Spectrum of supernova neutrinos in ultra-pure scintillators

C. Lujan-Peschard, G. Pagliaroli and F. Vissani

Laboratori Nazionali del Gran Sasso, INFN, Assergi (AQ), Italy
Departamento de Física, DCeI, Universidad de Guanajuato, León, Guanajuato, México
Gran Sasso Science Institute, INFN, L’Aquila (AQ), Italy

E-mail: carolup@fisica.ugto.mx, giulia.pagliaroli@lngs.infn.it, francesco.vissani@lngs.infn.it

Received February 28, 2014
Revised July 1, 2014
Accepted July 2, 2014
Published July 25, 2014

Abstract. There is a great interest in measuring the non-electronic component of neutrinos from core collapse supernovae by observing, for the first time, also neutral-current reactions. In order to assess the physics potential of the ultra-pure scintillators in this respect, we study the entire expected energy spectrum in the Borexino, KamLAND and SNO+ detectors. We examine the various sources of uncertainties in the expectations, and in particular, those due to specific detector features and to the relevant cross sections. We discuss the possibility to identify the different neutrino flavors, and we quantify the effect of confusion, due to other components of the energy spectrum, overlapped with the neutral-current reactions of interest.

Keywords: supernova neutrinos, core-collapse supernovas, neutrino detectors

ArXiv ePrint: 1402.6953
1 Introduction

A Core Collapse Supernova (SN) releases 99% of its total energy by emitting neutrinos of the six flavors. The capability to observe the electronic antineutrino component of this emission has already been proven by the detection of SN1987A neutrinos [1–3]. The very large statistics that we will collect from the next galactic supernova will allow us to study the time dependence of the spectrum, specific features of the $\bar{\nu}_e$ luminosity and of its average energy [4, 5]. The detection of the other neutrinos flavors, however, requires specific detectors and interactions, typically with smaller cross sections. This is true, in particular, for the non-electronic component of the spectrum, that can be observed only through Neutral Current (NC) interactions.

During the last years a new generation of ultra-pure liquid scintillators, Borexino (BRX) [6] and KamLAND (KAM) [7], have been operated, obtaining excellent results thanks to the unprecedented low background levels reached and the new sensitivity in the very low energy range, below 1 MeV. They have a particularly good physics potential for the detection supernova NC channels, and quite remarkably, the Elastic Scattering (ES) of (anti)neutrinos on protons [8]. It has been argued that the high statistics from this reaction should suffice to constrain the spectra of the non electronic component for a SN emission, already with the existing detectors [9]. In view of the importance of this conclusion, we would like to reconsider it in this work.

The outline of this paper is as follows. First of all, we summarize the available information regarding SN neutrino detection in the existing ultra-pure scintillators, and calculate for each of them the total number of expected events as well as their spectral features. We consider the contributions of all neutrino interaction channels and obtain in this way the spectrum of events for a galactic supernova. In this way, we are in the position to evaluate which are the capabilities of the present generation of ultra-pure scintillators to identify and measure the different neutrino flavors.
2 Emission from a standard core collapse supernova

The aim of this work is to discuss an important question: what we can really see with the existing ultra-pure scintillators and to which extent we can distinguish the different neutrino flavors. With this purpose in mind, we will use very conservative assumptions on the emission model. We suppose that the energy radiated in neutrinos is $E = 3 \times 10^{53}$ erg, which is a typical theoretical value that does not contradict what is found in the most complete analyses of SN1987A events [10, 11]. We also assume that the energy is partitioned in equal amount among the six types of neutrinos, that should be true within a factor of 2 [12].

In agreement with the recent studies, e.g., [13], we consider quasi-thermal neutrinos, each species being characterized by an average energy $\langle E_i \rangle$ and including a mild deviation from a thermal distribution described by the parameter $\alpha = 3$ for all flavors. Thus, the neutrino fluence differential in the neutrino energy $E$ is

$$\Phi_i = \frac{E_i}{4\pi D^2} \times \frac{E^{\alpha} e^{-E/T_i}}{T_i^{\alpha+2} \Gamma(\alpha + 2)}$$

where the energy radiated in each specie is $E_i = E f_i$, with $f_i = 1/6$ in the case of equipartition, and the ‘temperature’ is $T_i = \langle E_i \rangle / (\alpha + 1)$. In particular, the neutrino and antineutrino fluences relevant to NC interactions

$$\Phi_{\nu}^{SN} = 2\Phi_{\nu_e} + \Phi_{\nu_\mu}, \quad \Phi_{\bar{\nu}}^{SN} = 2\Phi_{\bar{\nu}_e} + \Phi_{\bar{\nu}_\mu}$$

since we suppose that the distribution of the 4 non-electronic species is identical.

The average energies are fixed by the following considerations: consistent with the simulations in [13] and with the findings from SN1987A [10, 11], we set the electron antineutrino average energy to $\langle E_{\bar{\nu}_e} \rangle = 12$ MeV. For the average energy of the non-electronic species, that cannot be seriously probed with SN1987A [11], we suppose that the non-electronic temperature is 30% higher than the one of $\bar{\nu}_e$: $\langle E_x \rangle = 15.6$ MeV, this is in the upper range of values, but still compatible with what is found in [12]. For a comparison we will consider also the worst case in which the energies of the non electronic component is equal to the one of the $\bar{\nu}_e$, namely $\langle E_x \rangle = 12$ MeV as showed in very recent simulation [14]. We calculate the electron neutrino average energy by the condition that the proton (or electron) fraction of the iron core in the neutron star forming is 0:4: this gives $\langle E_{\nu_e} \rangle = 9.5$ MeV.

Note that the NC reactions are independent from neutrino oscillations, while the CC interactions depend upon the assumptions on neutrinos oscillation. In fact, the observed electron neutrino fluence is a linear combination of the fluences in absence of oscillations

$$\Phi_{\nu_e} \rightarrow P_{\nu_e \rightarrow \nu_e} \Phi_{\nu_e} + (1 - P_{\nu_e \rightarrow \nu_e}) \Phi_{\nu_\mu}$$

and similarly for antineutrinos. In the following we will disregard the non linear part of neutrinos oscillations, that could lead to a spectral swap among flavors [15, 16] and consider the standard neutrino oscillation. The choice of the mass hierarchy has an important impact on the expectations. Thanks to the fact that $\theta_{13}$ is large, in normal mass hierarchy, the survival probability of electron neutrinos and antineutrinos are $|U_{e3}^2|$ and $|U_{e1}^2|$ respectively, whereas for inverted mass hierarchy, the two values become $|U_{e2}^2|$ and $|U_{e3}^2|$ [11, 17]. Thus, the approximate numerical values that we can assume in the calculations are

|            | $P_{\nu_e \rightarrow \nu_e}$ | $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ |
|------------|-------------------------------|-----------------------------------|
| Normal     | 0.0                           | 0.7                               |
| Inverted   | 0.3                           | 0.0                               |
Figure 1. Fluences expected for the different neutrinos flavors. The blue dotted line shows $\bar{\nu}_e$, the green dot-dashed line $\nu_e$, these two lines overlap in the case of $\langle E_x \rangle = \langle E_{\bar{\nu}_e} \rangle$. We assume standard neutrino oscillations and Normal mass Hierarchy (NH) for the fluences of each flavor. The black thick lines and the red dashed ones show the fluences relevant for the Neutral Current (NC) detection channels of neutrinos and antineutrinos, respectively.

The value of $P_{\bar{\nu}_e \rightarrow \bar{\nu}_e}$ in the case of inverted hierarchy means that what we measure as electronic antineutrinos in terrestrial detectors, are non-electronic antineutrinos at the emission in fact; thus, it has a particularly important impact on the interpretation of the data. We note also that these numerical values would imply that there are only little chances to probe the emission of electron neutrinos, which are, from the astrophysical point of view, the most important type of neutrinos emitted by a supernova.

In the following we will consider only the case of the normal mass hierarchy for definiteness and adding a bit of theoretical bias; recall however that this hypothesis is immaterial for the discussion of the neutral current events. The total fluences expected to reach the Earth under these assumptions are shown in figure 1 for a Supernova exploding at 10 kpc from us.

3 Interaction channels

In the scintillators and at SN energies, we need consider the several interaction processes.

**CC processes.** Those involving electronic antineutrinos are

- Inverse Beta Decay (IBD), i.e. $\bar{\nu}_e + p \rightarrow n + e^+$;
- $\bar{\nu}_e + ^{12}C \rightarrow ^{12}B + e^+$;

while those involving electronic neutrinos are
- Proton Knockout $^{12}C(\nu_e, pe^-)^{11}C$;
- $\nu_e + ^{12}C \rightarrow ^{12}N + e^-$.

**NC processes.** We considered the following channels,

- ES on protons, $^{(\nu)}+p \rightarrow ^{(\nu)}+p$;
- The 15.11 MeV de-excitation line of the $^{12}C$ nucleus, $\nu + ^{12}C \rightarrow \nu + ^{12}C^*$;
- The Proton Knockout $^{(\nu)} + ^{12}C \rightarrow ^{(\nu)} + p + ^{11}B$.

Moreover, we consider the ES on electrons, that receives a contribution from both CC and NC. Let us discuss these reactions in detail.
Detailed description of the cross sections. The IBD, i.e., $\bar{\nu}_e + p \rightarrow n + e^+$, represents the main signal not only in water Cherenkov and also in scintillator detectors. It produces a continuous spectrum due to the positrons energy release. The approximated kinematic of this reaction connects the neutrinos energy with the detected energy through $E_{\nu} = E_{vis} + Q - m_e$ where $Q \simeq 1.3$ MeV is the $Q$ value of the reaction and $m_e$ is the electron mass. For the calculations, the IBD cross section reported in [19] was used. The delayed neutron capture on a proton is characterized by a monochromatic $\gamma_{2.2}$ MeV emission. The coincidence in a typical time window of about 250 $\mu$s between the latter and the prompt signal from the $e^+$ gives a clear signature of an IBD event. This means that, in the time integrated events spectrum, there will be a very high peak around 2.2 MeV that integrates the same number of events expected for IBD, reduced by the efficiency of the tag. The spectral shape of this peak is due to both the energy resolution of the detector and the quenching of the gamma ray energy in the scintillator. In this work, due to lack of information, we neglect the last effect and consider the optimistic case in which the width of this peak is only due to the energy resolution.

The superallowed CC reactions $\nu_e + ^{12}\text{C} \rightarrow e^- + ^{12}\text{N}$ and $\bar{\nu}_e + ^{12}\text{C} \rightarrow e^+ + ^{12}\text{B}$ present physical thresholds of $E_{\nu_e} > 17.3$ MeV and $E_{\bar{\nu}_e} > 14.4$ MeV respectively. They are detectable through the prompt leptons $e^-$ ($e^+$), which give a continuous spectrum. Moreover the nucleus of both reactions in the final state, $^{12}\text{N}$ and $^{12}\text{B}$, are unstable. The former will decay $\beta^+$ to $^{12}\text{C}$ with a half life of $\sim 11$ ms. The latter will decay $\beta^-$ to $^{12}\text{C}$ with a half life of $\sim 20$ ms [20]. The high energy positrons and electrons emitted in these beta decays can be observed, giving the possibility to tag these events. The cross sections used for the evaluation are those reported in [21] and the spectra for the delayed signals are obtained from the nuclear data tabulated in [22].

In the NC channels all neutrino flavors are involved potentially increasing the number of signal events detected.

For the ES on protons channel the cross section in [23, 24] was used, with a proton strangeness of $\eta = 0.12$. However it is important to stress that the uncertainty on the number of events expected for this channel is not negligible due to the proton structure and amounts to about 20% [25]. To understand the spectral shape of this class of events it is necessary to model the quenching factor for protons in the scintillators; this accounts for the proton light output and depends on the liquid scintillator composition. A detailed description of this factor is given in the next section.

The cross section for the superallowed NC reaction $\nu + ^{12}\text{C} \rightarrow \nu + ^{12}\text{C}^*$ followed by the emission of a monochromatic $\gamma$ at 15.11 MeV is reasonably well known. It was measured in KARMEN [26], confirming the correctness of the calculations as reported in [21] within an accuracy of 20%. Future measurements, most remarkably in OscSNS [27], claim the possibility of measuring more than 1,000 events in one year with a systematic estimated at 5% level or better. The prominent spectral feature of this channel can permit the identification of these events, as a sharp peak around 15 MeV, standing out from the main signal due to IBD.

The total cross section for NC proton knockout $\nu + ^{12}\text{C} \rightarrow \nu + p + ^{11}\text{B}$ has been calculated in [28], as a part of a network of reactions needed to describe the nucleosynthesis of light elements. However, the calculation of [29] finds a cross section about 30% larger, which suggests an error of at least this order. The neutrino energy has to exceed a pretty high threshold, i.e. $E > [(M_B + m_p)^2 - M_C^2]/(2M_C) \simeq 15.9$ MeV (where we use obvious symbols for the masses of the carbon nucleus, of the boron nucleus and of the proton). The initial neutrino energy (minus the activation energy, quantified by the threshold) is shared by the
neutrino and the proton in the final state, $E + M_C \approx E' + T_p + M_B + m_p$ so that the maximum kinetic proton energy $T_p^{\text{max}}$ is obtained when the final state neutrino is almost at rest, $E' \approx 0$. The expression for the maximum of the proton kinetic energy is

$$T_p^{\text{max}} = \left[(M^* - m_p)^2 - M_B^2\right]/(2M^*),$$

with $M^* = \sqrt{M_C^2 + 2M_CE}$. In view of the smallness of this sample of events, we adopted a very simple procedure to describe the distribution in the kinetic energy of the proton $T_p$, namely, we resorted to the pure phase space, that gives $d\sigma/dT_p \propto d\Phi/dT_p \propto \sqrt{T_p(M^* - m_p - m_B - T_p)^2}$. We checked that the integral in the proton kinetic energy of this expression agrees at the level of few percent with the theoretical behaviour of the total cross sections as reported in [28].

In the $CC$ knockout proton reaction on $^{12}$C the outgoing kinetic energy is shared between the electron and the proton. The maximum kinetic proton energy $T_p^{\text{max}}$ is obtained when the final electron is at rest. Similarly to the previous case, this is given by

$$T_p^{\text{max}} = \left[(M^* - m_p - m_e)^2 - M_{C11}^2\right]/(2M^* - 2m_e),$$

where again $M^* = \sqrt{M_C^2 + 2M_CE}$. In this case the phase space is $d\sigma/dT_p \propto d\Phi/dT_p \propto \sqrt{T_p(M^* - m_p - m_{C11} - T_p)^2}$. The theoretical cross sections reported in [28] and the value estimated from pure phase space agree at the level of $\sim 20\%$.

In the Elastic Scattering on electrons all the flavors participate, but the cross section is slightly different for the different flavors. The current best measurement of this interaction cross section arises in a sample of 191 events [30, 31], and quotes 17% of total error. The error that we estimate in the standard model is instead absolutely negligible for our purposes.

Numerical formulae. Let us conclude this section by giving two numerical formulae to evaluate easily the main neutral current cross sections:

An easy-to-implement effective formula for the $\nu + ^{12}$C $\rightarrow \nu + ^{12}$C$^*$ cross section, that agrees with [21] results at better than 1% in the region below 100 MeV, is

$$\frac{1}{2} (\sigma_\nu + \sigma_\bar{\nu}) = \frac{G_F^2}{\pi} (E - 15.11 \text{ MeV})^2 \cdot 10^{p(E)},$$

with $p(E) = \sum_{n=0}^{3} c_n (E/100 \text{ MeV})^n$ where $E$ is the incoming neutrino energy, and the numerical coefficients are $c_0 = -0.146$, $c_1 = -0.184$, $c_2 = -0.884$, $c_3 = +0.233$.

A simple parametrization of the cross section for the ES scattering, $\nu p \rightarrow \nu p$, assuming that the proton strangeness is $\eta = 0.12$, is simply

$$\frac{1}{2} (\sigma_\nu + \sigma_\bar{\nu}) = G_F^2 E^2 \cdot 10^{q(E)},$$

where $q(E) = -0.333 - 0.16(E/100 \text{ MeV})$.

However, a word of caution is in order; while the above considerations on phase space are suggestive, they are just a reasonable way to explore of the consequences of this reaction in scintillator detectors: in fact, the distribution in $T_p$ of [28] is not available. Certainly, it would be better to have a true calculation of the distribution in $T_p$ of this reaction (or possibly its parameterization) along with an assessment of the theoretical error in the relevant energy range.
4 Description of the ultra-pure scintillating detectors

We consider the ultrapure liquid scintillators detectors that are running or under construction, namely the following three: Borexino (BRX) [6] (0.3 kt of $C_9H_{12}$) in Gran Sasso National Laboratory, Italy, KamLAND (KAM) in Kamioka Observatory, Japan [7] (1 kt of mixture of $C_{12}H_{20}(80\%)$ and $C_9H_{12}(20\%)$) and SNO+ (0.8 kt of $C_6H_5C_{12}H_{25}$) currently under construction in the SNOLAB facility, located approximately 2 km underground in Sudbury, Ontario, Canada [32].

We assume that the energy resolution for each detector is a Gaussian with an error described by $\sigma(E_{\text{vis}}) = A \times \sqrt{E_{\text{vis}}/\text{MeV}}$ and a different value of the constant $A$ for each detector. The overall light collection in Borexino is $\approx 500$ photoelectrons (p.e.)/MeV of deposited energy. The resolution is $\approx 5\%$ at 1 MeV (namely $A = 50$ keV). For Borexino we assume an analysis threshold of $E_{\text{thr}} = 200$ keV. This assumption deserves an appropriate discussion, being a lower value than the one usually adopted by the collaboration for the analysis of solar neutrinos, i.e. 250 keV [33]. To determine the analysis threshold we have used the measurements of the background obtained at the Counting Test Facility (CTF) [51] in similar experimental conditions. We noted that below 150 keV the background due to $^{14}\text{C}$ is overwhelming, also considering that the SN signal is collected in a time window of only 20 seconds: background events due to pileup of $^{14}\text{C}$ dominate between 150 and 200 keV. However it is possible to safely lower the analysis threshold to 200 keV to make negligible also this background contribution.\footnote{In the region between 150 keV and 250 keV we estimate about 10 signal events and a similar number of background events, mostly due to pileup of $^{14}\text{C}$.}

The efficiency in KamLAND currently reaches 100% at $E_{\text{thr}} = 350$ keV. The energy resolution of the KamLAND detector can be expressed in terms of the deposited energy as $\sim 6.9\%/\sqrt{E_{\text{vis}}/\text{MeV}}$ (i.e., $A = 69$ keV) [9]. The energy threshold expected for SNO+ is the optimistic one of $E_{\text{thr}} = 200$ keV [34] and we assume that the energy resolution and the tagging efficiencies are the same as in Borexino.

As we mentioned earlier when the detected particle is a proton, the visible energy is only a fraction of the kinetic energy $T_p$, as described by the ‘quenching function’. Each detector has its own quenching function, that depends on its chemical composition; for Borexino detector we consider the quenching function discussed in [25], for KamLAND the one recently discussed in [36] and finally for SNO+ the response to proton in LAB scintillator as measured in [37].

Following [35] a simple parametrization of the quenching function is

$$E_{\text{vis}} = a_1 [1 - \exp (a_2 + a_3 \cdot T_p)] \cdot T_p$$

The values for the constants $a_1$, $a_2$ and $a_3$ that should be used for the different detectors are reported in Table 1 and the resulting functions are shown in figure 2.

At this point, we obtain the following important conclusion:

\textit{in ultrapure scintillators, the observation of protons from the NC elastic scattering reaction allows us to observe only the high energy part of the neutrino spectra.}

In fact, due to the thresholds and to the quenching, the protons below a minimum kinetic energy cannot be detected; this is 0.9 MeV for SNO+, 1.8 MeV for Kamland and 1.1 MeV for Borexino. Thus, taking into account the kinematical relation between the proton kinetic energy and the one of incoming neutrinos, we find that the elastic scattering on protons is
Table 1. Detector characteristics adopted in the paper, namely mass, energy resolution and analysis threshold, followed by the three constants appearing in the parametrized formula of the quenching function here used.

|        | $M$ [kton] | $\sigma(E)/\sqrt{E}$ | $E_{\text{thr}}$ [keV] | $a_1$ | $a_2$ | $a_3$ [MeV$^{-1}$] |
|--------|------------|------------------------|-------------------------|-------|-------|-------------------|
| BRX    | 0.3        | 5%                     | 200                     | 0.624 | -0.175| -0.154            |
| KAM    | 1.0        | 6.9%                   | 350                     | 0.581 | -0.0335| -0.207            |
| SNO+   | 0.8        | 5%                     | 200                     | 0.629 | -0.286| -0.163            |

Figure 2. Quenching functions used to convert the proton kinetic energy in the visible energy $E_{\text{vis}}$ for Borexino (red line), KamLAND (black dashed line) and SNO+ (blue dotted line), respectively.

sensitive to neutrino energies above a threshold of 22 MeV in the best situation of SNO+, it becomes 23 MeV for Borexino, and raises to 30 MeV in the case of Kamland. In view of these considerations, one concludes that the exploration of the low energy region of the spectrum via neutral currents is not possible with the existing ultrapure scintillators.

5 Results: observable spectra and number of events

For each detection channel, we estimate the number of expected events and report them in table 2. Moreover, we plot the energy distributions of the events, considering the specific features of the ultrapure scintillating detectors in figure 3.

The IBD channel (red line) starts to dominate the global signal at 5 MeV and reaches the maximum around 14 MeV. The total number of interactions expected for a supernova located at 10 kpc is of about 54 events for Borexino, 257 for Kamland and 176 for SNO+. These results are reported in the first row of table 2. The subsequent gamma from neutron capture gives the peak at 2.2 MeV, shown by a purple line. The efficiency of the neutron tag is (85$\pm$1)% in Borexino (see [44]), (78$\pm$2)% in KamLAND (see [7]). The condition for a successful IBD tag [44] is that no more than one interaction occurs during the time between the IBD interaction and the neutron capture inside a specific volume, namely

$$R_{\text{IBD}} \times \Delta t \Delta V \rho \leq 1$$  \hspace{1cm} (5.1)
| Channel                  | Color code | Signal | BRX      | KAM       | SNO+      |
|-------------------------|------------|--------|----------|-----------|-----------|
| $\bar{\nu}_e + p \rightarrow n + e^+$ | red        | $e^+$  | 54.1 (49.6) | 256.5 (235.3) | 175.8 (161.2) |
| $n + p \rightarrow D + \gamma_{2.2\text{MeV}}$ | purple     | $\gamma$ | 46.0 (42.1) | 200.1 (183.5) | 149.4 (137.1) |
| $\nu + p \rightarrow \nu + p$              | blue       | $p$    | 16.0 (5.7)   | 29.0 (6.2)   | 74.9 (29.2)   |
| $\nu + e^- \rightarrow \nu + e^-$          | orange     | $\gamma$ | 4.7 (2.1)    | 15.0 (6.7)   | 12.3 (5.5)    |
| $\nu_e +^{12}\text{C} \rightarrow e^- +^{12}\text{N}$ | magenta    | $e^-$  | 4.4 (4.6)    | 14.8 (15.5)  | 12.0 (12.4)   |
| $\nu_e +^{12}\text{C} \rightarrow e^- +^{12}\text{N}$ | black thin | $e^+$  | 1.2 (0.8)    | 3.7 (2.6)    | 3.0 (2.1)     |
| $\nu +^{12}\text{C} \rightarrow \nu + p +^{11}\text{B}$ | yellow     | $p$    | 0.8 (0.2)    | 2.4 (0.6)    | 2.1 (0.6)     |
| $\nu_e +^{12}\text{C} \rightarrow e^- + p +^{11}\text{C}$ | red dashed | $p$    | 0.5 (0.1)    | 1.5 (0.3)    | 1.3 (0.2)     |

Table 2. Summary table for all the number of events from the various interaction channels. The result are given for the emission model where the energy of non-electronic components is 30\% bigger then the one of $\bar{\nu}_e$; in brackets, we indicate the correspondent values assuming that the energies of $\bar{\nu}_e$ and $\nu_x$ are the same. The color code (2nd column) refers to the lines of figure 3.

where $R_{\text{IBD}}$ is the rate of IBD events per second and per unit mass, $\Delta t$ is the temporal window of the tag, that we assume to be $\Delta t = 2\tau = 512\mu s$, $\Delta V$ is the volume of a sphere with 1 meter of radius, $\rho$ is the density of the scintillator. This is related to the detector mass and to the distance of the supernova by

$$
R_{\text{IBD}} = \frac{256.5}{T} \cdot \left( \frac{10\text{kpc}}{D} \right)^2 \cdot \left( \frac{M}{1\text{kton}} \right),
$$

where $M$ is the mass of the detector, $D$ is the distance of the SN and $T$ is the duration of the emission. For example to allow the IBD tag in a detector with the density of Borexino and 1 kton of mass, considering that 50\% of the total emission is expected during the first second [11], then the minimum distance of a SN is $D \geq 0.16$ kpc, that is not a severe limitation.

Let us discuss now the NC elastic proton scattering. This channel dominates the low energy part of the spectrum, represented with the blue line in figure 3. As we see from table 2, the total number of interactions expected is of about 16 events for Borexino, 29 for Kamland and 75 for SNO+ in the best assumption. It is evident from figure 3 that the event spectrum rapidly increases in the low energy region and the total number of integrated events strongly depends on the analysis threshold and on the quenching of the proton signal. The analysis threshold used in the case of KamLAND is an optimistic value, since we assumed a threshold of 350 keV, lower than the one that can be obtained with the current radioactivity level, i.e., 600 keV [45]. If this higher threshold is assumed the ES with protons on KamLAND gives only 17 signal events.

It is important to remark that the number of events due to this channel is also very sensitive to the SN emission parameters; in fact, as discussed in the end of the previous section, this interaction is sensitive only to the high energy tail of the SN neutrinos spectra. In particular, the predicted average energy of the different neutrino flavors have gradually been changing in recent years, moving toward lower mean values [46] and toward minor differences between the average energies of the different components [13, 47]. For comparison
Figure 3. Theoretical event spectrum in the visible energy $E_{\text{vis}}$ in ultrapure scintillators for a Supernova exploding at 10 kpc. The top panels refer to Borexino detector, the bottom panels to SNO+, those in the middle to KamLAND. On the left panels, the expectations for the emission model where energy of non-electronic component is 30% higher than the one of $\bar{\nu}_e$; on the right panels, the corresponding expectations for the case when the non-electronic components and the $\bar{\nu}_e$ have the same average energy. See table 2 and the text for the explanation of the individual lines.

we have considered the new paradigm of emission, where the average energy of non-electronic flavors is the same as of the electronic antineutrinos, namely $\langle E_x \rangle = 12$ MeV [13, 46] and have investigated the two different cases to outline the impact on NC processes. As shown by the values in brackets in table 2, the expectations in this case are quite meager.

The NC reaction $\nu + ^{12}C \rightarrow \nu + ^{12}C^*$ followed by the emission of a monochromatic $\gamma$ is shown in orange in figure 3. This channel does not require the low energy threshold and the efficiency for its detection is taken 100% for all the detectors considered. The total number of events expected is: 5 events for Borexino, 15 for Kamland and 12 for SNO+. The possibility of a successful identification of this channel is affected by the quality of the energy resolution...
of the detector and by the effectiveness to tag the IBD signal. These events can be observed if the IBD events are identified through the correlated neutron capture signal, since they are expected to occur in the same energy region. With the assumed energy resolutions we have that this neutral current reaction can be observed in the energy range (14–17) MeV. For Borexino, the number of events due to the IBD signal in the same range is 5.7; thus, more than the 50% of the total signal collected in this energy window is due to the IBD channel, while for KamLAND and SNO+ the IBD signal is 26.9 and 18.4, representing about 60% of the total one. In the case of Borexino, if the tagging efficiency is of 85% as assumed in the plot, we expect only 1 event due to IBD not identified, so the uncertainty on the $\gamma_{15.11\text{MeV}}$ signal is reduced to 14%.

The ESs involves all the flavors of neutrinos and we expect to collect about 4 events for Borexino, 15 for KamLAND and 12 for SNO+. Their spectrum is reported with a dark green line in the spectra of figure 3, and dominates in the energy region between the ES on protons and the IBD signals. As we mentioned the cross section for the different flavors are slightly different; the $\nu_e$ contribution produces half of the events.

The rest of the detection channels have a low signal. All of them show a continuos spectrum, being from $e^-$, $e^+$ or protons. The two CC superallowed reactions are indicated by a magenta line for the $^{12}N$ final state nucleus and by a black thin line for the $^{12}B$ one. The decay products of the unstable nucleus are also considered in figure 3, using dotted lines of the same color of the related prompt signal. The branching ratio of these delayed decays is 100% and we assumed a full efficiency for the tag.

For both knockout channels, besides the high energy thresholds, the quenching has to be considered, so the total number of events collected for them is pretty small. The one due to NC is shown in yellow, while the one due to CC is shown with the dashed red line. In particular the NC knockout channel will give at most 1 event in Borexino, 2 in KamLAND and 2 in SNO+.

6 Neutral current events: summary and discussion

As mentioned in the introduction, a major reason of specific interest for a future supernova is the possibility to observe neutral current interactions of neutrinos. We have investigated the three possible reactions of detection in ultrapure scintillators, namely: 1) the elastic scattering with protons, 2) the 15.11 MeV $\gamma$ de-excitation line, 3) the NC proton knockout channel. To highlight the uncertainty on these NC signals due to different channels overlapping in the same energy region we report in figure 4 the event spectrum obtained after the statistical subtraction of all the channels that can be tagged. With the same aim we show in table 3 the number of events obtained integrating this plots in two different energy windows. Let us discuss and summarize the results.

**Elastic Scattering on protons.** This reaction is characterized by the larger number of expected NC events in all the detectors; however the number of detectable events is strongly limited by the energy thresholds. Moreover the systematic uncertainty on the total number of elastic scattering on protons, due to the proton structure, amounts to the 20%; moreover in the same energy region where this reaction can be observed there are also the indistinguishable events due to the elastic scattering with electrons and those due to NC and CC proton knockout. In other words, all we can observe is the total number of events collected in the energy region from the detector threshold to the starting point of the IBD signal, around
Figure 4. Theoretical event spectrum in the visible energy \( E_{\text{vis}} \) in ultrapure scintillators for a Supernova exploding at 10 kpc after the application of the statistical subtraction of tagged signals.

Table 3. The number of events expected in the two different energy windows after the statistical subtraction of the tagged channels. We report the expectations for the case of \( \langle E_x \rangle = 1.3 \langle E_\bar{\nu} \rangle \). The quoted errors are first the statistical error followed by the systematic one.

|       | \([E_{\text{thr}}, 1.8]\) MeV |       | \([14,17]\) MeV |
|-------|--------------------------------|-------|-----------------|
|       | NC±stat±syst                   | Background | NC±stat±syst | Background |
| BRX   | 18.0 ± 4.2 ± 3.6               | 0.9    | 4.7 ± 2.2 ± 0.9 | 1.6 |
| KAM   | 28.9 ± 5.4 ± 5.8               | 2.8    | 15.0 ± 3.9 ± 3.0 | 10.0 |
| SNO+  | 74.9 ± 8.7 ± 14.9              | 2.5    | 12.3 ± 3.5 ± 2.5 | 5.0 |

1.8 MeV. In fact the energy window \((E_{\text{thr}}-1.8)\) MeV is the first optimal window for the observation of NC events because both elastic scattering on proton and NC proton knockout are mainly contained inside this window. This is evident from table 3 where we perform a comparison of the signal events due to NC processes to the rest of the channels (which we will call background) in two different energy windows and for the optimistic assumption on the emission model, namely \( \langle E_x \rangle = 1.3 \langle E_\bar{\nu} \rangle \).

Table 3 shows the number of events expected followed by the uncertainty due to statistical fluctuations, i.e. \( \sqrt{N} \) and by the systematic error related to the uncertainty on the cross section and on the quenching. For the ES on proton the 20% of systematic uncertainty due to the cross section is summed in quadrature with the uncertainty on the quenching function quoted by the collaborations that is of the order of 2%. In the first detection window discussed, we have found that for Borexino a fraction of 5% (19% in the case of \( \langle E_x \rangle = \langle E_\bar{\nu} \rangle \)) of the signal is due to the other channels and this uncertainty is small but irreducible. For SNO+ this becomes 3% (8% in the case of \( \langle E_x \rangle = \langle E_\bar{\nu} \rangle \)).

The gamma line from carbon de-excitation. The gamma line due to neutrino-induced \(^{12}\)C de-excitation is in principle easier, giving a signal at higher energies; the events are expected to be collected in a small energy window dictated by the energy resolution of the detector and by the gamma quenching function. In the detectors considered in this work the signal due to this NC channel is totally contained in the window (14–17) MeV of visible energy. However, in the same window we will have also the positrons due to IBD reaction;
thus, the efficiency to tag the concomitant neutron will be of crucial importance to identify cleanly a sample of this NC reaction. The spectral feature of this monoenergetic gamma line can be used to increase the capability of extraction of this NC channel. However the total number of events expected for a SN exploding at 10 kpc of distance is not enough to allow a good spectral analysis in Borexino, Kamland and SNO+. This is simply due to the fact that the statistical fluctuations of the number of events are large. This is evident from the figure 5, where we show two stacked histograms: the left panel concerns the region of low energy sensitive to the elastic scattering on proton, while the right panel concerns the region of high energy sensitive to the $^{12}$C de-excitation gamma line. The events have been obtained by Monte Carlo extraction assuming the detector parameters of SNO+ and the optimistic case $\langle E_x \rangle = 1.3 \langle E_\bar{e} \rangle$.

We have also performed a spectral fit of this line, assuming that the shape of the gamma line dictated by the energy resolution is perfectly known, adding also a flat component for the backgrounds signals. The error on the determination of the normalization of the gamma line is of order 35%, rather similar to the 40% error obtained simply comparing the integrated number in table 3.

It should be noted that, if the energy of non-electronic neutrinos is low, the number of events due to this reaction is too small to permit the investigation of the shape of the $\nu_x$ spectrum at the level discussed in [9]. At present, SNO+ has the best potential to perform a similar analysis, as soon as it will reach the planned operational parameters. The chances will improve if the next galactic supernova should explode closer than at 10 kpc, simply thanks to the fact that the number of events scale with the inverse of the distance squared.

**Proton knockout.** Finally, we have shown that the proton knockout will give a comparably small number of NC events.

### 7 Conclusion and open issues

In this paper, we have obtained and discussed the spectra of supernova neutrino events in ultrapure scintillators, for a supernova exploding at 10 kpc from the Earth. We have discussed
the chances and the limitation to measure the fluence of non-electronic neutrinos by mean of the NC events, that are present in these observable spectra.

The experimental situation will most likely improve when the huge detectors of the next generation as LENA [49] and/or JUNO [50] (Jiangmen Underground Neutrino Observatory) will become operational. Both detectors will be probably LAB-based scintillator detectors with a target mass of 50 kt for LENA and 20 kton for JUNO. The goal for the energy resolution in JUNO is of $3\%/\sqrt{E}$ [50] while for LENA we assume the same resolution of Borexino. In this manner, we estimate the total number of events for these detectors in the three NC channels showed in table 4. It should be noted that both the channels (NC scattering on protons and NC on carbons) have uncertainties dominated by the 20% of systematics due to the cross sections.

We would like to conclude stressing experimental issues, that concern the high and the low energy regions, where the NC signal can be observed in a scintillator. Using the case of Borexino as an example, we note

- To the best of our knowledge, the value of the systematic contribution in the error function $\sigma(E)$ is not quoted in the literature; this is particularly important at high energies. E.g., in the position of the NC gamma line, $E = 15.1 \text{ MeV}$, the statistical error is as small as $\sigma/E = 1.3\%$ in Borexino; thus, if the systematic contribution is of this order of magnitude, the line will be broadened, and the interpretation of the observations could be affected (see figure 5).

- The choice of the energy thresholds of table 1 makes the contamination of background events negligible. At lower energies, the background plays a larger role and the interpretation of the observations becomes strongly detector dependent. For instance, considering again the case of Borexino, we can rely on the measurements of the background obtained at the counting test facility [51] in similar experimental conditions. Even considering a time window of the signal of 20 seconds, it is impossible to use an analysis threshold below 150 keV because the background due to $^{14}\text{C}$ is overwhelming. However it is possible to lower the analysis threshold for a SN burst at 200 keV allowing to increase of the 33% the number of events due to NC scattering on proton, namely from 12, obtained for the solar threshold of 250 keV, to 16, from a distance of 10 kpc.

In our opinion, both issues deserve further attention from the experimental collaborations, in view of the great importance of detecting a NC signal from a galactic supernova.

Acknowledgments

We thank an anonymous Referee for thoughtful and useful comments.
References

[1] KAMIOKANDE-II collaboration, K. Hirata et al., *Observation of a Neutrino Burst from the Supernova SN 1987a*, Phys. Rev. Lett. 58 (1987) 1490 [SPIRE].

[2] R.M. Bionta, G. Blewitt, C.B. Bratton, D. Casper, A. Ciocio et al., *Observation of a Neutrino Burst in Coincidence with Supernova SN 1987a in the Large Magellanic Cloud*, Phys. Rev. Lett. 58 (1987) 1494 [SPIRE].

[3] E.N. Alekseev, L.N. Alekseeva, V.I. Volchenko and I.V. Krivosheina, *Possible Detection of a Neutrino Signal on 23 February 1987 at the Baksan Underground Scintillation Telescope of the Institute of Nuclear Research*, JETP Lett. 45 (1987) 589 [SPIRE].

[4] Super-Kamiokande collaboration, M. Ikeda et al., *Search for Supernova Neutrino Bursts at Super-Kamiokande*, Astrophys. J. 669 (2007) 519 [arXiv:0706.2283] [SPIRE].

[5] IceCube collaboration, R. Abbasi et al., *IceCube Sensitivity for Low-Energy Neutrinos from Nearby Supernovae*, Astron. Astrophys. 535 (2011) A109 [arXiv:1108.0171] [SPIRE].

[6] Borexino collaboration, G. Alimonti et al., *The Borexino detector at the Laboratori Nazionali del Gran Sasso*, Nucl. Instrum. Meth. A 600 (2009) 568 [arXiv:0806.2400] [SPIRE].

[7] KamLAND collaboration, K. Eguchi et al., *First results from KamLAND: Evidence for reactor anti-neutrino disappearance*, Phys. Rev. Lett. 90 (2003) 021802 [hep-ex/0212021] [SPIRE].

[8] J.F. Beacom, W.M. Farr and P. Vogel, *Detection of supernova neutrinos by neutrino-proton elastic scattering*, Phys. Rev. D 66 (2002) 033001 [hep-ph/0205220] [SPIRE].

[9] B. Dasgupta and J.F. Beacom, *Reconstruction of supernova $\nu_\mu$, $\nu_\tau$, anti-$\nu_\mu$ and anti-$\nu_\tau$ neutrino spectra at scintillator detectors*, Phys. Rev. D 83 (2011) 113006 [arXiv:1103.2768] [SPIRE].

[10] T.J. Loredo and D.Q. Lamb, *Bayesian analysis of neutrinos observed from supernova SN-1987A*, Phys. Rev. D 66 (2002) 063002 [astro-ph/0107260] [SPIRE].

[11] G. Pagliaroli, F. Vissani, M.L. Costantini and A. Ianni, *Improved analysis of SN1987A antineutrino events*, Astropart. Phys. 31 (2009) 163 [arXiv:0810.0466] [SPIRE].

[12] M.T. Keil, G.G. Raffelt and H.-T. Janka, *Monte Carlo study of supernova neutrino spectra formation*, Astrophys. J. 590 (2003) 971 [astro-ph/0208035] [SPIRE].

[13] I. Tamborra, B. Müller, L. Hudepohl, H.-T. Janka and G. Raffelt, *High-resolution supernova neutrino spectra represented by a simple fit*, Phys. Rev. D 86 (2012) 125031 [arXiv:1211.3920] [SPIRE].

[14] B. Müller and H.-T. Janka, *A New Multi-Dimensional General Relativistic Neutrino Hydrodynamics Code for Core-Collapse Supernovae IV. The Neutrino Signal*, Astrophys. J. 788 (2014) 82 [arXiv:1402.3415] [SPIRE].

[15] B. Dasgupta, A. Dighe, G.G. Raffelt and A.Y. Smirnov, *Multiple Spectral Splits of Supernova Neutrinos*, Phys. Rev. Lett. 103 (2009) 051105 [arXiv:0904.3542] [SPIRE].

[16] H. Duan, G.M. Fuller and Y.-Z. Qian, *Collective Neutrino Oscillations*, Ann. Rev. Nucl. Part. Sci. 60 (2010) 569 [arXiv:1001.2799] [SPIRE].

[17] A. Strumia and F. Vissani, *Neutrino masses and mixings and...*, hep-ph/0606054 [SPIRE].

[18] H. Duan, G.M. Fuller, J. Carlson and Y.-Q. Zhong, *Neutrino Mass Hierarchy and Stepwise Spectral Swapping of Supernova Neutrino Flavors*, Phys. Rev. Lett. 99 (2007) 241802 [arXiv:0707.0290] [SPIRE].

[19] A. Strumia and F. Vissani, *Precise quasielastic neutrino/nucleon cross-section*, Phys. Lett. B 564 (2003) 42 [astro-ph/0302055] [SPIRE].
[20] F. Ajzenberg-Selove, *Energy levels of light nuclei A = 11–12*, *Nucl. Phys. A* 506 (1990) 1 [inSPIRE].

[21] M. Fukugita, Y. Kohyama and K. Kubodera, *Neutrino Reaction Cross-Sections on $^{12}$C Target*, *Phys. Lett. B* 212 (1988) 139 [inSPIRE].

[22] S.Y.F. Chu, L.P. Ekstrom and R.B. Firestone, *The Lund/LBNL Nuclear Data Search* (1999) http://nucleardata.nuclear.lu.se/toi/index.asp.

[23] L.A. Ahrens, S.H. Aronson, P.L. Connolly, B.G. Gibbard, M.J. Murtagh et al., *Measurement of neutrino-proton and antineutrino-proton Elastic Scattering*, *Phys. Rev. D* 35 (1987) 785 [inSPIRE].

[24] http://theory.lngs.infn.it/astroparticle/sn.html.

[25] G. Pagliaroli, C. Lujan-Peschard, M. Mitra and F. Vissani, *Using Low-Energy Neutrinos from Pion Decay at Rest to Probe the Proton Strangeness*, *Phys. Rev. Lett.* 111 (2013) 022001 [arXiv:1210.4225] [inSPIRE].

[26] KARMEN Collaboration. collaboration, B.E. Bodmann et al., *Neutrino interactions with carbon: Recent measurements and a new test of electron-neutrino, anti-muon-neutrino universality*, *Phys. Lett. B* 332 (1994) 251 [inSPIRE].

[27] OscSNS collaboration, H. Ray, *OscSNS: Precision Neutrino Measurements at the Spallation Neutron Source*, *J. Phys. Conf. Ser.* 136 (2008) 022029 [arXiv:0810.3175] [inSPIRE].

[28] T. Yoshida, T. Suzuki, S. Chiba, T. Kajino, H. Yokomakura et al., *Neutrino-Nucleus Reaction Cross Sections for Light Element Synthesis in Supernova Explosions*, *Astrophys. J.* 686 (2008) 448 [arXiv:0807.2723] [inSPIRE].

[29] A. Heger, E. Kolbe, W.C. Haxton, K. Langanke, G. Martinez-Pinedo et al., *Neutrino nucleosynthesis*, *Phys. Lett. B* 606 (2005) 258 [astro-ph/0307546] [inSPIRE].

[30] LSND collaboration, L.B. Auerbach et al., *Measurement of electron-neutrino electron elastic scattering*, *Phys. Rev. D* 63 (2001) 112001 [hep-ex/0010139] [inSPIRE].

[31] R.C. Allen, H.H. Chen, P.J. Doe, R. Hausammann, W.P. Lee et al., *Study of electron-neutrino electron elastic scattering at LAMPF*, *Phys. Rev. D* 47 (1993) 11 [inSPIRE].

[32] H.M. O’Keeffe, E. O’Sullivan and M.C. Chen, *Scintillation decay time and pulse shape discrimination in oxygenated and deoxygenated solutions of linear alkylbenzene for the SNO+ experiment*, *Nucl. Instrum. Meth. A* 640 (2011) 119 [arXiv:1102.0797] [inSPIRE].

[33] Borexino collaboration, C. Arpesella et al., *Direct Measurement of the $^7$Be Solar Neutrino Flux with 192 Days of Borexino Data*, *Phys. Rev. Lett.* 101 (2008) 091302 [arXiv:0805.3843] [inSPIRE].

[34] SNO+ collaboration, G. Lefeuivre et al., *From SNO to SNO+, upgrading a neutrino experiment*, *Nucl. Instrum. Meth. A* 718 (2013) 506 [inSPIRE].

[35] R. Madey et al., *The response of NE-228A, NE-228, NE-224, and NE-102 scintillators to protons from 2.43 to 19.55 MeV*, *Nucl. Instrum. Meth. 151* (1978) 445.

[36] S. Yoshida, T. Ebihara, T. Yano, A. Kozlov, T. Kishimoto et al., *Light output response of KamLAND liquid scintillator for protons and $^{12}$C nuclei*, *Nucl. Instrum. Meth. A* 622 (2010) 574 [inSPIRE].

[37] B. von Kroisigk, L. Neumann, R. Nolte, S. Rottger and K. Zuber, *Measurement of the proton light response of various LAB based scintillators and its implication for supernova neutrino detection via neutrino-proton scattering*, *Eur. Phys. J. C* 73 (2013) 2390 [arXiv:1301.6403] [inSPIRE].

[38] D.K. Nadyozhin, *The neutrino radiation for the hot neutron star formation and the envelope outburst problem*, *Astrophys. Space Sci.* 53 (1978) 131 [inSPIRE].
[39] H.A. Bethe and R. Wilson, James, *Revival of a stalled supernova shock by neutrino heating*, *Astrophys. J.* 295 (1985) 14 [arXiv:1402.6143] [INSPIRE].

[40] G. Badino et al., *The 90 ton liquid scintillator detector in the Mont Blanc Laboratory*, *Nuovo Cim. C* 7 (1984) 573.

[41] N.Y. Agafonova, M. Aglietta, P. Antonioli, G. Bari, V.V. Boyarkin et al., *Study of the effect of neutrino oscillations on the supernova neutrino signal in the LVD detector*, *Astropart. Phys.* 27 (2007) 254 [hep-ph/0609305] [INSPIRE].

[42] P. Antonioli, W. Fulgione, P. Galeotti and L. Panaro, *Simulation of low-energy neutrino interactions in liquid scintillation counters*, *Nucl. Instrum. Meth. A* 309 (1991) 569 [INSPIRE].

[43] T. Totani, K. Sato, H.E. Dalhed and J.R. Wilson, *Future detection of supernova neutrino burst and explosion mechanism*, *Astrophys. J.* 496 (1998) 216 [astro-ph/9710203] [INSPIRE].

[44] Borexino collaboration, G. Bellini et al., *Observation of Geo-Neutrinos*, *Phys. Lett. B* 687 (2010) 299 [arXiv:1003.0284] [INSPIRE].

[45] KamLAND collaboration, K. Tolich, *Supernova detection with KamLAND*, *Nucl. Phys. Proc. Suppl.* 221 (2011) 355 [INSPIRE].

[46] H.-T. Janka, *Explosion Mechanisms of Core-Collapse Supernovae*, *Ann. Rev. Nucl. Part. Sci.* 62 (2012) 407 [arXiv:1206.2503] [INSPIRE].

[47] C.D. Ott, E. Abdikamalov, P. Mosta, R. Haas, S. Drasco et al., *General-Relativistic Simulations of Three-Dimensional Core-Collapse Supernovae*, *Astrophys. J.* 768 (2013) 115 [arXiv:1210.6674] [INSPIRE].

[48] N. Smith, K.H. Hinkle and N. Ryde, *Red Supergiants as Potential Type IIn Supernova Progenitors: Spatially Resolved 4.6 μm CO Emission Around VY CMa and Betelgeuse*, *Astron. J.* 137 (2009) 3558.

[49] LENA collaboration, M. Wurm et al., *The next-generation liquid-scintillator neutrino observatory LENA*, *Astropart. Phys.* 35 (2012) 685 [arXiv:1104.5620] [INSPIRE].

[50] Y.-F. Li, *Overview of the Jiangmen Underground Neutrino Observatory (JUNO)*, *Int. J. Mod. Phys. Conf. Ser.* 31 (2014) 1460300 [arXiv:1402.6143] [INSPIRE].

[51] Borexino collaboration, G. Alimonti et al., *Measurement of the 14C abundance in a low-background liquid scintillator*, *Phys. Lett. B* 422 (1998) 349 [INSPIRE].