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Triggering on Neutrino Bursts in LVD

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The capability of a supernova neutrino detector to identify clusters of signals is discussed. A definition of the detector sensitivity in terms of maximum detectable distance is proposed. Different trigger strategies, implemented in the running LVD detector, running in the INFN Gran Sasso National Laboratory, are compared and discussed.

1. Introduction

The detection of neutrinos from SN1987A marked the beginning of a new phase of neutrino astrophysics [1]. In spite of the lack of a “standard” model of the gravitational collapse of a massive star, the correlated neutrino emission appears to be well established.
However since this first ν observation was guided by the optical one, the detector capabilities of identifying a ν burst in the absence of an ”external trigger” should be demonstrated very carefully. In the presence of an optical counterpart, on the other hand, the prompt identification of the neutrino signal could alert the worldwide network of observatories allowing to study the rare event in all the different aspects since its onset.
LVD, located in Hall A of the INFN Gran Sasso National Laboratory (Italy), at the depth of 3500 m w.e., is a 1 kt liquid scintillator detector consisting of 840 identical counters whose major purpose is monitoring the Galaxy to study neutrino bursts from Gravitational Stellar Collapses (GSC) [2]. Its modularity and rock overburden together with the trigger strategy make this detector particularly suited to on line disentangle, from the background, a neutrino signal. We will show in this paper the criteria for neutrino burst identification (section 2), consisting in two steps: the filters applied to the data and the selection algorithms. In section 3 we will discuss the detector sensitivity in terms of physical parameters such as the fluence or the source distance.

2. Event Selection

2.1 Data Filters

There are two different filtering levels: the first is applied on the data, to reject signals not considered pertinent (e.g., atmospheric muons); the second is applied on the counters (to reject poorly performing ones) and determines the LVD active mass (M_{act}). The following filters are applied to the data:

1. the energy corresponding to detected pulses must be $E_{th} \leq E_{pulse} \leq 100$ MeV ($E_{th} = 7$ MeV);

2. coincidences among 2 or more counters in a time window $\delta t = 200$ ns are rejected (muon rejection).

For the counters selection we reject:

1. counters that, during the previous run and after the energy cut, have a counting rate $R \geq 3 \cdot 10^{-3}$ s^{-1};

2. counters which participate to a cluster with a multiplicity m_i which correspond to $P_{k \geq m_i}(m/N_c) \leq 1 \cdot 10^{-7}$, where m is the cluster multiplicity and N_c the number of active counters (topological cut).

2.2 Selection Algorithms

2.2.1 *Time Sequence Algorithm*

In the time sequence algorithm the searched signal is a cluster of pulses detected inside a time window of a defined duration, δt . All other signal characteristics like detailed time structure of the clustered pulses, energy spectrum and flavor signatures, are left to a subsequent independent analysis. The signal is simply characterized by its multiplicity m, i.e., the number of pulses detected during δt, and by δt itself.
Each time period of data taking T is scanned by an on-line algorithm, called Supernova Monitor, through a "sliding window" that has been chosen of duration $\delta t = 20$ s: T will then be divided into $N = 2 \cdot \frac{T}{\delta t} - 1$ intervals, each one starting at the middle of the previous one. The background imitation frequency for a cluster (m, 20 s) will be: $F_{im}(m, f_{bk}, 20) = 8640 \cdot P_{k \geq m}(20 \cdot \frac{f_{bk}}{s^{-1}})$ event $\cdot$ day^{-1}
Knowing the detector background rate, f_{bk}, to any imitation frequency corresponds a minimum multiplicity m_{90} of the detectable cluster (such that $P_{k \geq m}(m_{90}) \geq 0.9\ m_{90}$[3], to take into account fluctuations).
For LVD running in stand-alone mode the on-line alarm threshold is set at the level of $F_{im} = 1 \cdot 10^{-2} \cdot$ y^{-1}, corresponding to $m_{90} \geq 21$. On the other hand, running in coincidence with other detectors (e.g., in the SNEWS project [4]) naturally reduces the amount of fake alarms: in this case the LVD alarm threshold is set to $F_{im} = 1 \cdot$ week^{-1}, corresponding to $m_{90} \geq 16$.

2.2.2 *The Inverse Beta Decay Signature*

Independently on the unknown neutrino properties and in the frame of "standard" Supernova models, it is reasonable to state that the inverse beta decay (ibd) reaction ($\bar{\nu}_e + p \rightarrow e^+ + n$) is responsible for at least 90% of the total number of interactions due to a GSC in a Hydrogen-based detector. Since LVD is able to recognize the ibd reaction with a known efficiency $\epsilon_n \sim 0.6$, we consider, in each cluster, only "signed" pulses, i.e., those accompanied by a delayed one (IBD-1). In the background imitation frequency formula, f_{bk} is substituted by $f_{bk}|_d$, with $f_{bk}|_d = f_{bk}(M_{act}) \cdot \bar{P}_{Lbk} = 2.8 \cdot 10^{-5} \cdot \frac{M_{act}}{1ton} s^{-1}$ ($\bar{P}_{Lbk}$ being the average probability for a pulse to be followed by a delayed one due to background).
Additionally, we can relax the condition on the ibd signature requiring that only part of the pulses in the cluster are accompanied by delayed ones (IBD-2).
In this case we reject all the clusters which have a number of "signed" pulses $\leq k$, such: $\sum_{r=0}^{r=k} P(r, m, p) \leq P_0$, where $P(r, m, p)$ is the binomial probability to have r signed pulses in a cluster of multiplicity m. We choose $P_0 = 0.1$ as an example (the case $P_0 = 0$ corresponds to the pure time sequence algorithm).
Both algorithms are of course more sensitive to lower multiplicities with respect to the pure time sequence one (see table 1). However, because of the n-capture efficiency ϵ_n, the IBD-1 method is less effective, while the IBD-2, even if more efficient than IBD-1, still is not powerful enough to justify the loss in model independence.

Table 1.

		$F_{im} = 1 \cdot week^{-1}$		$F_{im} = 1 \cdot 10^{-2} \cdot y^{-1}$	
strategy	E_{th}	m_{min}	$\int_0^{20} dt \int_{E_{th}+.8}^{\infty} \frac{d^2\phi_{min}}{dEdt}\sigma dE$	m_{min}	$\int_0^{20} dt \int_{E_{th}+.8}^{\infty} \frac{d^2\phi_{min}}{dEdt}\sigma dE$
time seq.	7	16	$2.1 \cdot 10^{-31}$	21	$2.8 \cdot 10^{-31}$
IBD-1	7	7	$2.6 \cdot 10^{-31}$	10	$3.4 \cdot 10^{-31}$
IBD-2	7	14(5)	$1.9 \cdot 10^{-31}$	18(7)	$2.4 \cdot 10^{-31}$
time seq.	10	7	$1.3 \cdot 10^{-31}$	10	$1.7 \cdot 10^{-31}$
IBD-1	10	4	$1.8 \cdot 10^{-31}$	6	$2.4 \cdot 10^{-31}$
IBD-2	10	6(2)	$1.2 \cdot 10^{-31}$	9(4)	$1.6 \cdot 10^{-31}$

Burst detection efficiency for different strategies and for two values of imitation frequency F_{im}, for $M_{tr} = 1000$ ton. E_{th} is expressed in MeV; t in seconds. m_{min} represents the minimum detectable cluster multiplicity (90% c.l.) (between parenthesis the minimum number of double pulses requested in the cluster).

3. ν Burst Sensitivity

We discuss here the detector sensitivity in term of physical parameters, like for example the minimum detectable fluence (time integrated ν flux at the detector) or the maximum detectable distance.

The cluster multiplicity, m_s, due to the signal, detected during a time interval δt, in the case of pulsed $\bar{\nu}_{\rm e}$ emission, is:

$$N_{\rm ev} = M_{\rm act} \cdot N_{\rm p} \cdot \epsilon \cdot \int_0^{\delta t} dt \int_{E_{\rm th}+0.8MeV}^{\infty} \frac{d^2\phi_{\bar{\nu}_{\rm e}}}{dE_{\bar{\nu}_{\rm e}}dt}\sigma(E_{\bar{\nu}_{\rm e}})dE_{\bar{\nu}_{\rm e}}$$

where: ϵ is the detector efficiency, $M_{\rm act}$ [t] is the detector active mass, $N_{\rm p}$ is the number of free protons per scintillator ton, $\sigma(E_{\bar{\nu}_{\rm e}})$ is the neutrino interaction cross section, and $\frac{d^2\phi_{\bar{\nu}_{\rm e}}}{dE_{\bar{\nu}_{\rm e}}dt}$ is the differential $\bar{\nu}_{\rm e}$ flux at the detector.

In the absence of any hypothesis on the source emission spectra and on ν oscillation parameters, we can express the detector burst sensitivity in terms of 90% c.l. minimum flux at Earth · cross-section, integrated over δt: $\int dt \int \frac{d^2\phi}{dEdt}\sigma dE = \frac{m_{90} - f_{bk}\delta t}{M_{\rm tr}\cdot N_{\rm p}\cdot\epsilon}$. These are shown in Table 1, for the different selection criteria, and for $F_{im} = 1 \cdot 10^{-2} \cdot$ y^{-1} and $F_{im} = 1 \cdot$ week^{-1}.

To infer the LVD sensitivity, we compare such values of $\int dt \int dE \frac{d^2\phi}{dEdt}\sigma$ with the one measured by Kamiokande II on the occasion of the SN1987A (at 52 kpc), ranging between 6.3 and $7.7 \cdot 10^{-32}$. [1] Under the hypothesis of isotropic ν emission, this value can be scaled to different distances: e.g., at 10 kpc, it would correspond to $1.9 \cdot 10^{-30}$ and $4.7 \cdot 10^{-31}$ at 20 kpc. Comparing these with the results of Table 1, it follows that, with any of the selection algorithms applied to LVD in the present background conditions, we get a burst selection sensitivity well suited to cover the entire Galaxy. Based on such definition of sensitivity to neutrino bursts, taking into account that the LVD active mass is dynamical, it is straightforward to derive that the detector is sensitive to the entire Galaxy ($D \leq 20$ kpc) if $M_{act} \geq 500$ t for $F_{im} = 1 \cdot 10^{-2} \cdot$ y^{-1}.

[1] The range is determined by the value of the detected number of events: either 11, if all the events are considered as $\bar{\nu}_e$ interactions, or 9, when taking into account the possible contribution due to background contamination and elastic scattering on electrons [5].

4. Conclusions

We have shown that the LVD neutrino observatory is able to identify on line neutrino bursts from Gravitational Stellar Collapses occurring in the whole Galaxy. In the occurrence of the next galactic core collapse supernova, even in the absence of an optical counterpart, LVD will be able to trigger other observations. This capability is attained, besides through its large mass and deep location, by an optimization of the event selection chain as we have described in the paper.

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