\nu}_e} \sim E_{\nu_e} \sim E_{\nu_x} \sim E_B/6$ (where ν_x denotes generically $\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$ flavors). The energy spectra are approximatively a Fermi-Dirac distribution, but with different mean temperatures, since ν_e, $\bar{\nu}_e$ and ν_x have different couplings with the stellar matter: $T_{\nu_e} < T_{\bar{\nu}_e} < T_{\nu_x}$. LVD is able to detect $\bar{\nu}_e$ interactions with protons, which give the main signal of supernova neutrinos, with a very good signature. Moreover, it can detect ν_e through the elastic scattering reactions with electrons, and it is also sensitive to neutrinos of all flavors detectable through neutral and charged currents interactions with the carbon nuclei of the scintillator. The iron support structure of the detector can also act as a target for electron neutrinos and antineutrinos. The products of the interaction can exit iron and be detected in the liquid scintillator. The amount of neutrino-iron interaction can be as high as about 20% of the total number of interactions.

The described features of stellar collapses are in fact common to all existing models and lead to rather model independent expectations for supernova neutrinos. Thus, the signal observable in LVD, in different reactions and due to different kinds of neutrinos, besides provid-

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ing astrophysical informations on the nature of the collapse, is sensitive to intrinsic ν properties, as oscillation of massive neutrinos and can give a contribution to define some of the neutrino oscillation properties still missing.

2. The LVD experiment

The detector

The LVD experiment has been in operation since 1992, under different increasing configurations. During 2001 the final upgrade took place: LVD became fully operational, with an active scintillator mass $M = 1000$ t. LVD now consists of an array of 840 scintillator counters, 1.5 m^3 each, arranged in a compact and modular geometry. There are two subsets of counters: the external ones (43 %), operated at energy threshold $\mathcal{E}_h \simeq 7$ MeV, and inner ones (57 %), better shielded from rock radioactivity and operated at $\mathcal{E}_h \simeq 4$ MeV. In order to tag the delayed γ pulse due to n-capture, all counters are equipped with an additional discrimination channel, set at a lower threshold, $\mathcal{E}_l \simeq 1$ MeV.

SN neutrino interactions

The observable neutrino reactions in the liquid scintillator (LS) are:

- *(1)* $\bar{\nu}_e p, e^+ n$, (physical threshold $E_{\bar{\nu}_e} > 1.8$ *MeV*) observed through a prompt signal from e^+ above threshold $\mathcal{E}_h$ (detectable energy $E_d \simeq E_{\bar{\nu}_e} - 1.8$ MeV $+2m_e c^2$), followed by the signal from the $np, d\gamma$ capture ($E_\gamma = 2.2$ MeV), above $\mathcal{E}_l$ and with a mean delay $\Delta t \simeq 180\ \mu$s. The cross section for this reaction has been recently recalculated (Strumia 2003) with a better treatment of the $10 - 100$ MeV region, i.e. the SN neutrino energy. The efficiency for the prompt signal is $\epsilon_{\bar{\nu}_e p, e^+ n} = 95\%$, while for the neutron capture is 50%.
- *(2)* $\nu_e\, {}^{12}C, {}^{12}N\, e^-$, (physical threshold $E_{\nu_e} > 17.3$ *MeV*) observed through two signals: the prompt one due to the e^- above $\mathcal{E}_h$ (detectable energy $E_d \simeq E_{\nu_e} - 17.3$ MeV) followed by the signal, above $\mathcal{E}_h$, from the β^+ decay of ${}^{12}N$ (mean life time $\tau = 15.9$ ms). The efficiency for the detection of the ${}^{12}N$ beta decay product is 90%.
- *(3)* $\bar{\nu}_e\, {}^{12}C, {}^{12}B\, e^+$, (physical threshold $E_{\bar{\nu}_e} > 14.4$ *MeV*) observed through two signals: the prompt one due to the e^+ (detectable energy $E_d \simeq E_{\bar{\nu}_e} - 14.4\,\mathrm{MeV} + 2m_e c^2$) followed by the signal from the β^- decay of ${}^{12}B$ (mean life time $\tau = 29.4$ ms). As for reaction *(2)*, the second signal is detected above the threshold $\mathcal{E}_h$ and the efficiency for the detection of the ${}^{12}B$ beta decay product is 75%.
- *(4)* $\overset{(-)}{\nu}_\ell\ {}^{12}C, \overset{(-)}{\nu}_\ell\ {}^{12}C^*$ ($\ell = e, \mu, \tau$), (physical threshold $E_\nu > 15.1$ *MeV*), whose signature is the monochromatic photon from carbon de-excitation ($E_\gamma = 15.1$ MeV), above $\mathcal{E}_h$, detected with a 55% efficiency.
- *(5)* $\overset{(-)}{\nu}_\ell\ e^-, \overset{(-)}{\nu}_\ell\ e^-$, which yields a single signal, above $\mathcal{E}_h$, due to the recoil electron.

The LVD detector presents an iron support structure made basically by two components: the tank (mean thickness: 0.4 *cm*) which contains the LS and the "portatank" (mean thickness: 1.5 *cm*) which hosts a cluster of 8 tanks. Indeed, the higher energy part of the ν flux could be detected also with the $\nu(\bar{\nu})$Fe interaction, which results in an electron (positron) that could exit iron and release energy in the LS. The considered reactions are:

- *(6)* $\nu_e\, {}^{56}Fe, {}^{56}Co\, e^-$. The mass difference between the nuclei is $\Delta_{m_n} = m_n^{\mathrm{Co}} - m_n^{\mathrm{Fe}} = 4.055$ MeV; moreover the first Co allowed state is at 3.589 MeV. Other higher energy allowed states are present in Cobaltum 56, indeed we consider $E_{e^-}^{\mathrm{kin}} = E_{\nu_e} - \Delta_{m_n} - E_{\mathrm{level}} - m_e$ MeV, where E_{level} is the energy difference between the excitation level and the ground state level: it can take values: $3.589, 4.589, 7.589, 10.589\ MeV$. A number of gammas are produced in the interaction, depending on the excitation level considered.

  A full simulation of the LVD support structure and LS geometry has been developed in order to get the efficiency for electron and gammas, generated randomly in the iron structure, to reach the LS with energy higher than $\mathcal{E}_h$. It is greater than 20% for $E_\nu > 30$ MeV and grows up to 70% for $E_\nu > 100$ MeV. On average, the electron energy detectable in LS is $E_d \simeq 0.45 \times E_\nu$.

– *(7)* $\bar{\nu}_e$ ^{56}Fe,^{56}Mn e^+, the energy threshold is very similar to reaction *(6)* and the same efficiency is considered.

3. Results

LVD has been continuously monitoring the Galaxy since 1992 in the search for neutrino bursts from GSC [1]. Its active mass has been progressively increased from about 330 t in 1992 to the present 1000 t, always guaranteeing a sensitivity to GSC up to distances d = 20 kpc from the Earth, even for the lowest ν-sphere temperature.
The telescope duty cycle has been continuously improving since 1992, in the last five years the average duty cycle was ¿99.3%.

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, we can conclude that no gravitational stellar collapse has occurred in the Galaxy in the whole period of observation: the resulting upper limit to the rate of GSC at 90% c.l. is 0.2 event/yr.

The reliability of LVD to detect and recognize on-line ν-bursts with different characteristics, has been tested by inducing clusters of pulses - with different multiplicity and duration - in the LVD counters. The cluster injector, consisting of a generator of light pulses in a certain number of counters, allowed us to evaluate the system efficiency in detecting and disentangling bursts from the background, even with different background conditions. Moreover, the on-line algorithm is continuously checked through the high-rate mode of the supernova monitor used for the SNEWS.
SNEWS
The SNEWS (SuperNova Early Warning System) (Snews 2000; Antonioli 2004) is a collaboration among several neutrino-sensitive experiments. The primary goal of SNEWS is to provide the astronomical community with a prompt alert for a galactic supernova. An additional goal is to optimize global sensitivity to supernova neutrino physics, by such cooperative work as downtime coordination.
The charter member experiments of SNEWS are LVD in Italy, Super-K in Japan and SNO in Canada. Representatives from Amanda, IceCube will eventually join the active members of the network.
There is currently a single coincidence server, hosted by Brookhaven National Laboratory. We expect that additional machines will be deployed in the future. The BNL computer continuously runs a coincidence server process, which waits for alarm datagrams from the experiments' clients, and provides an alert if there is a coincidence within a specified time window (10 seconds for normal running). A scheme of "GOLD" and "SILVER" alerts has been implemented: GOLD alerts are intended for automated dissemination to the community; SILVER alerts will be disseminated among the experimenters, and require human checking. As of today, SILVER alerts only between LVD and Super-K are activated.
Up to now, no inter-experiment coincidence, real or accidental, has ever occurred (except during a special high rate test mode), nor any core collapse event been detected within the lifetimes of the currently active experiments.

[1] The results of this search have been periodically updated and published (LVD 1993, 1995, 1997, 1999, 2001, 2003)

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