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Supernova neutrino detection in Borexino

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Summary. — In this paper, the performances of Borexino as a Supernova neutrino detector are analyzed and discussed. The expected neutrino signal from a typical Type II Supernova at a distance of 10 kpc is calculated: a burst of around 240 events would appear in Borexino within a time interval of about 10 s. Most of these events would come from the reaction channels $\bar{\nu}_e + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}$ and $\nu + \mathrm{p} \to \nu + \mathrm{p}$, while about 30 events would be induced by the interaction of the Supernova neutrino flux on ^{12}C in the liquid scintillator: for most of these reactions, Borexino features unique detection capabilities, thanks to its low-energy sensitivity, ultra-low radioactive background and large homogeneous volume. The possibility to tag and identify the different neutrino detection reactions gives access to key information concerning Supernova physics and non-standard neutrino properties. The detection of neutrinos via elastic scattering off protons in Borexino is discussed here for the first time: this reaction is proven to be a powerful component of the neutrino-induced burst of events. Finally, a viable "Supernova trigger" condition is established, which allows to detect a Supernova explosion up to a distance of 63 kpc.

PACS `14.60.Pq` – Neutrino mass and mixing.
PACS `25.30.Pt` – Neutrino scattering.
PACS `95.55.Vj` – Neutrino, muon, pion, and other elementary particle detectors; cosmic ray detectors.
PACS `97.60.Bw` – Supernovae.

1. – Introduction

The Borexino experiment (presently in its final installation phase at the Gran Sasso Laboratories, Italy) has been designed and built in order to explore the sub-MeV region of the solar neutrino spectrum, namely the monochromatic ^{8}Be line at 860 keV. Besides this challenging low-energy neutrino detection, the facility can be applied to a broad range of frontier questions in particle physics, astrophysics and geophysics.

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The Borexino detector [1] is composed of 300 t of liquid scintillator, observed by an array of 2212 photomultipliers. The complete detector is designed in order to reduce γ-ray background in the core via a graded shielding, made of different layers of increasingly radio-pure materials. Its unique low-energy sensitivity and ultra-low background bring new capabilities to attack key problems in astroparticle physics. Much of this research can be undertaken simultaneously with solar neutrino observations; this is the case for the detection of neutrinos and antineutrinos produced in the reactions occurring during the final explosive phase of the evolution of massive stars, the so-called Supernova events.

A typical Type II Supernova explosion at a distance of 10 kpc would produce in Borexino a burst of around 240 neutrino events, reaching the detector within a time interval of about 10 s [2]. Most of these events would come from the reaction channels $\bar{\nu}_{\mathrm{e}} + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}$ and $\nu_x + \mathrm{p} \to \nu_x + \mathrm{p}$, while about 30 events would be induced by the interaction of the Supernova neutrinos on ^{12}C in the liquid scintillator: the detection of the neutrino interactions with ^{12}C atoms, as well as the detection of elastic-scattering interactions on protons, are almost unique features of the Borexino detector.

2. – The role of neutrinos in Supernova events

The gravitational collapse events associated with Type II Supernovae and neutron star formation are copious producers of neutrinos. As stated in [3], regardless of the detail of the collapse, core bounce and explosion processes, in order to form a remnant neutron star there must be an energy release equal to the binding energy $\varepsilon_{\mathrm{B}} \simeq 3 \times 10^{53}$ erg. The total light emitted in the Supernova outburst is about 1% of this energy; the remainder of the binding energy comes off in the form of neutrinos. Neutrinos are produced at different stages of the Supernova event, through different processes, but most of the binding energy of the star is carried away by the $\nu\bar{\nu}$ pairs produced during the thermal cooling phase of the hot remnant core. These neutrinos, created in pair-production processes such as: $\mathrm{e}^+ + \mathrm{e}^- \to \nu_i + \bar{\nu}_i$, are the most efficient energy carriers and constitute the main neutrino signal we can receive, on Earth, from the Supernova event [3].

The ν_i-$\bar{\nu}_i$ pairs produced during the cooling phase do not immediately escape the core. The reason is the weak interaction: at densities $> 10^{11}$ g/cm^3 the scattering of neutrinos off nuclei happens so often that the neutrinos get trapped. Despite this, the neutrino mean free path remains large, so that they are still efficient energy carriers and they can escape as soon as they pass the neutrino-sphere, defined as the surface within which neutrinos are trapped. This occurs at a density $\sim 5 \times 10^{10}$ g/cm^3.

The temperature of the neutrino-sphere characterizes the energy distribution spectrum of the neutrinos. ν_μ and ν_τ and their antiparticles present lower opacities than ν_{e} and $\bar{\nu}_{\mathrm{e}}$, since they interact only via neutral current weak interaction (ν_{e} and $\bar{\nu}_{\mathrm{e}}$ also do charged current). This means their neutrino-sphere is deeper inside the core and their spectrum is hotter than the one of ν_{e} and $\bar{\nu}_{\mathrm{e}}$. Moreover, the neutrino decoupling takes place in a neutron rich matter, less transparent to ν_{e} than $\bar{\nu}_{\mathrm{e}}$. The temperature hierarchy is, then: $T_{\nu_{\mathrm{e}}} < T_{\bar{\nu}_{\mathrm{e}}} < T_{\nu_x}$ (ν_x refers to ν_μ, ν_τ and their antiparticles).

The theoretical prediction is that all the neutrino species are produced in the cooling phase with the same luminosity, in agreement with an equipartition principle: this means there will be more ν_{e} than ν_μ and ν_τ, since their average energy is lower. The expected neutrino spectra from a Supernova with binding energy $\varepsilon_{\mathrm{B}} = 3 \times 10^{53}$ erg are shown in fig. 1: for each family, the energy spectrum features a Fermi-Dirac distribution, with zero chemical potential.

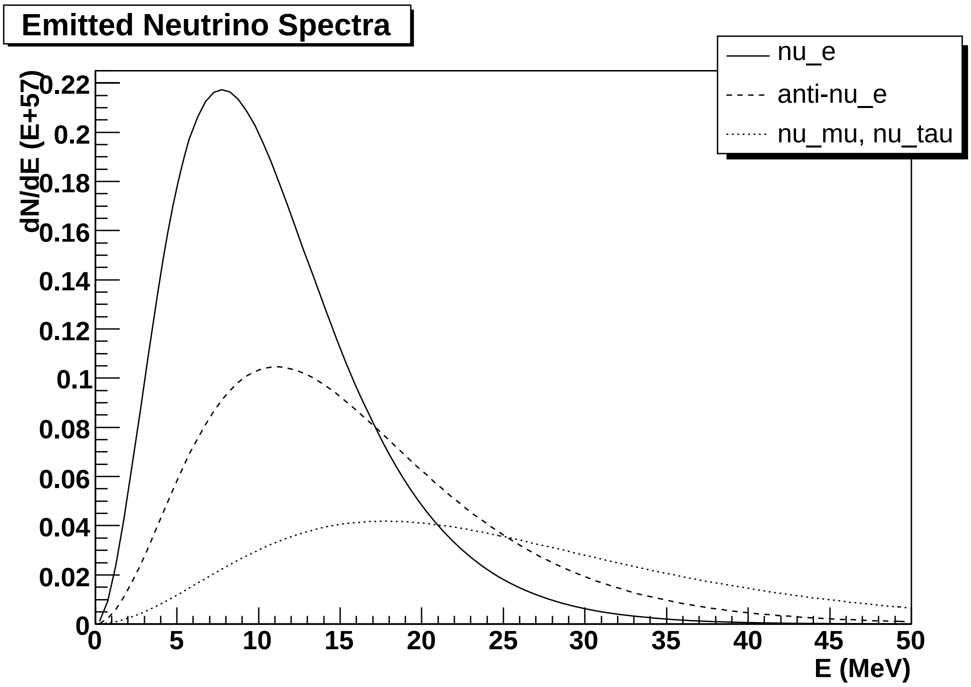

Fig. 1. – Neutrino thermal spectra, for $\varepsilon_{\mathrm{B}} = 3 \times 10^{53}$ erg: the solid line is the ν_{e} spectrum, the dashed one is for $\bar{\nu}_{\mathrm{e}}$ and the dotted line is the spectrum of ν_μ, ν_τ and their antiparticles.

3. – Supernova neutrino signatures in Borexino

The neutrino flux from a Supernova event will interact in the Borexino sensitive volume through the following reactions:

– Scattering off electrons:

$$\nu + \mathrm{e}^- \to \nu + \mathrm{e}^- .$$

This is a thresholdless reaction, sensitive to all leptonic flavors. The cross-section for neutrino-lepton scattering can be estimated with the formalism of the standard electroweak theory; if the incoming neutrino energy is $E_\nu \gg m_{\mathrm{e}}$, we obtain

$$\sigma = \frac{2G_{\mathrm{F}}^2 m_{\mathrm{e}} E_\nu}{\pi}\left[c_{\mathrm{L}}^2 + \frac{1}{3}c_{\mathrm{R}}^2\right].$$

The total cross-section for $\nu-\mathrm{e}$ scattering is then linearly proportional to the neutrino energy: $\sigma(E_\nu) = \tilde{\sigma} \cdot E_\nu$, with $\tilde{\sigma} \simeq$ constant. The numerical values are

$$\begin{aligned}\sigma(\nu_{\mathrm{e}}) &= 9.20 \times 10^{-45}\ E_\nu(\mathrm{MeV})\,\mathrm{cm}^2,\\ \sigma(\bar{\nu}_{\mathrm{e}}) &= 3.83 \times 10^{-45}\ E_\nu(\mathrm{MeV})\,\mathrm{cm}^2,\\ \sigma(\nu_{\mu,\tau}) &= 1.57 \times 10^{-45}\ E_\nu(\mathrm{MeV})\,\mathrm{cm}^2,\end{aligned}$$

$$\sigma(\bar{\nu}_{\mu,\tau}) = 1.29 \times 10^{-45}\ E_\nu(\mathrm{MeV})\,\mathrm{cm}^2.$$

These cross-sections can be averaged over the proper thermal neutrino spectrum, with $E_{\mathrm{thr}} = 0$; it is then straightforward to calculate the expected number of events of this type in Borexino, as a consequence of a Supernova collapse: in 300 t of liquid scintillator there would be ~ 5 scattering events due to a standard Type II Supernova at 10 kpc distance.

– Inverse β decay of the proton

$$\bar{\nu}_{\mathrm{e}} + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}.$$

This reaction, with an energy threshold of 1.80 MeV, is the favorite channel for the detection of Supernova neutrinos (see sect. **5**).

The total cross-section for this reaction, for sufficiently low energy, is given by

$$\sigma = \frac{G_{\mathrm{F}}^2 E_{\bar{\nu}}^2}{\pi} |\cos^2\theta_c|^2 \left[1 + 3\left(\frac{g_{\mathrm{A}}}{g_{\mathrm{V}}}\right)^2\right].$$

This approximation is valid for neutrino energies up to about 50 MeV; in our case, the average $\bar{\nu}_{\mathrm{e}}$ energy is $\langle E_{\bar{\nu}_{\mathrm{e}}}\rangle = 16$ MeV and only 0.3% of the $\bar{\nu}_{\mathrm{e}}$ spectrum is above 50 MeV. It is safe, then, to assume the cross-section for this reaction depends on the neutrino energy as $\sigma(E_\nu) = \bar{\sigma}(E_\nu - 1.3)^2$, with $\bar{\sigma} = \mathrm{const} = 9.5 \times 10^{-44}\ \mathrm{cm}^2/\mathrm{MeV}^2$.

The expected event number in Borexino (300 t sensitive volume) results to be ~ 79 counts, for the standard 10 kpc Type II Supernova. This reaction will be discussed in details in the sect. **5**, as a candidate for a "Supernova trigger" condition.

– Elastic scattering off protons

$$\nu + \mathrm{p} \to \nu + \mathrm{p}.$$

This reaction is sensitive to all neutrino flavors, with the same cross-section. At the energies considered here, the total cross-section yields [4]

$$\sigma = \frac{G_{\mathrm{F}}^2 E_\nu^2}{\pi}(c_{\mathrm{V}}^2 + 3c_{\mathrm{A}}^2).$$

This cross-section is of the same form as the total cross-section for the charged-current reaction $\bar{\nu}_{\mathrm{e}} + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}$, but is approximately 4 times smaller. However, this is compensated in the yield by the contributions of all six flavors, as well as the higher temperature assumed for ν_μ and ν_τ ($T = 8$ MeV instead of 5 MeV): thus, the total yield from $\nu_x + \mathrm{p} \to \nu_x + \mathrm{p}$ is larger than from $\bar{\nu}_{\mathrm{e}} + \mathrm{p} \to \mathrm{e}^+ + \mathrm{n}$, when the detector threshold is neglected. A detailed discussion of the number of events produced in this reaction, considering the performances of a real scintillation detector, is presented in sect. **4**.

The contributions of the different neutrino flavors to the $\nu - p$ scattering are shown in fig. 2, where incoming neutrino energy spectra are compared with their convolution with the cross-section: the summed contribution of ν_μ, ν_τ (and their antiparticles) gives the most significant fraction of events.

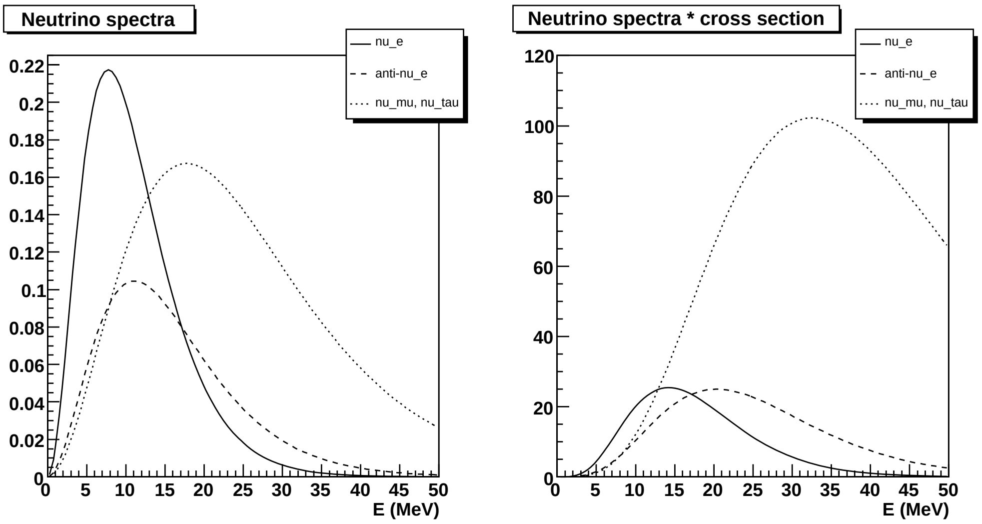

Fig. 2. – Contribution of the different neutrino flavors to the $\nu - p$ elastic scattering: incoming neutrino energy spectra (left) and their convolution with the cross-section (right). The solid line is the ν_{e} distribution, the dashed line is the $\bar{\nu}_{\mathrm{e}}$ profile and the dotted line is the summed contribution of the other flavors.

– Reactions on ^{12}C

Borexino can clearly distinguish between the neutral-current excitations $^{12}\mathrm{C}(\nu,\nu')$ $^{12}\mathrm{C}^*$ and the charged-current reactions $^{12}\mathrm{C}(\nu_{\mathrm{e}},\mathrm{e}^-)^{12}\mathrm{N}$ and $^{12}\mathrm{C}(\bar{\nu}_{\mathrm{e}},\mathrm{e}^+)^{12}\mathrm{B}$, via their distinctive event signatures. The ratio of the charged-current to neutral-current neutrino event rates and their time profiles, with respect to each other, can provide a handle on non-standard neutrino physics (see sect. **6**).

Although the main Supernova signal comes from the $\bar{\nu}$ capture, the reactions of neutrino capture on ^{12}C are particularly interesting in detectors based on organic scintillator, such as Borexino. Three different reactions are possible:

– Charged current capture of $\bar{\nu}_{\mathrm{e}}$:

$$\begin{array}{lll} \bar{\nu}_{\mathrm{e}} +^{12}\mathrm{C} \rightarrow & ^{12}\mathrm{B} + \mathrm{e}^+ , & Q = 13.37\ \mathrm{MeV}, \\ & ^{12}\mathrm{B} \rightarrow ^{12}\mathrm{C} + \mathrm{e}^- + \bar{\nu}_{\mathrm{e}} , & \tau_{1/2} = 20.20\ \mathrm{ms}. \end{array}$$

– Charged current capture of ν_{e}:

$$\begin{array}{lll} \nu_e +^{12}\mathrm{C} \rightarrow & ^{12}\mathrm{N} + \mathrm{e}^- , & Q = 17.34\ \mathrm{MeV}, \\ & ^{12}\mathrm{N} \rightarrow ^{12}\mathrm{C} + \mathrm{e}^+ + \nu_e , & \tau_{1/2} = 11.00\ \mathrm{ms}. \end{array}$$

– Inelastic scattering of ν_x:

$$\begin{array}{lll} \nu_x +^{12}\mathrm{C} \rightarrow & ^{12}\mathrm{C}^* + \nu'_x , & E_{\mathrm{thr}} = 15.11\ \mathrm{MeV}, \\ & ^{12}\mathrm{C}^* \rightarrow ^{12}\mathrm{C} + \gamma , & E_\gamma = 15.11\ \mathrm{MeV}. \end{array}$$

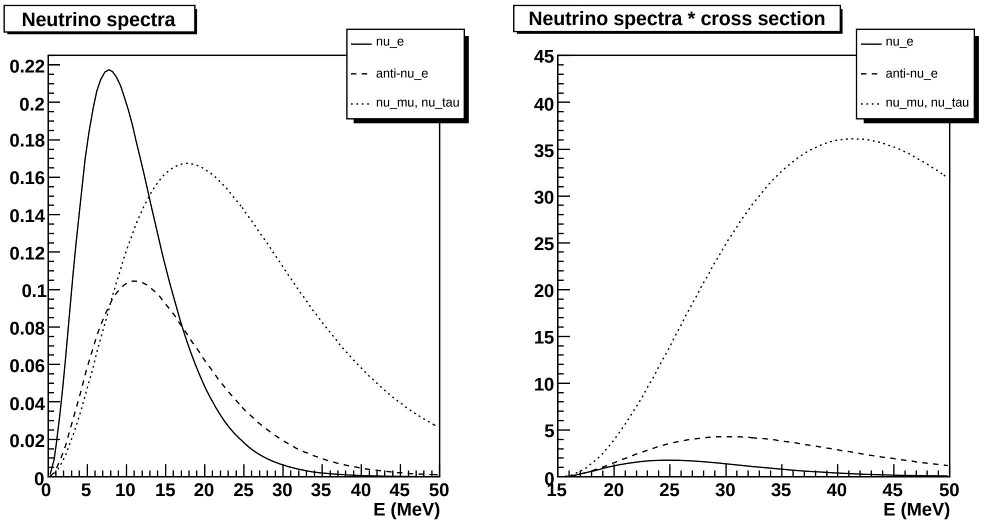

Fig. 3. – Contribution of the different neutrino flavors to the neutral current reaction $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^*$(15.11 MeV): incoming neutrino energy spectra (left) and their convolution with the cross-section (right). The solid line is the ν_e distribution, the dashed line is the $\bar{\nu}_\mathrm{e}$ profile and the dotted line is the summed contribution of the other flavors.

All these three reactions on ^{12}C can be tagged in Borexino: both $^{12}\mathrm{C}(\nu_\mathrm{e},\mathrm{e}^-)^{12}\mathrm{N}$ and $^{12}\mathrm{C}(\bar{\nu}_\mathrm{e},\mathrm{e}^+)^{12}\mathrm{B}$ present a delayed coincidence of an electron and a positron, with a few milliseconds delay; while the inelastic scattering $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^*$ is followed by a mono-energetic γ-ray at 15.11 MeV.

Efficient detection and resolution of the 15.1 MeV γ's will be a unique feature of Borexino and KamLAND [5] detectors. The large, homogeneous volume of liquid scintillator effectively contains the total energy of this γ-ray; moreover, the detector energy resolution allows the neutral-current events to be easily identified [2].

The cross-sections for the neutrino-carbon reactions are complicated by the presence of nuclear matrix elements: for this reason, they have been investigated theoretically and experimentally over the past 20 years and are now well established. The agreement between the theoretical predictions to the measured data is good and a combined theoretical and experimental average value for the $^{12}\mathrm{C}(\nu_\mathrm{e},\mathrm{e}^-)^{12}\mathrm{N}$ reaction, can be set as $\langle\sigma\rangle_\mathrm{exp} = 9.2\times10^{-42}\mathrm{cm}^2$ [2]. The cross-section measurements were averaged over the neutrino energies relevant to the experiments: it is straightforward to scale these measured values to give averaged cross-sections for Supernova neutrinos [2].

The neutral-current cross-section can also be extracted from the experimental $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^*$ cross-section data. Using an averaged value $\langle\sigma\rangle_\mathrm{exp} = 10\times10^{-42}$ cm^2, these data are scaled for Supernova neutrino fluxes and energies. These calculations allow to estimate the following event numbers in Borexino (300 t): 23 neutral-current events, 4 events due to $\bar{\nu}_\mathrm{e}$ capture on ^{12}C and less than one event due to ν_e capture, from a typical galactic Supernova at 10 kpc [2].

The contributions of the different neutrino flavors to the neutral current reaction $^{12}\mathrm{C}(\nu,\nu')^{12}\mathrm{C}^*(15.11\,\mathrm{MeV})$ are shown in fig. 3, where incoming neutrino energy spectra

Table I. – *Predicted neutrino events in Borexino (*300 *t), due to a Supernova explosion at a distance of* 10 *kpc, with* $\varepsilon_B = 3 \times 10^{53}$ *erg binding energy release (the event rates for the* $\nu_x - p$ *reaction are given for a thresholdless detector).*

Reaction channel	$\langle E_\nu \rangle$ (MeV)	$\langle \sigma \rangle$ (cm^2)	N_{events}
$\nu_e - e$	11	1.02×10^{-43}	2.37
$\bar{\nu}_e - e$	16	6.03×10^{-44}	0.97
$\nu_x - e$	25	3.96×10^{-44}	0.81
$\bar{\nu}_x - e$	25	3.25×10^{-44}	0.67
Total $\nu - e$			4.82
$\bar{\nu}_e + p \rightarrow e^- + n$	16	2.70×10^{-41}	79
$\nu_e - p$	11	6.84×10^{-42}	14
$\bar{\nu}_e - p$	16	6.84×10^{-42}	20
$\nu_x - p$	25	6.84×10^{-42}	127
Total $\nu - p$			161
$^{12}C(\nu_e, e^-)^{12}N$	11	1.85×10^{-43}	0.6
$^{12}C(\bar{\nu}_e, e^+)^{12}B$	16	1.87×10^{-42}	4.1
$\nu_e + ^{12}C$	11	1.33×10^{-43}	0.4
$\bar{\nu}_e + ^{12}C$	16	6.88×10^{-43}	1.5
$\nu_x + ^{12}C$	25	3.73×10^{-42}	20.9
Total $^{12}C(\nu, \nu')^{12}C^*$			22.9

are compared with their convolution with the cross-section: the summed contribution of ν_μ, ν_τ (and their antiparticles) gives the only significant fraction of events above threshold; the summary of expectations on Supernova neutrino events from the various contributions is listed in table I.

4. – Detection of Supernova neutrinos by $\nu - p$ elastic scattering

In a recent study [4], it was pointed out for the first time that the neutrino-proton elastic scattering reaction ($\nu + p \rightarrow \nu + p$) can be used for the detection of Supernova neutrinos in scintillator detectors. The neutrino-proton elastic scattering has been observed at accelerators at GeV energies, but has never been demonstrated to be a realistic detection channel for low-energy neutrinos: in this section, are described the main experimental issues related to the observation of this channel in a real scintillation detector (cross-sections have been reported in sect. **3**).

In case of ν+p elastic scattering, the scattered protons will have kinetic energies of a few MeV. Obviously, these very non-relativistic protons will be completely invisible in any Čerenkov detector like Super-Kamiokande. However, such small energy depositions can be readily detected in scintillator detectors such as KamLAND and Borexino.

For highly ionizing particles like low-energy protons, the quenching effect in scintillator has to be considered; the observable light output E_{equiv} is given by Birk's law:

$$\frac{dE_{\text{equiv}}}{dx} = \frac{dE/dx}{1 + K_B(dE/dx)},$$

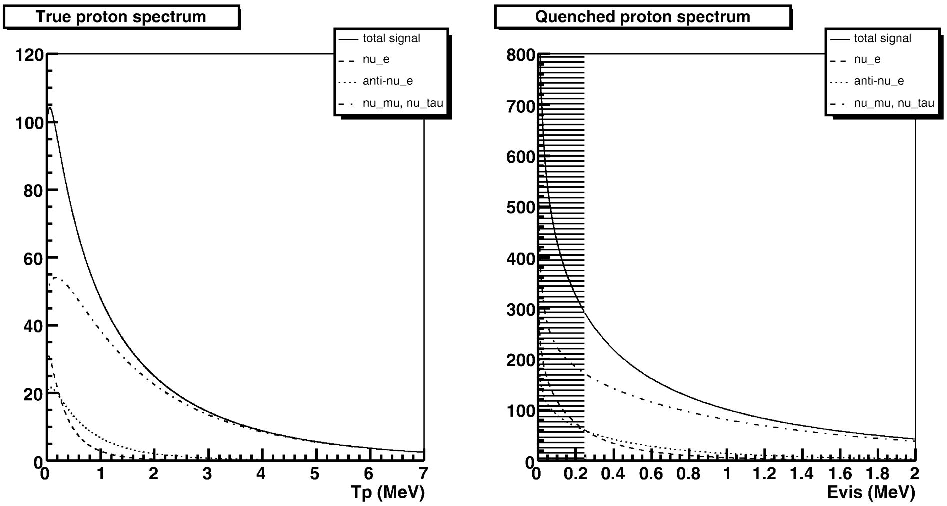

Fig. 4. – Left: the theoretical proton spectrum in Borexino, from $\nu - p$ elastic scattering; the contributions from ν_e, $\bar{\nu}_{\rm e}$ and the sum of ν_μ, ν_τ, $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$ are shown with dotted or dashed lines; the solid line is the sum spectrum for all flavors. Right: the same spectrum, with the quenching effect taken into account (the dotted region represents the energy range suppressed by the solar neutrino threshold at 250 keV).

where $k_{\rm B}$ is a constant of the scintillation material, assumed to be $k_{\rm B} \simeq 0.010$ for Borexino, as deduced from recent CTF data [6]. Visible proton spectrum for Borexino is shown in fig. 4, compared to the theoretical spectrum: the effect of the quenching results in a significant shift of the spectrum towards lower energy values.

In the absence of threshold, 161 scattered protons would be detected in Borexino 300 t (for a standard Supernova at 10 kpc); but the real number of $\bar{\nu}_{\rm e} + {\rm p} \rightarrow {\rm e}^+ + {\rm n}$ events will be determined by the experimental threshold, which is in turn determined by the natural radioactivity of the scintillator (namely by the ^{14}C countrate): since the Supernova event rate will be of the order of 10 Hz, an acceptable threshold could be slightly lower than in the solar neutrino case (250 keV), where the ^{14}C rate is of the Hz order.

A detailed study of the ^{14}C activity has been performed using the present data from CTF detector, a prototype of Borexino with 4 t scintillator as active material [7]. With this detector, it was possible to measure the ^{14}C rate in the energy range 100–250 keV, for the same scintillating mixture that will be used in Borexino; this measurement allows to estimate the number of ^{14}C events, expected in Borexino in a 10 s interval (the typical duration of a Supernova burst).

An experimental threshold between 100 and 250 keV would preserve most of the events from $\nu - p$ scattering: the "optimal" threshold will be therefore determined by comparing the number of protons surviving the energy cut with the residual ^{14}C events in 10 s. The result of this comparison is shown in table II: all the thresholds between 150 and 250 keV are suitable for this detection, since they provide a signal to background ratio greater than 10 (a lower ratio would be quite unsatisfactory, because no distinctive feature can help in discriminating the two categories of events).

In case of a galactic Type II Supernova explosion, Borexino would therefore detect a large number of events from $\nu - p$ elastic scattering, which would represent the main

TABLE II. – *Detectable protons in Borexino (*300 *t), produced via ν-p elastic scattering, according to four different experimental thresholds and compared to the expected background from* ^{14}*C. All the thresholds between* 150 *and* 250 *keV are suitable for this detection, since they provide a signal to background ratio greater than* 10.

Experimental threshold	Detectable scattered protons	^{14}C events in 10 s
100 keV	135 ± 12	64 ± 8
150 keV	126 ± 11	9 ± 3
200 keV	118 ± 11	4 ± 2
250 keV	111 ± 10	–

detection reaction. These events, in combination with the events produced in the inverse β-decay of the proton, would provide a powerful handle to access non-standard properties of neutrinos, as explained in sect. **6**.

5. – Considerations about a "Supernova trigger"

A key issue in the study of Supernova neutrinos is the identification of a "trigger" condition, namely a threshold on the number of events to be detected in a given time interval, in order to identify certainly a Supernova explosion. The best reaction for such a purpose is the inverse beta-decay of protons ($\overline{\nu}_{\rm e} + {\rm p} \rightarrow {\rm n} + {\rm e}^+$): the delayed coincidence tag featured by these events allow to perform a background-free analysis.

The $\overline{\nu}_{\rm e}$ are detected in scintillator liquid through the classic Reines reaction of capture by protons: $\overline{\nu}_{\rm e} + {\rm p} \rightarrow {\rm n} + {\rm e}^+$. The positron visible energy (kinetic energy +1.02 MeV annihilation energy) yields $E = E(\overline{\nu}_{\rm e}) - Q$, where the threshold energy is $Q = 1.8$ MeV. The $\overline{\nu}_{\rm e}$ tag is made possible by the delayed coincidence between the positron signal and the 2.2 MeV γ-ray emitted by neutron capture on proton, after a ~ 210 μs delay: the tag suppresses completely the background from natural radioactivity, if associated with an energy cut (see below).

The large homogeneous detection volume in Borexino ensures efficient neutron capture and efficient detection of the 2.2 MeV γ: if a hypothetical detector lacks the low-energy threshold of Borexino or is not able to contain the neutron produced by the $\bar{\nu}_{\rm e} - {\rm p}$ reaction, it will not be able to exploit the delayed coincidence signature to identify these events (the $\bar{\nu}_{\rm e} - {\rm p}$ events will appear as single positrons). Borexino-like detectors provide thus an unique possibility to detect and tag Supernova antineutrinos.

To determine a threshold on the number of $\overline{\nu}_{\rm e} + {\rm p} \rightarrow {\rm n} + {\rm e}^+$ events to be detected in a 10 s interval in order to identify certainly a Supernova event, an accurate evaluation of the antineutrino background must be performed: this can be done through an analysis of neutron capture events in CTF data. Analyzed data have been collected during a 341 live days period, from December 2001 to May 2003: 454 neutron capture events have been selected, according to the features of the event pair in the ${\rm e}^+ - \gamma$ coincidence (the coincidence time must be in the range 2 μs–1 ms, the first event energy above 1.5 MeV, the second event energy in the range 1–2.8 MeV). As stated before, this analysis is completely free from natural radioactivity background, since no radioactive chain features a delayed coincidence with both events above 1 MeV (reconstructed energy in liquid scintillator).

The selected events are shown in fig. 5; in the left part of the figure is represented the time difference between the two events in coincidence: the exponential behavior of the

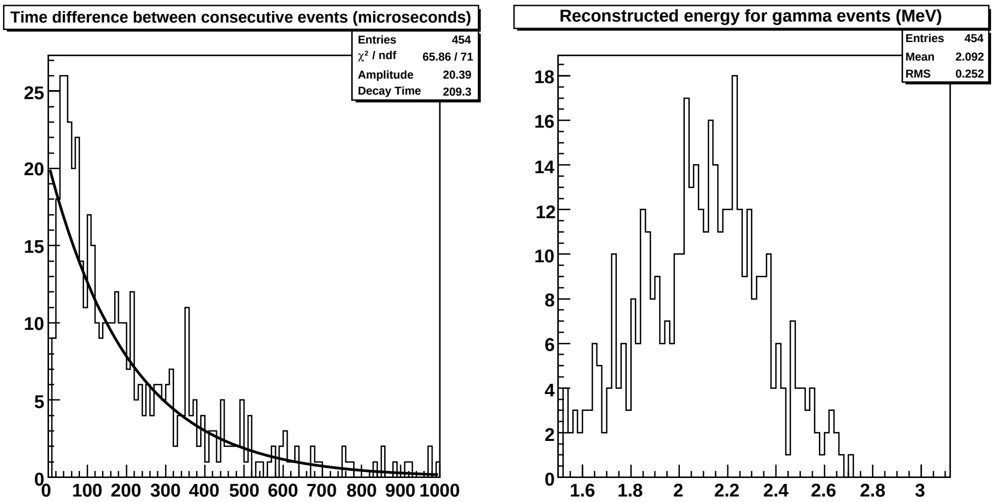

Fig. 5. – Neutron capture events in CTF. Left: time difference between the two events in coincidence: the exponential behavior of the neutron capture is well reproduced by the measured time constant of (209 ± 16) μs. Right: reconstructed energy for the γ candidate: the mean value of (2.09 ± 0.25) MeV is consistent with the expected γ energy; the smearing of the peak towards lower energies demonstrates the incomplete containment of γ's in the active volume.

neutron capture ($\tau = 210$ μs) is well reproduced by the measured time decay constant of (209 ± 16) μs. In the right part of the figure, the reconstructed energy for the second event (γ candidate) is shown: also in this case, the mean value of (2.09 ± 0.25) MeV is consistent with the expected neutron capture energy (2.2 MeV); the smearing of the peak towards lower energies demonstrates the incomplete containment of 2.2 MeV γ's in the active volume (this effect is especially evident for events reconstructed close to the border of the liquid scintillator).

Once selected the neutron capture sample, the events induced by residual cosmic rays must be rejected: using the tag provided by the CTF μ-veto detector, 450 of the initial 454 events have been identified as cosmogenic. Finally, with the remaining 4 events, the antineutrino rate in Borexino can be estimated, assuming 70% efficiency for neutron capture in CTF [6] and 100% efficiency in Borexino: this calculation results in a rate of 460 events per year in Borexino, corresponding to 1.46×10^{-4} events in 10 s.

At this point, the determination of a Supernova trigger condition is straightforward: assuming a poisson distribution with $\mu = 1.46 \times 10^{-4}$, the probability to have two or more random events in 10 s is $P(\nu \geq 2) = 1.08 \times 10^{-8}$, corresponding to a rate of accidental coincidences (two or more antineutrino events in 10 s) of 0.034 per year. This rate can be compared, as a reference, to the requirement established for a neutrino detector to be included in the "SuperNova Early Warning System" [8]: in this case, the alarm rate for each experiment must not exceed 1 per week. The alarm rate for Borexino (0.034 per year) is much lower than the SNEWS requirement: therefore, this trigger condition (two or more antineutrino events in 10 s) can be considered satisfactory.

Finally, we can estimate the Borexino sensitivity to a Supernova explosion at a given distance: since a $\varepsilon_{\mathrm{B}} = 3 \times 10^{53}$ erg Supernova at 10 kpc would produce in Borexino 79 events through the $\overline{\nu}_{\mathrm{e}} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^{+}$ reaction, the number of antineutrino events produced by a Supernova at a distance x can be estimated as: $N_x = N_{10\mathrm{kpc}}(10/x)^2$. If the minimum number of detectable event is 2 (our trigger condition), the maximum distance at which a Supernova explosion can be detected in Borexino results in 63 kpc.

6. – Non-standard neutrino physics from Supernova events

The detection of a Supernova neutrino burst in our galaxy has the potential to probe non-standard physics. In particular, the Borexino elastic-scattering and neutral-current detection capabilities will be a powerful tool in exploring non-standard features of neutrinos, like mass and flavor oscillations.

– Neutrino mass limits from time of flight.

The present direct limits on neutrino masses, obtained in laboratory experiments [9], are still unsatisfactorily high ($m_{\nu_{\mathrm{e}}} < 2.2$ eV; $m_{\nu_{\mu}} < 170$ keV; $m_{\nu_{\tau}} < 18.2$ MeV), if compared to the cosmological limit ($m_{\nu_{\mathrm{e}}} + m_{\nu_{\mu}} + m_{\nu_{\tau}} < 0.71$ eV [10]). The limits on the masses of ν_{μ} and ν_{τ} could be significantly improved through a study of the arrival time of neutrinos of different flavors.

Suppose the neutrino flux is composed of two species, one with mass and the other massless. The massive neutrinos will reach Earth with a delay (with respect to the massless species) that can be estimated with a simple relativistic calculation:

$$\Delta t = \frac{D}{2c}\left(\frac{m_{\nu}}{E_{\nu}}\right)^2,$$

where D is the distance to the Supernova. Measuring this time delay requires being able to distinguish the massive species from the massless neutrino interactions.

In Borexino, the $\nu - \mathrm{p}$ elastic scattering and the neutral-current excitation of $^{12}\mathrm{C}$ are dominated by ν_{μ} and ν_{τ}, due to their higher average energy; in these reactions, more than 80% of the events come from the heavy flavor neutrinos. Their relative contribution to the elastic scattering and to the neutral-current event rates are illustrated in figs. 2 and 3 (right). The $\bar{\nu}_{\mathrm{e}} - p$ charged-current events provide the "time stamp" for the massless species: thus, in Borexino, determining the time delay between the neutral-current or scattering events and charged-current events provides a handle on the mass of ν_{μ} and/or ν_{τ}.

A detailed discussion of the Borexino sensitivity to neutrino mass differences is reported in [2], considering different models for the Supernova neutrino burst and different mass scenarios: the expected mass limits (for the heavy neutrino species) are in the range 30–100 eV, well below the present direct limits.

– Neutrino oscillations from reactions on $^{12}\mathrm{C}$

Neutrino oscillations can be probed by comparing the Supernova neutrino event rates for different reactions. The extent of limits on Δm^2 depend on the L/E ratio which, for distances of kilo-parsecs, is many orders of magnitude lower than presently explored regions (*e.g.*, solar neutrino vacuum oscillations).

The implications of vacuum oscillations on the detection of Supernova neutrinos in Borexino can be studied: the main consideration is that higher energy ν_{μ} could oscillate into ν_{e}, resulting in an increased event rate since the expected ν_{e} energies are just at or below the charged-current reaction threshold. The cross-section for $^{12}\mathrm{C}(\nu_{\mathrm{e}}, \mathrm{e}^{-})^{12}\mathrm{N}$

increases by a factor of 35 if we average it over a ν_e distribution with $T = 8$ MeV, rather than 3.5 MeV. The gain in cross-section for $^{12}\mathrm{C}(\bar{\nu}_\mathrm{e}, \mathrm{e}^+)^{12}\mathrm{B}$ is a factor of 5. The large increase in the ν_e induced reaction rate is a pseudo-appearance signature for oscillations. A comparison between the number of events from $^{12}\mathrm{C}(\bar{\nu}_\mathrm{e}, \mathrm{e}^+)^{12}\mathrm{B}$, $^{12}\mathrm{C}(\nu_\mathrm{e}, \mathrm{e}^-)^{12}\mathrm{N}$ and $^{12}\mathrm{C}(\nu, \nu')^{12}\mathrm{C}^*$ might, then, give strong constraints on the mixing parameters (the constant neutral-current rate fixes the flavor-independent luminosity) [2]. Therefore, the charged-current and neutral-current reactions on $^{12}\mathrm{C}$ offer an important tool for probing neutrino oscillations.

7. – Conclusions

A galactic Type II Supernova explosion would produce in Borexino a large burst of neutrino events, detected trough several channels: for most of these channels, Borexino features an almost unique detection capability, thanks to its low-energy sensitivity, ultra-low radioactive background and large homogeneous volume.

In this paper, is reported for the first time a detailed discussion about the possibility to detect Supernova neutrinos via elastic scattering off protons; the number of detectable events is calculated for Borexino, taking into account the background and the experimental threshold: we demonstrate that, in case of a Supernova explosion, this channel would produce the largest contribution to the measured neutrino rate.

We also define the trigger condition which allows to identify certainly a Supernova explosion: for the triggering purpose, the most suitable reaction would be the inverse beta decay of proton, which features a powerful tag to reject background from natural radioactivity. The Borexino background to this reaction has been estimated using the CTF data: the established trigger condition (two or more $\bar{\nu}_\mathrm{e}$ events in 10 s), will allow to detect Supernova explosions up to a 63 kpc distance.

The comparison of arrival times and total rates from the different reactions can provide a handle on Supernova physics and non-standard neutrino properties (neutrino mass and flavor oscillation): the expected sensitivity on neutrino mass limit is much smaller than the present direct limits.

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