Neutrino energy measurement in LVD to reconstruct Supernova emission

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1 Introduction

The Large Volume Detector (LVD), operating in the INFN Gran Sasso Laboratory (Italy) since 1992, is a multipurpose detector consisting of a large volume of liquid scintillator. Its major purpose is search for neutrinos from gravitational stellar collapses within to our Galaxy.

In spite of the lack of a “standard” model of the gravitational collapse of a massive star, some features of its dynamics and, in particular, of the correlated neutrino emission appear to be well established. At the end of its burning phase a massive star \((M > 10M_\odot)\) explodes into a Supernova (SN), originating a neutron star which emits its binding energy \(E_B \approx 2.5 \times 10^{53}\) erg mostly in neutrinos.

The largest part of this energy, almost equipartitioned among neutrino and antineutrino species, is emitted in the cooling phase: \(E_{\nu_e} \approx E_{\bar{\nu}_e} \approx E_{\nu_x} \approx E_B/6\) (where \(\nu_x\) denotes generically \(\nu_e, \nu_{\mu}, \nu_{\tau}, \nu_x\) flavours).

The energy spectra are approximately Fermi-Dirac distributions with different mean temperatures since \(\nu_e, \nu_x\) 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 neutrinos of all flavours through neutral and charged current interactions with the carbon nuclei of the scintillator.

In my PhD thesis I will present in details all the features of the SN neutrino emission as described by the most recent theories, considering the effects of neutrino oscillations.

I will show how these neutrinos are detected by LVD and how their energy is measured. I will discuss how the in-depth knowledge of the apparatus energy measurement and of the detection efficiency of the most important reaction impact the SN event characterization.

Then I will study the systematic errors on energy calibration and the neutron detection efficiency as a function of the energy threshold to increase the experiment signal/noise ratio (S/N ratio).

At the end of my thesis I will present two possible future improvement of the detector performances: the measurement of single photomultiplier signal and
the use of Gadolinium doped scintillator.

2 Neutrinos from gravitational stellar collapses

2.1 Gravitational stellar collapse model

At the end of its life a massive star \( M = 10 - 40 M_\odot \) has an iron core inert to nuclear reactions. The gravitational force is balanced by the degeneracy pressure of (quasi)free electrons if the core mass is less than the Chandrasekhar mass \( 1.4 M_\odot \). When it exceeds this value it collapses under its weight. The supernova explosion event that follows this collapse could be divided into four phases [1, 2, 3, 4, 5]:

1. “Infall” phase. The neutron density of the innermost part of the core (the ’inner-core’ \( M \sim 0.6 M_\odot \)) enlarges progressively due to iron photodissociation followed by electron capture. When it reaches nuclear densities the increase in matter pressure is sufficient to halt the collapse. The ’outer-core’ (which is still free-falling onto the center of the star) undergoes a bounce on the stiff inner-core.

2. “Flash” phase. An outward-going shock-wave forms, producing a prompt neutronization in the shocked material with mass about \( \gtrsim 0.4 M_\odot \).

3. “Accretion” phase. The shock wave enters a phase of stall, trying to make its way through the outer part of the core. This turns the propagating wave into a shock of accretion that involves rest of the initial iron core, about \( 0.5 M_\odot \). During this phase, convective motions and neutrinos (the “delayed mechanism”) should revive the shock (that subsequently can eject outer star’s layers - The SN explosion).

4. “Cooling phase”. The inner core settles in a new quasi equilibrium state called protoneutron star, that smoothly cools and contracts radiating neutrinos of all types.

The gravitational binding energy released during the collapse process is \( \varepsilon_B \sim (1 - 5) \times 10^{53} \text{erg} \).

About \( \sim 1\% \varepsilon_B \) is emitted as kinetic energy of the ejecta, about \( \sim 0.01\% \) as photons and unknown, but probably even less, is the fraction of energy emitted as gravitational waves (it depends on the symmetry of the explosion). The overwhelming part of this huge energy is carried away by neutrinos.
2.2 Neutrino emission

Correspondingly to the four phases, it is possible to distinguish between an early neutrino emission, during the “infall” and “flash” phase and a late phase of emission (or “thermal” phase) during the “accretion” and “cooling”.

The most uncertain phase is the “accretion” one that, together with the “cooling” one, accounts for most of the energy (almost 100%).

The evolution of neutrino luminosity [6, 7] is shown in figures 1 and 2: one can distinguish a $\nu_e$ flash at the shock, an abrupt turn-on of the $\bar{\nu}_e$ and $\nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau})$,

an initial rise of the luminosity after the shock, followed by a slower, approximately exponential, decrease which ends when the core becomes transparent.

Since the $\nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau})$ opacities are lower than the $\nu_e$, $\bar{\nu}_e$ ones, we expect that the $\nu_{\mu,\tau}(\bar{\nu}_{\mu,\tau})$ emission should fall off first.

Figure 1: The luminosity [erg/s] vs time [ms] for the $\nu_e$’s, $\bar{\nu}_e$’s, and, collectively, the $\nu_{\mu}(\bar{\nu}_{\mu})$’s and $\nu_{\tau}(\bar{\nu}_{\tau})$’s during the first 220 ms of the neutrino burst

Figure 2: The luminosity [erg/s] vs time [s] for the $\nu_e$’s, $\bar{\nu}_e$’s, and, collectively, the $\nu_{\mu}(\bar{\nu}_{\mu})$’s and $\nu_{\tau}(\bar{\nu}_{\tau})$’s during the first 50 s of the neutrino burst

The spectra of neutrinos from the late phase are not exactly thermal. Since the neutrino interaction cross-section increases with energy, even for the same species of neutrinos, the effective neutrinosphere radius increases with increasing energies. Then, even if the neutrinos at their respective neutrinospheres are in thermal equilibrium with matter, the spectrum gets “pinched”, i.e. depleted at the higher as well as the lower end of energies in comparison with thermal spectrum. It can be shown that the pinching of the instantaneous spectrum is the consequence of the following two facts: the temperature inside the supernova decreases with increasing radius and the density decreases faster than $1/r$ [8].

The pinching of the instantaneous spectrum can be extended to the pinching of
the time-integrated spectrum as long as the time variation of the average energy of the spectrum is small. Numerical simulations of the neutrino spectra confirm the pinching of the spectra [9, 10].

One way to parametrize the pinched neutrino spectra is to introduce an effective temperature $T_i$ and an effective degeneracy parameter $\eta_i$ in the Fermi-Dirac thermal spectrum for each species $i$ (figure 3, 4) [11, 12]:

$$N_i(E) \propto \frac{E^2}{e^{E/T_i - \eta_i} + 1}$$  \hspace{1cm} (1)

Where:

$T_e = 3 - 4$ MeV, $T_\mu = 5 - 6$ MeV, $T_\tau = 7 - 9$ MeV

$\eta_e \simeq 0 - 3$, $\eta_\mu \simeq 0 - 3$, $\eta_\tau = \eta_\mu \simeq 0 - 2$.

Figure 3: Fermi-Dirac spectra of all neutrino flavours ($T_e = 4$ MeV, $T_\mu = 5$ MeV, $T_\tau = 7.5$ MeV, $\eta = 0$).

Figure 4: Number of $\bar{\nu}_e$ events for (a) a thermal spectrum ($T=3$ MeV, $\eta=0$), (b) a pinched spectrum ($T=3$ MeV, $\eta=3$).

The energy differential fluence for each neutrino species and for a distance $D$ from the source (without considering neutrino oscillations) is:

$$\frac{dF_0^i}{dE} \propto \frac{1}{4\pi D^2 f_i E^2} \frac{E^2}{e^{E/T_i - \eta_i} + 1}$$  \hspace{1cm} (2)

where $f_i$ is the amount of the total energy $\varepsilon_B$ carried away by the different neutrino flavors. Simulations indicate an energy equipartition with $f_i = 1/6$. This fluence, integrated over the whole surface of emission and over all neutrino energies, gives the number of $i$-type neutrinos ($N_0^i$) emitted during the thermal
phase:

\[ N^0_i = 4\pi D^2 \int dE \frac{dI^0_i}{dE} = \frac{f_{\nu B}}{< E_i >} \]

where \(< E_i >\) is the mean energy of neutrinos of flavour \(i\).

2.3 Neutrino oscillations

To calculate the neutrino flux at Earth we must consider the oscillation effects on the supernova neutrino flux [11, 12]. The neutrino oscillation theory considers the system of three active neutrinos \(\nu_f = (\nu_e, \nu_\mu, \nu_\tau)\), mixed in vacuum, such that \(\nu_f = U \nu_m\), where \(\nu_m = (\nu_1, \nu_2, \nu_3)\) is the vector of mass eigenstates and \(U\) is the mixing matrix.

If neutrinos have mass they could oscillate between flavours. The oscillation is resonantly enhanced if a flavour-asymmetric medium is present (MSW matter effect). The medium density \(\rho\) for the resonance to occur depends on the oscillation parameters \(\Delta m^2\) (i.e. the mass squared difference between two eigenstates: \(\Delta m_{ji}^2 = m_i^2 - m_j^2\) with \(i,j=1,2,3\)) and \(U\):

\[ \rho = \frac{1}{2\sqrt{2}G_f} \frac{\Delta m^2 m_N}{E Y_e \cos^2 \theta} \]

where \(G_f\) is the Fermi constant, \(m_N\) is the mass of a nucleon, \(E\) is the neutrino energy and \(Y_e\) is the electron fraction.

The wide range of density value in the SN matter allows for two resonance levels: the high density level at \(\rho_H = 10^3 g/cm^3\), depending on \((\Delta m_{32}^2, U_{2e}^3)\) and \(\rho_L = 30 - 140g/cm^3\), depending on \((\Delta m_{21}^2, U_{2e}^2)\).

The probability of transition between the eigenstates of the Hamiltonian (jumping probability) in a resonance layer can be written as:

\[ P_f = \exp[-(\frac{E_{na}}{E})^{2/3}] \]

where:

\[ E_{na} = (\frac{\pi}{12})^{3/2} \frac{\Delta m^2 \sin^2 \Theta}{\cos^2 \Theta} \frac{2\sqrt{2}G_f Y_e}{m_N} \frac{A}{A^{1/2}} \]

and \(A\) is the proportionality constant of the star density profile \(\rho = A/r^n\).

In the study of SN neutrinos, \(\nu_e\), \(\nu_\mu\) and \(\nu_\tau\) are indistinguishable both in the star and in the detector because of the corresponding charged lepton production threshold. Consequently, in the frame of three flavour oscillations, the relevant parameters are just \((\Delta m_{21}, U_{2e}^2)\) and \((\Delta m_{32}, U_{e3}^2)\).

The most recent analysis including atmospheric, solar, CHOOZ and KamLAND data gives the following numerical data for these parameters [13]:

\(\Delta m_{21} \approx 8 \times 10^{-5} eV^2, \Delta m_{32} \approx 2.4 \times 10^{-3} eV^2, U_{e3}^2 \approx \sin^2 \theta_{12} \approx 0.3, U_{e1}^2 \approx \cos^2 \theta_{12} \approx 0.7, \sin^2 \theta_{23} \approx 0.5, U_{e3}^2 \approx \sin^2 \theta_{13} < few\%\).
For SN we always have conditions of adiabatic transition at the low density (L) resonance (i.e. the jumping probability between two mass eigenstates is $P_L = 0$), while at the high density (H) resonance these depend on the value of $U_{e3}$. When $U_{e3} > 5 \times 10^{-4}$ the conversion is completely adiabatic (i.e. the jumping probability is $P_H = 0$) and when $U_{e3} < 5 \times 10^{-4}$ the conversion is completely non adiabatic (i.e. the flip probability is $P_H = 1$). The resonance is expected for $\nu$ or $\bar{\nu}$ depending on the mass hierarchy. Normal mass hierarchy (NH) means $\Delta m_{23}^2 > 0$, while inverted mass hierarchy (IH) means $\Delta m_{23}^2 < 0$.

In case of NH the two resonant layers are set in the $\nu$ sector, while in case of IH the H resonant layer is set in the $\bar{\nu}$ sector and the L resonant layer is set in the $\nu$ sector.

Summarizing we will have four different cases for SN neutrino oscillations:

1. normal mass hierarchy with adiabatic transition at the H resonance (NH$_{ad}$);
2. normal mass hierarchy with non-adiabatic transition at the H resonance (NH$_{non-ad}$);
3. inverted mass hierarchy with adiabatic transition at the H resonance (IH$_{ad}$);
4. inverted mass hierarchy with non-adiabatic transition at the H resonance (IH$_{non-ad}$).

Disregarding the geometric factor $1/D^2$ (D=distance of the source), we calculate the $\nu_\alpha$($\bar{\nu}_\alpha$) flux at Earth $F_\alpha$($F_{\bar{\alpha}}$) from the original fluxes at source $F^0_\alpha$, $F^0_{\bar{\alpha}}$ in the following way:

- **NH**:  
  $$F_\alpha = [U^2_{e2}P_H + U^2_{e3}(1 - P_H)]F^0_\alpha + 1 - [U^2_{e2}P_H + U^2_{e3}(1 - P_H)]F^0_{\bar{\alpha}}$$  
  $$F_{\bar{\alpha}} = U^2_{e1}F^0_\alpha + (1 - U^2_{e1})F^0_{\bar{\alpha}}$$

- **IH**:  
  $$F_\alpha = U^2_{e2}F^0_\alpha + (1 - U^2_{e2})F^0_{\bar{\alpha}}$$  
  $$F_{\bar{\alpha}} = [U^2_{e1}P_H + U^2_{e3}(1 - P_H)]F^0_\alpha + 1 - [U^2_{e1}P_H + U^2_{e3}(1 - P_H)]F^0_{\bar{\alpha}}$$

Considering the possible values of the flip probability and neglecting $U^2_{e3}$, because of its smallness, we will obtain:

- **NH$_{ad}$**:  
  $$F_\alpha = F^0_\alpha$$  
  $$F_{\bar{\alpha}} = U^2_{e1}F^0_\alpha + (1 - U^2_{e1})F^0_{\bar{\alpha}}$$

- **NH$_{non-ad}$**:  
  $$F_\alpha = U^2_{e2}F^0_\alpha + (1 - U^2_{e2})F^0_{\bar{\alpha}}$$  
  $$F_{\bar{\alpha}} = U^2_{e1}F^0_\alpha + (1 - U^2_{e1})F^0_{\bar{\alpha}}$$
\[ F_e = U_{2e}^2 F_0^o + (1 - U_{2e}^2) F_0^x \]
\[ F_e = F_0^x \]

- **IH\textsubscript{ad}**:
  \[ F_e = U_{2e}^2 F_0^o + (1 - U_{2e}^2) F_0^x \]

- **IH\textsubscript{non-ad}**:
  \[ F_e = U_{2e}^2 F_0^o + (1 - U_{2e}^2) F_0^x \]
  \[ F_e = U_{2e}^1 F_0^o + (1 - U_{2e}^1) F_0^x \]

Note that, \( \bar{\nu}_e \) flux at Earth is affected for a 30% by \( \bar{\nu}_x \) flux at source in the NH\textsubscript{ad}, NH\textsubscript{non-ad} and IH\textsubscript{non-ad} cases, while it is only composed by the \( \bar{\nu}_x \) original flux in the IH\textsubscript{ad} case.

This means that oscillations influence the flux and the energy spectra of the different neutrino flavours detected at Earth.

### 3 LVD experiment

#### 3.1 Detector description

LVD consists of an array of 840 scintillator counters, 1.5 m\(^3\) each arranged in a compact and modular geometry [14]. The active scintillator mass is \( M \approx 1000 t \).

The scintillator (\( C_n H_{2n+2} \) with \( < n > \approx 9.6 \)) is observed from the top of each counter by three photomultipliers (PMTs, 15 cm diameter). The signal produced from each PMT is discriminated at two different thresholds (high \( \xi_h \) and low \( \xi_l \)) and the three-fold coincidence of the 3 PMTs of each counter within 150 ns is requested.

The sum of the three PMTs signals is sent to the ADC and TDC [15]. The charge measurement and the time of each event are recorded in a FIFO memory.

After each \( \xi_h \) trigger the threshold of the counter is set to the \( \xi_l \) value for 1 ms to tag the delayed \( \gamma \) pulse due to \( n \)-capture.

#### 3.2 Neutrino interactions with the liquid scintillator

Neutrinos are mainly detected by LVD by the following reactions:

- Inverse \( \beta \)-decay: \( \bar{\nu}_p e^+ n \), observed through a prompt signal from \( e^+ \) above threshold \( \xi_h \) (detectable energy \( E_d \approx E_{\bar{\nu}_e} - 1.8\,\text{MeV} + 2m_e c^2 \)), followed by the signal from the \( np, d\gamma \) capture (\( E_\gamma = 2.2\,\text{MeV} \)), above \( \xi_l \) and with a mean delay \( \Delta t \approx 180\,\mu\text{s} \).

- \( \nu_i \) and \( \bar{\nu}_i \) neutral current interactions with \( ^{12}\text{C} \):
  \[ \nu_i (\bar{\nu}_i) ^{12}\text{C}, \nu_i (\bar{\nu}_i) ^{12}\text{C}^* \] (\( i = e, \tau, \mu \)), whose signature is the monochromatic photon from carbon de-excitation (\( E_\gamma = 15.11\,\text{MeV} \)) above \( \xi_h \).
• $\nu_e$ charged current interactions with $^{12}\text{C}$: $\nu_e^{12}\text{C} \rightarrow ^{12}\text{Ne}^-$, observed through two signals: the prompt one due to the $e^-$ above $\xi_h$ (detectable energy $E_d \approx E_{\nu_e} - 17.3\text{MeV}$) followed by the signal, above $\xi_h$, from the $\beta^+$ decay of $^{12}\text{N}$ (mean life $\tau = 15.9\text{ms}$).

• $\bar{\nu}_e$ charged current interactions with $^{12}\text{C}$: $\bar{\nu}_e^{12}\text{C} \rightarrow ^{12}\text{Be}^+$, observed through two signals: the prompt one due to the $e^+$ above $\xi_h$ (detectable energy $E_d \approx E_{\nu_e} - 14.4\text{MeV} + 2m_e c^2$) followed by the signal from the $\beta^-$ decay of $^{12}\text{B}$ (mean life $\tau = 29.4\text{ms}$). As the previous reaction, the second signal is detected above the threshold $\xi_h$.

3.3 Supernova neutrino signature

As previously discussed, the observable quantities of a SN neutrino burst are time distribution, neutrino flux and energy spectrum. Time distribution data permit the validation of important aspects of the present gravitational stellar collapse models and LVD has a good time signature with a relative resolution of 12.5 ns and an absolute one of 1 $\mu$s.

The number of detected events depends on SN and neutrino features as well as on the mass of the detector. Taking into account the effects of oscillation on the SN neutrino flux, I calculated the number of expected ($\nu p$) events in LVD. Figure 5 shows the result of this calculation as a function of the $\nu_e$ neutrinosphere temperature. Black line represents the case without oscillation, red line the IH case and green line the other three cases (which are coincident).

As shown in section 2 the $\nu$ energy spectra at Earth depend on the emission spectra and on the oscillation parameters. For this reason, the observation of a SN neutrino burst can help to distinguish between different scenarios of massive neutrinos and astrophysical parameters. In particular, with LVD, we can calculate the $\nu_e$ neutrinosphere temperature $T_e$ from the $\nu_e$ detected energy spectrum, and by comparing it with the $T_x$ estimated by an other experiment, we can distinguish between direct and inverse mass hierarchy. Indeed, $T_e > T_x$ implies a completely adiabatic transition in inverse mass hierarchy conditions. I am investigating LVD neutron detection efficiency to improve the signature of the inverse beta decay interaction ($\bar{\nu}_e$ signal) and the systematic errors of the calibration to improve neutrino energy estimation.
4 Study of the detection and energy performances of the apparatus

4.1 The counter simulation

The LVD counter simulation is divided in two parts:

- a GEANT 3 main simulation which reproduces the counter geometry, the scintillator features and the interactions between particles and liquid scintillator.

  By giving type, energy and position of the particles as input data, it gives as output all the information about the particle-detector interactions (energy release inside the counter, type of interaction, times, etc).

- The energy released in the counter is used as input of a second simulation which gives as output the spectrum in ADC channel. This is made by taking into account the light collection and the electronic acquisition system of one counter.

4.2 Neutron detection efficiency in LVD

To find the best S/N ratio in neutron detection from $\bar{\nu}_e p, e^+ n$ I measured n-detection efficiency for different E thresholds by using a californium source.
The $^{252}\text{Cf}$ has mean life 2.65 y. It decays emitting $\alpha$ particles in the 97% of the cases and making nuclear fission in the remaining 3%, with the production of about 20 $\gamma$s ($E_\gamma < 1$ MeV) and, in average, 3.735 neutrons/fission ([16], [17]). This measurement has been carried out in the external Gran Sasso Laboratory from November 2005 to nowadays. I have used a facility with the same electronics and setup of the underground counters.

The Cf has been placed in the center of the counter by using a steel stick. Around the source there is a Surface Barrier Counter (SBC) which generates the fission trigger ([18]). The trigger signal is amplified and discriminated in order to distinguish fission events from the $\alpha$ background, then, the fission time is recorded (ADC-TDC C176). Within about 1 ms after each fission the electronics records time and charge of the events seen in 3-fold coincidence by the 3 PMTs (figure 6).

The background measurements are made by using the same electronic chain:

the only difference is that the trigger is produced by a pulse generator with period of about 2 s and recorded on a different TDC channel.

The background data are taken during the measurement. In this way, we can inspect whether the background changes during the long term neutron measurement.

I will then use the simulation to extend the results obtained from these measurements to the case of randomly generated neutrons inside the counter as coming from inverse $\beta$ decay: $\nu_e + p \rightarrow n + e^+$. 
4.3 Energy calibration

The LVD energy calibration is made on a counter basis by using cosmic ray muons. A muon event is selected as a signal detected by, at least, two counters, within 250 ns. The value of the peak of the muon spectrum in ADC channels corresponds to $185\pm5$ MeV (figure 7). This energy value has been calculated by using a simulation which considers the angular and energy distributions of cosmic ray muons inside LVD and reproduces the geometrical acceptance of the experiment.

As a first step of my thesis I verified the muon energy peak value with my simulation.

Then, I studied the systematic errors of the calibration at the following energy values:

1. $2.2$ MeV: gammas from neutron capture on hydrogen
2. $9$ MeV: gammas generated by a NiCl source
3. $e^+e^-$ energy distribution ($\sim30$ MeV) from stopping $\mu$ inside the counter

For each of these three cases, I made experimental energy measurements (presented in the following sections) and I used the simulation to reproduce both the released and the detected energy spectrum inside a counter. By comparing the first simulated spectrum with the experimental one I can find the systematic error of the calibration at each energy point. Then, I can set the parameters of the second part of the simulation by minimizing the difference ($\chi^2$ method) between the second simulated spectrum and the
experimental one. Each parameter is representative of the functioning characteristics of one part of the counter (scintillator, geometry, PMTs, electronics) so their values indicate the causes of the systematics. In this way I can try to eliminate the errors.

4.4 2.2 MeV point: gammas from neutron capture on hydrogen

These energy data have been collected during the neutron detection efficiency measurement so the set up is the one described in section 4.2.

4.5 9 MeV point: gammas generated by a NiCf source

The gamma source consists of a $^{252}$Cf neutron source placed in the center of a nickel($\sim 20\%$)-paraffin($\sim 80\%$) cylinder (diameter=20 cm, height=20 cm). Neutrons produced by the Cf source interact with hydrogen (of the paraffin) producing $\gamma$s with $E_\gamma = 2.2$ MeV and with nickel producing $\gamma$s with the energy spectrum shown in figure 8.

The source has been placed on the top of a LVD counter for about 2 months and on the side to the same counter for 3 additional months. I can compare the experimental spectra taken with the source placed on the top and on the side of the counter to estimate the geometrical effects on the

![Figure 8: E spectrum of $\gamma$s from (n,Ni) capture.](image)
4.6 \( e^+e^- \) energy distribution (~30 MeV) from stopping \( \mu \) inside the counter

It is well known that muons decay according to the:

\[
\mu^-(\mu^+) \rightarrow e^- (e^+) + \nu_e (\nu_e) + \nu_\mu (\bar{\nu}_\mu) \tag{7}
\]

with \( \tau = 2.2 \mu s \) and \( Q \simeq 106 \text{ MeV} \). Figure 9 shows the simulated energy distribution of \( e^- (e^+) \) generated by \( \mu \)-stop inside a counter: due to the kinematics of the reaction, the maximum energy is \( Q/2 \simeq 53 \text{ MeV} \).

This measurement has been performed in the LNGS external facility because the stopping to crossing muons ratio outside is about 10 times greater than underground and the muon flux is higher (of a factor of about \( 10^7 \)).

The calibration of this counter has been performed by using the simulation: the energy and the direction of muons are selected from the energy distribution of cosmic muons at the external laboratory altitude and from the \( \cos^2 \theta \) angular distribution [19].
5 Future improvement of the experiment: the single photomultiplier signal and the Gd doped scintillator

5.1 Single PMT

A study on the opportunity of lowering the high threshold of the experiment led to the discovery of the importance of having the single charges of the phototubes of a counter instead of its sum. In Figure 10 one can see the integral spectra of the sum of the charges of the 3 PMTs of a counter at 3 different thresholds. An excess of events is evident on the right part of the spectra for the lower thresholds.

With the simulation I have demonstrated that the tail points correspond to events that occur near one PMT of the counter: the direct light reaches this PMT which overestimates the event energy. When the threshold is high enough, the three-fold coincidence discriminator will disregard these events with an high probability because only one PMT is overseeing the energy. The lower the threshold the lower the probability to disregard the event.

With the simulation I found the selection and correction algorithms of these events. They are based on the single PMT signal. For this reason now it is under test a new electronic setup able to collect the charge information of the
5.2 Gd doped scintillator

To improve the S/N ratio in the $\bar{\nu}_e p, e^+ n$ signature Gadolinium doped scintillator is on test.

This element has two advantages: larger cross section (about $10^5$ times more then hydrogen) for neutron capture, and the emission of gammas with total energy about 8 MeV, making neutrons more easily detectable.

In my degree thesis I made a simulation to compare the LVD detection efficiency of the thermal neutrons in pure scintillator with the efficiency of a scintillator doped with 0.45 g/l of Gd [20]. The result of this simulation shows that the present efficiency could be improved of about 9 % if the detector is doped with gadolinium. This improvement will be tested with a counter doped with an higher percentage of Gd. The improvement in the n-capture S/N ratio will be discussed.

6 Conclusions

In this work I analyzed systematic errors on LVD energy calibration to improve the detected neutrino characterization. The optimization of the signal to noise ratio of the $(np, d\gamma)$ delayed reaction allows to better identify $\bar{\nu}_e$ from stellar collapses.

Since a Supernova explosion is an extremely rare event, it is essential that LVD be ready to reconstruct as good as possible any event. With this motivation I worked to improve the knowledge on the energy measurement in LVD, and, when possible, to increase the detector performances.

References


