IDENTIFYING THE NEUTRINO MASS SPECTRUM
FROM A SUPERNOVA NEUTRINO BURST

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Abstract

We study the role that the future detection of the neutrino burst from a galactic supernova can play in the reconstruction of the neutrino mass spectrum. We consider all possible 3ν mass and flavor spectra which describe the solar and atmospheric neutrino data. For each of these spectra we find the observable effects of the supernova neutrino conversions both in the matter of the star and the earth. We show that studies of the electron neutrino and antineutrino spectra as well as observations of the neutral current effects from supernova will allow us (i) to identify the solar neutrino solution, (ii) to determine the type of mass hierarchy (normal or inverted) and (iii) to probe the mixing $|U_{e3}|^2$ to values as low as $10^{-4} - 10^{-3}$.

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1 Introduction

The reconstruction of the neutrino mass and flavor spectrum is one of the fundamental problems of particle physics. It also has important implications for cosmology and astrophysics. The knowledge of neutrino masses and mixing will allow us to clarify the role of neutrinos in the mechanism of the star explosion and supernova nucleosynthesis.

With the present data on the atmospheric and solar neutrinos, we are taking the first steps in the reconstruction of the spectrum. The SuperKamiokande (SK) results on atmospheric neutrinos, confirmed by the recent SOUDAN and MACRO data, allow us to claim with a high confidence level that the atmospheric neutrinos oscillate. Moreover, the oscillations are due to neutrino masses and the mixing in vacuum. The data also indicates $\nu_\mu \leftrightarrow \nu_\tau$ as the dominant mode. All the existing experimental results can be well described in terms of the $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillations with the mass squared difference and the mixing parameters given by [?]

$$|\Delta m^2_{\text{atm}}| = (1 - 8) \cdot 10^{-3} \text{ eV}^2, \quad \sin^2 2\theta = 0.8 - 1.0.$$  \hspace{1cm} (1)

There is no compelling evidence that the electron neutrinos participate in the oscillations of atmospheric neutrinos. Moreover, the CHOOZ experiment gives an upper bound on the mixing of $\nu_e$ with $\Delta m^2 \sim \Delta m^2_{\text{atm}}$:

$$\sin^2 2\theta_e \leq 0.1 \quad \text{for} \quad |\Delta m^2| > 2 \cdot 10^{-3} \text{ eV}^2.$$  \hspace{1cm} (2)

The oscillation interpretation of the atmospheric neutrino data indicates that the solution of the solar neutrino problem is also related to nonzero neutrino masses and mixing. At the moment, however, there are several possible solutions. Moreover, various sorts of data – spectral distortions, day-night effects, seasonal variations – favor different possible solutions. A good description of all the existing data can be obtained by [?]:

1. the small mixing angle (SMA) MSW solution:

$$\Delta m^2_{\odot} = (4 - 10) \cdot 10^{-6} \text{ eV}^2, \quad \sin^2 2\theta_{\odot} = (2 - 10) \cdot 10^{-3},$$  \hspace{1cm} (3)

2. the large mixing angle (LMA) MSW solution:

$$\Delta m^2_{\odot} = (1 - 10) \cdot 10^{-5} \text{ eV}^2, \quad \sin^2 2\theta_{\odot} = 0.7 - 0.95,$$  \hspace{1cm} (4)

3. the vacuum oscillation (VO) solution:

$$\Delta m^2_{\odot} = \frac{(4 - 6) \cdot 10^{-10} \text{ eV}^2}{(6 - 8) \cdot 10^{-11} \text{ eV}^2}, \quad \sin^2 2\theta_{\odot} = 0.8 - 1.0.$$  \hspace{1cm} (5)

Some other possibilities are also not excluded – e.g. the LOW MSW solution with $\Delta m^2 \sim (0.5 - 2) \cdot 10^{-7} \text{ eV}^2$ and $\sin^2 2\theta_{\odot} = 0.9 - 1.0$ (see [?], [?]). Results from future experiments with
the existing and new detectors will remove this ambiguity, thus identifying the correct solution to the solar neutrino problem.

Another evidence for the neutrino oscillations follows from the LSND results [?], which are not confirmed, but also not excluded by the KARMEN experiment [?]. The LSND results cannot be reconciled with the solutions of the atmospheric and solar neutrino problems in the context of only three known neutrinos, thus requiring the introduction of sterile neutrinos. [?]. In this paper, we shall consider only the mixing between the known three neutrinos (spectra with sterile neutrinos will be discussed elsewhere).

The atmospheric and solar neutrino results ([?]-[?], [?]) as well as the existing bounds from the other oscillation experiments and the \( \beta \beta_0 \nu \) searches lead to several possible spectra of neutrino masses and mixing. The ambiguity is related to (i) the unidentified solution of the solar neutrino problem (ii) unknown mixing of \( \nu_e \) in the third mass eigenstate which is described by the matrix element \( U_{e3} \) (iii) type of hierarchy (normal or inverted) which is related to the mass of the third mass eigenstate (whether it is the lightest or the heaviest one). The absolute scale of mass is also unknown, however this cannot be established from the oscillation phenomena.

In this paper, we reconsider the effects of oscillations on supernova neutrinos. With the existing data on neutrino masses and mixing, we can sharpen the predictions of the oscillation effects in the supernova neutrinos. On the other hand, we clarify the extent to which the studies of supernova neutrinos can contribute to the reconstruction of the neutrino masses and flavor spectrum. We will show that three ambiguities mentioned above can in principle be resolved by supernova data.

The effects of neutrino mixing on the neutrino fluxes from the supernova have been extensively discussed in the context of \( 2\nu \) mixing. For a wide range of mixing parameters (\( \Delta m^2 \lesssim 10^4 \) eV\(^2\)), the neutrinos encounter their MSW resonance densities inside the star, hence the studies of resonant neutrino conversions inside the star [?]-[?] are crucial. For very low values of \( \Delta m^2 \) (e.g. \( \Delta m^2 \lesssim 10^{-14} \) eV\(^2\)), the vacuum oscillations on the way from the star to the earth need to be taken into account [?, ?]. In the presence of a strong magnetic field, the spin-flip effects become important [?]: the spin-flavor precession [?] and resonant spin-flavor conversions [?] may affect the observed neutrino fluxes. If sterile neutrinos are involved in the neutrino conversions, they may enable the r-process nucleosynthesis [?].

The effects of the neutrino conversions can be observed through, e.g. (i) the disappearance (partial or complete) of the neutronization peak; (ii) the interchange of original spectra and the appearance of a hard \( \nu_e \) spectrum; (iii) distortions of the \( \nu_e \) energy spectrum; (iv) modification of the \( \bar{\nu}_e \) spectrum (in particular, the effects of large lepton mixing on the \( \bar{\nu}_e \) spectrum have been extensively studied [?]); (v) earth matter effects. The observation of the neutrino burst from SN1987A [?] has already given bounds on the large mixing of active neutrinos ([?], [?], [?]-[?]) and on the mixing of \( \nu_e \) with sterile neutrinos [?].
The main features of transitions of supernova neutrinos in the case of $3\nu$ mixing ([?],[?],[?]) can be understood in terms of the $2\nu$ mixing. The system has two resonances\(^3\). Under the assumptions of mass hierarchy and smallness of mixing, the dynamics of the two level crossings splits. As a result, the factorization of probabilities occurs [?]. In the presence of sterile neutrinos, multi-level conversions take place [?], which may be interpreted in terms of the constituent $2\nu$ conversions for small mixing angles and $\Delta m^2$ hierarchy [?].

In this paper, we study the conversions of supernova neutrinos in the $3\nu$ context, taking into account the recent results on the neutrino masses and mixing. We consider the effects for all possible schemes of neutrino masses and mixing which explain the atmospheric and solar neutrino data. For each scheme, we find the modifications of (i) the neutronization peak (ii) the $\nu_e$ energy spectrum and (iii) the $\nu_e$ energy spectrum, which can be observed directly. We also determine the spectrum of the non-electron neutrinos which can in principle be studied by neutral current interactions in reactions with different energy thresholds.

The paper is organized as follows. In Sec. II we describe the features of initial neutrino fluxes from the supernova and the dynamics of neutrino conversion on their way out to the surface of the star. In Sec. III, we derive general expressions for the transition probabilities for the schemes with normal mass hierarchy. We also calculate the earth matter effects on the neutrino spectra. In Sec. IV, we find the final neutrino spectra at detectors for the schemes with the normal mass hierarchy. In Sec. V, we perform similar studies for the schemes with the inverted mass hierarchy. In Sec. VI, we discuss the observable signals and the signatures of various mixing schemes. In Sec. VII, comparing results for various schemes we conclude about the possibility to discriminate the schemes by future observations of neutrino bursts from a galactic supernova.

2 Mass spectra, fluxes and dynamics of conversion

In this section, the generic properties of the initial neutrino fluxes will be summarized. We identify the neutrino mass and mixing parameters relevant for the supernova neutrino conversions, and consider main aspects of dynamics of neutrino conversion inside the star: the transition regions, the factorization of dynamics and adiabaticity. Finally, we construct the level crossing schemes for the normal and the inverted mass hierarchy.

2.1 Neutrino fluxes

In what follows we will summarize the generic features of the original fluxes which do not depend on the model and the parameters of the star. The deviations from these features will testify for

\(^3\)The radiative corrections to $m_{\nu_e}$ and $m_{\nu_\tau}$ imply the existence of one more resonance between the two non-electron neutrinos, but since the two non-electron neutrinos cannot be distinguished at the detector, the conversions between them do not affect the observations. See sec. ??.
The diagram illustrates the mass distributions of different neutrino types: $\nu_e$, $\nu_\mu$, and $\nu_\tau$. The mass scales are given in eV, ranging from $10^{-5}$ to $10^0$. The mass distributions are indicated with horizontal bars, with the lengths representing the magnitude. The diagram also includes arrows labeled $v_{solar}$ and ATM, indicating the directions of certain processes or transitions.
\[ \overline{\nu}_e, \overline{\nu}_{\mu'}, \overline{\nu}_{\tau'} \]

\[ v_3, v_2, v_1 \]

(a) \hspace{1cm} (b) \hspace{1cm} (c) \hspace{1cm} (d)
\[ \Delta m^2 \left( \text{eV}^2 \right) \quad \text{and} \quad \sin^2 2\theta \]
The diagram illustrates the mass spectrum of neutrinos in units of eV. The horizontal axis represents the neutrino flavors $\nu_e$, $\nu_\mu$, and $\nu_\tau$, with $\nu_1$, $\nu_2$, and $\nu_3$ indicating their respective mass states.

- $\nu_e$ is shown at $10^{-1}$ eV.
- $\nu_\mu$ is shown at $10^{-2}$ eV.
- $\nu_\tau$ is shown at $10^{-3}$ eV.

The solar neutrino $\nu_{solar}$ is indicated at $10^{-5}$ eV.

The atmospheric neutrino $\nu_{ATM}$ is shown at the highest energy level, $10^{-2}$ eV, with a transition arrow pointing towards $\nu_3$. The diagram also includes a notation for $v_{solar}$ with an arrow pointing towards $\nu_1$ and $\nu_2$.
