Supernova Neutrino Signal at HALO: Learning about the Primary Neutrino Fluxes

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2011-03/vaananen

We predict the numbers of one- and two-neutron charged and neutral-current electron-neutrino scattering on lead events including collective effects due to the neutrino-neutrino interactions and the Mikheev-Smirnov-Wolfenstein (MSW) effect due to the neutrino interactions with the background matter. We show that the ratios of one- to two-neutron events are sensitive to the pinching parameters of neutrino fluxes at the neutrinosphere, almost independently of the presently unknown neutrino properties. Besides, such events have an interesting sensitivity to the spectral split features that depend upon the presence/absence of energy equipartition among neutrino flavors.

1 Introduction

The features of the *primary* (i.e. at the neutrinosphere) neutrino fluxes encode information on supernova dynamics, including the microscopic processes determining the neutrino transport within the supernova core and the equation of state of the neutron star. The details of the neutrino spectra at the surface of the star depend upon such primary neutrino fluxes and upon unknown neutrino parameters – in particular the mass hierarchy and the third neutrino mixing angle. Extracting information on the primary fluxes from future observations, in spite of the unknowns and of the complexity of flavor conversion phenomena in such media, represents an important test of supernova models. Important progress has been made in our understanding of flavor conversion in these environments (for a recent review on $\nu\nu$ interaction effects, see e.g. [1]). However, several aspects still need a full understanding. Work is also needed to finally assessing its phenomenological impact in a future core-collapse supernova signal.

Most of the existing and proposed observatories, with a capability to detect supernova neutrinos, are sensitive to electron anti-neutrinos through scattering on protons. While liquid argon and scintillator detectors like LENA are sensitive to ν_e, a new detector is currently under construction at SNOLAB: the Helium And Lead Observatory (HALO). This dedicated supernova neutrino detector is able to observe the neutrons emitted from electron-neutrino scattering on lead from charged- and neutral-current events.

In this contribution, we discuss the information that can be extracted, with a detector like HALO, on the characteristics of the neutrino spectra at the neutrinosphere, taking into account the existing uncertainties from the unknown neutrino properties and from the different supernova simulations. More details on this work can be found in [2].

2 Neutrino flavor evolution: the formalism

We follow the neutrino flavor evolution from the neutrinosphere of an iron core-collapse supernova (SN) up to Earth. We propagate probabilities using the approximation of factorized dynamics. This allows us to use analytical expressions to compute the fluxes. Such an approximation has been shown to be reliable if one is not considering phase effects (from shock wave or from the Dirac CP violating phase [3]), which is our case. The primary neutrino fluxes at the neutrinospheres can be expressed using modified power law energy distribution as

$$F^0_\nu(E_\nu) \propto \frac{L_\nu}{\langle E^0_\nu\rangle} E_\nu^{\alpha_\nu} \exp\left[-\left(\alpha_\nu+1\right)\frac{E_\nu}{\langle E^0_\nu\rangle}\right] ,$$

where L_ν is neutrino luminosity, $\langle E^0_\nu\rangle$ average neutrino energy and α_ν characterizes pinching.

In the collective region, we follow the results of the full three flavor numerical calculations with/without equipartition for the neutrino luminosity (as in [4]). These calculations show that after the collective effects there can be no splits, one low (or high) energy split or both low and high energy splits in (anti)neutrino spectra, depending on the neutrino flux parameters and mass hierarchy. We have assumed all the splits in energy to be sharp. In the computation of event numbers we have used numerical values $E^s_l = 8$ MeV and $E^s_h = 23$ MeV (E^s_l and E^s_h are the low and high split energies, respectively), when appropriate. Non-electron-type (anti)neutrino fluxes are assumed to be equal.

After the collective effects have ceased, the neutrinos enter the MSW region. In this region, neutrino flavor evolution depends on how the MSW resonances are crossed. The measured values of the solar parameters make the flavor transition at the low resonance always adiabatic for typical density profiles from supernova simulations. We consider the still unknown mixing angle θ_{13} to be very small (0.001) or close to the present Chooz limit (0.1). This implies that all the processes at the high resonance are assumed to be completely adiabatic (large) or non-adiabatic (very small θ_{13}). For the other mixing angles we use the values $\sin^2 2\theta_{12} = 0.86$, $\sin^2 2\theta_{23} = 0.99$. We set the Dirac CP phase to zero.

Once the (anti)neutrinos have reached the surface of the star as mass eigenstates ν_i ($i = 1, 2, 3$), they travel up to Earth and are detected as flavor eigenstates ν_ℓ ($\ell = e, \mu, \tau$). The probabilities of a certain flavor neutrino ν_ℓ being in a given mass eigenstate ν_i is given by $|U_{\ell i}|^2 = |\langle\nu_\ell|\nu_i\rangle|^2$, where $U_{\ell i}$ is an element of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix $U_{\rm PMNS}$.

3 Expected events in the Helium and Lead Observatory

The detector is currently under construction and should start to be operating soon [5]. In phase-I HALO is made of 79 tons of lead while in phase-II the mass is planned to be increased to 1 kton. Such a detector exploits the following detection channels:

$$\begin{array}{ll} \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Bi} + n + e^- & \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{207}\mathrm{Pb} + n + \nu_x \\ \nu_e + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Bi} + 2n + e^- , & \nu_x + {}^{208}\mathrm{Pb} \rightarrow {}^{206}\mathrm{Pb} + 2n + \nu_x \end{array}$$

where neutrons are detected using ^{3}He counters as done for SNO experiment. In phase-I, one-neutron ($1n$-) and two-neutron ($2n$-) detection efficiencies are about 50 % and 25 %, respectively, while the detector will have a good time resolution of about 30 ms. Since HALO does not identify

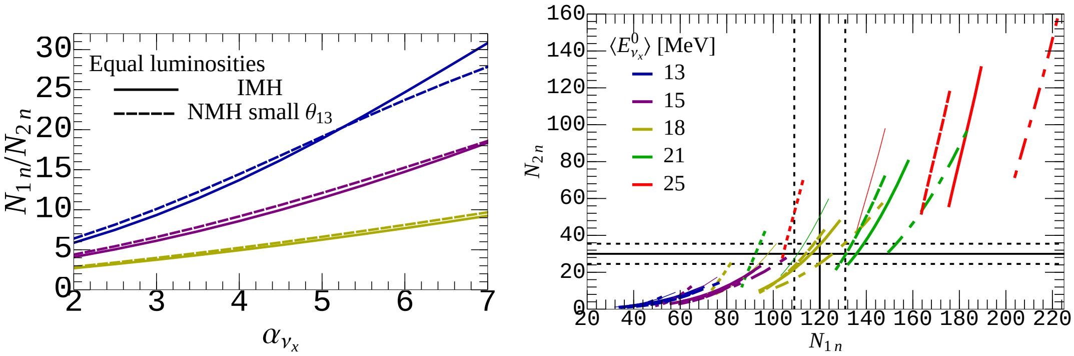

Figure 1: (color online) Left: Ratios of one- (N_{1n}) to two-neutron (N_{2n}) event rates as a function of primary non-electron neutrino pinching parameter α_{ν_x} with different primary non-electron-type neutrino average energies. Here equal luminosities and IMH are assumed. Average energies are from top to bottom $\langle E^0_{\nu_x}\rangle = 13, 15$ and 18 MeV. Right: One- and two-neutron event rates with different values of α_{ν_x}: at the top (bottom) of each curve $\alpha_{\nu_x} = 2$ (7). Solid lines are for equal luminosities (thick IMH, thin NMH with small θ_{13}), others for $L_{\nu_x} = 2L_{\nu_e}$: dotted IMH, dashed NMH with large θ_{13} and dash-dotted NMH with small θ_{13}.

the outgoing lepton, the total event rates are given by the sum of charged- and neutral-current event rates. The neutrino-lead cross sections we use are from a microscopic calculation based on the Random Phase Approximation (RPA) (see table I of ref.[6]).

In ref. [2] we have performed new predictions for the $1n$- and $2n$-events (from galactic supernova at 10 kpc) going beyond the previous calculations [6, 7] and including collective effects. In all of our calculations we assume a 100 % detection efficiency and consider HALO phase-II (1 kton). Since $1n$- and $2n$-events can be well identified, it is attractive to consider the corresponding ratio which is independent of common normalization factors (see e.g. left panel of Figure 1 valid for equal luminosities and IMH). From the figure it is clear that these ratios are sensitive to the pinching regardless of the physical scenario i.e. luminosities, neutrino mass hierarchy and the value of θ_{13}. The measured ratio would allow to identify different degenerate combinations of non-electron-type primary neutrino average energies and pinching parameters (even without a precise knowledge of the physical scenarios and common flux parameters). By knowing (or assuming) the non-electron-type primary neutrino average energy, it would be possible to give tight constraints on pinching.

We have summarized our results in the right panel of Figure 1 in which all the $1n$- and $2n$-events, in our considerations, are shown. The values are taken for a typical cooling phase (the total time-integrated luminosity is 10^{53} erg). The straight lines correspond to an example where 120 one-neutron events and 30 two-neutron events are measured during the explosion, with the associated statistical errors. This example case shows that while from the point of view of neutrino properties (mass hierarchy and θ_{13}) all scenarios are possible, rather tight constraints on the primary flux parameters – average energy and pinching parameter – can be obtained. However, notice that, if the $1n$- and $2n$-event numbers are e.g. 220 and 140, respectively (corresponding to $\langle E^0_{\nu_x}\rangle \approx 25$ MeV and $\alpha_{\nu_x} \approx 2-4$), one can obtain also a clear indication on the mass hierarchy, the value of θ_{13} and the luminosity case: the most favorable would be $L_{\nu_x} = 2L_{\nu_e}$ and NMH with small θ_{13}.

4 Conclusions

We have presented new predictions of the expected neutrino events from iron core-collapse supernovae in a lead-based observatory, such as Helium and Lead Observatory (HALO) under construction at SNOLAB. Our calculations include collective flavor conversion and the MSW effects while possible shock wave, turbulence or Earth matter effects are not considered.

We have shown that the measurement of $1n$- and $2n$-event rates as well as of their ratio is particularly sensitive to the non-electron neutrino primary average energy and pinching parameter. Using information from other detectors, the combination of $1n$- and $2n$-event rates should allow to identify degenerate solutions of average energies and pinching values. Moreover, from the ratio of these events, HALO alone can be used to give constraints on these parameters. Furthermore, from the combination of $1n$- and $2n$-event rate measurement it may be possible to give an indication on the presence/absence of the energy equipartition among neutrino flavors.

The present work emphasizes the interest of having more information on the characteristics of the high-energy component of the neutrino distributions at the neutrinosphere from future supernova simulations. It also furnishes a good example of how, having a network of detectors with different energy thresholds, constitute a unique tool to probe different components of the neutrino fluxes from a supernova explosion and to unravel interesting information on the neutrino emission and on neutrino properties. However, to be able to extract the most from future observations, a precise measurement of neutrino-lead cross sections is called for. This could be realized either at a low energy beta-beam facility [8], or nearby one of the future intense Spallation Sources [9].

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