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Prospect of measuring the neutrino mass hierarchy at $\theta_{13} \to 0$ via a supernova neutrino signal

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Collective neutrino flavor transformations deep inside a supernova are sensitive to the neutrino mass hierarchy even at extremely small values of θ_{13}. Exploiting this effect, we show that comparison of the antineutrino signals from a galactic supernova in two megaton class water-Cherenkov detectors, one of which is shadowed by the Earth, will enable us to distinguish between the hierarchies if $\sin^2\theta_{13} \lesssim 10^{-5}$, where long baseline neutrino experiments would be ineffectual.

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1. Introduction

It has been recently discovered that the paradigm of neutrino flavor transformation in supernovae (SNe), based on only the MSW effect with the ordinary matter, was incomplete. New surprising and unexpected effects have been found to be important in the region close to the neutrinosphere, where the neutrino density is so high that effects of neutrino-neutrino interactions dominate the flavor evolution. These effects have been characterized in an increasingly realistic way in a long series of papers (see, e.g. [1] and references therein). Neutrino-neutrino refractive index thus effectively provide a large potential due to the neutrinos themselves, that cause large-scale transitions between the flavors. The transitions occur collectively, i.e. in a coherent fashion over the entire energy range of neutrinos and antineutrinos, as a result collective pair conversions $\nu_e\bar{\nu}_e \leftrightarrow \nu_y\bar{\nu}_y$ (where ν_y is a proper combination of ν_μ and ν_τ) take place within the first $\mathscr{O}(100)$ km even for extremely small values of θ_{13}. Assuming a typical hierarchy of number fluxes $N_{\nu_e} > N_{\bar{\nu}_e} > N_{\nu_y} = N_{\bar{\nu}_y}$, one obtains that for normal hierarchy (NH) the spectra remain unaffected by collective oscillations. Instead, for inverted hierarchy (IH) the end of collective oscillations is marked by a complete exchange of the e and y flavor spectra for $\bar{\nu}$, while for ν the swap occurs only above a characteristic energy fixed by lepton number conservation, giving rise to a spectral split in the ν energy distributions. As a consequence, neutrino fluxes which are further processed by MSW matter effects are significantly different for the two hierarchies.

Although the study of collective SN neutrino oscillations is still in an exploratory phase, it seems important to start analyzing the possibility to detect some signatures produced by these collective effects in supernovae. Here we propose to exploit Earth matter effects on SN neutrino oscillations as a probe of collective effects and of mass hierarchy. The plan of this work is as follows. In Section 2 we discuss the effects of flavor conversions on the supernova neutrino burst, taking into account collective oscillations and MSW conversions in the supernova envelope, as well as further oscillation effects associated to Earth matter crossing of SN neutrinos. We focus on supernova $\bar{\nu}_e$, observable in future water-Cherenkov detectors through the inverse beta decay process $\bar{\nu}_e + p \to e^+ + n$. In Section 3 we propose a strategy to identify the Earth matter effects by comparing the antineutrino signals from a galactic supernova in two megaton class water-Cherenkov detectors, one of which is shadowed by the Earth. We show that this technique will enable us to distinguish between the hierarchies if $\sin^2\theta_{13} \lesssim 10^{-5}$, where long baseline neutrino experiments would be ineffectual. Finally, in Section 4 we conclude. This paper is based on [2], to which we address the interested reader for further details.

2. Collective oscillations, MSW flavor conversions and Earth matter effects

The primary SN neutrino fluxes (at the neutrinosphere) are processed by collective effects and MSW conversions before they get emitted from the SN. Near the neutrinosphere, due to the large neutrino density, the neutrino-neutrino interaction energy is very large. This ensures that the neutrinos exhibit synchronized oscillations, i.e. neutrinos of all energies oscillate coherently with the average frequency. These oscillations do not give rise to any effective flavor conversion since the effective mixing angle is highly supressed due to the large MSW potential. As the neutrinos stream outward, the neutrino density becomes smaller, and bipolar oscillations begin to take place.

In the case of inverted hierarchy (IH), these oscillations have a large amplitude even for a very small mixing angle. These oscillations, in the presence of a slowly decreasing background neutrino density, leads to a complete swapping of the $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra for inverted hierarchy. The ν_e and ν_x spectra cannot swap completely, because of lepton number conservation, and the swap occurs only above a certain energy E_c, giving rise to a spectral split. Eventually, beyond a few hundred kilometers, the neutrino-neutrino interaction energy becomes negligible, and collective effects cease to be important (see [3] for detailed numerical simulations).

We work in the modified flavor basis $(\nu_e, \nu_x, \nu_y) = R^{\dagger}_{23}(\theta_{23})(\nu_e, \nu_\mu, \nu_\tau)$, where R_{23} is the rotation matrix. Here we concentrate on the $\bar{\nu}_e$ spectra. In inverted hierarchy, MSW matter effects in SN envelope are characterized in terms of the level-crossing probability P_H [4] of antineutrinos, which is in general a function of the neutrino energy and θ_{13}. In the following, we consider two extreme limits, $P_H \simeq 0$ when $\sin^2\theta_{13} \gtrsim 10^{-3}$ ("large"), and $P_H \simeq 1$ when $\sin^2\theta_{13} \lesssim 10^{-5}$ ("small"). While propagating through the Earth, the $\bar{\nu}_e$ and $\bar{\nu}_x$ spectra partially mix. The neutrino fluxes F_ν at the Earth surface for normal hierarchy, as well as for inverted hierarchy with large θ_{13}, are given in terms of the the primary fluxes F^0_ν by

$$\begin{aligned} F_{\bar{e}} &= \cos^2\theta_{12} F^0_{\bar{e}} + \sin^2\theta_{12} F^0_{\bar{x}} \ , \\ F_{\bar{x}} &= \sin^2\theta_{12} F^0_{\bar{e}} + \cos^2\theta_{12} F^0_{\bar{x}} \ . \end{aligned} \tag{2.1}$$

For inverted hierarchy with small θ_{13}, we have

$$\begin{aligned} F_{\bar{e}} &= \cos^2\theta_{12} F^0_{\bar{y}} + \sin^2\theta_{12} F^0_{\bar{x}} \approx F^0_{\bar{x}} \ , \\ F_{\bar{x}} &= \sin^2\theta_{12} F^0_{\bar{y}} + \cos^2\theta_{12} F^0_{\bar{x}} \approx F^0_{\bar{x}} \ . \end{aligned} \tag{2.2}$$

Earth effect can be taken into account by just mapping $\cos^2\theta_{12} \to P(\bar{\nu}_1 \to \bar{\nu}_e)$ and $\sin^2\theta_{12} \to 1 - P(\bar{\nu}_1 \to \bar{\nu}_e)$, where $P(\bar{\nu}_1 \to \bar{\nu}_e)$ is the probability that a state entering the Earth as mass eigenstate $\bar{\nu}_1$ is detected as $\bar{\nu}_e$ at the detector [4].

From Eqs. (2.1) and (2.2), one expects to observe Earth matter effect in normal hierarchy independently of θ_{13}, while in inverted hierarchy it is expected only at large θ_{13}. For small θ_{13} and inverted hierarchy, the $\bar{\nu}_e$ spectrum arriving at the Earth is identical to the $\bar{\nu}_x$ spectrum arriving at the Earth, so any oscillation effect among them is unobservable. This implies that if next generation neutrino experiments bound θ_{13} to be small, from the (non)observation of Earth matter effect we could identify the neutrino mass hierarchy.

3. Observing Earth matter effects

A strategy to observe Earth matter signatures in neutrino oscillations is to compare the signal at two detectors. The difference between the $\bar{\nu}_e$ flux $F^D_{\bar{e}}$ at a shadowed detector and the $\bar{\nu}_e$ flux $F_{\bar{e}}$ at a detector that is not shadowed by the Earth can be written as

$$\Delta F = F^D_{\bar{e}} - F_{\bar{e}} = f_{\rm reg}(F^0_{\bar{e}} - F^0_{\bar{x}}) \ , \tag{3.1}$$

for normal hierarchy as well as for inverted hierarchy with large θ_{13}. Here $f_{\rm reg} = P(\bar{\nu}_1 \to \bar{\nu}_e) - \cos^2\theta_{12}$ is the Earth regeneration factor. In inverted hierarchy for small θ_{13}, we get $\Delta F = 0$. If the

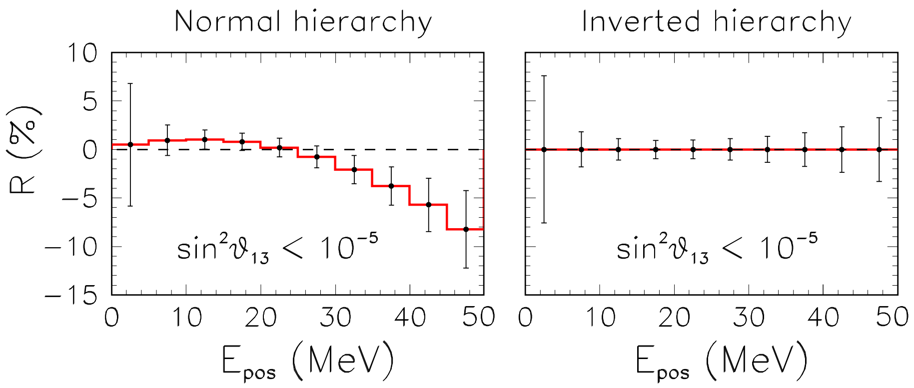

Figure 1: *Plot of the ratio R defined in Eq. (3.3), as a function of the observable positron energy for normal hierarchy (left panel) and inverted hierarchy (right panel), with* $\sin^2\theta_{13} < 10^{-5}$. *For* $\sin^2\theta_{13} > 10^{-3}$, *the ratio R will be identical to the left panel for either hierarchy.*

$\bar{\nu}$ trajectories cross only the Earth mantle, characterized by an approximately constant density, $f_{\rm reg}$ is simply given by

$$f_{\rm reg} = -\sin 2\tilde{\theta}_{12} \sin(2\tilde{\theta}_{12} - 2\theta_{12}) \sin^2\left(\frac{\Delta\tilde{m}^2_{\odot} L}{4E}\right) , \tag{3.2}$$

where $\tilde{\theta}_{12}$ is the effective value of the antineutrino mixing angle θ_{12} in matter, $\Delta\tilde{m}^2_{\odot}$ is the solar mass squared difference in matter, and L is the path length in Earth. In Earth matter, we have $\sin 2\tilde{\theta}_{12} > 0$ and $\sin(2\tilde{\theta}_{12} - 2\theta_{12}) < 0$, which tells us that $f_{\rm reg} \geq 0$.

To illustrate the above, we consider a galactic supernova explosion at a distance of 10 kpc, with typical neutrino luminosities and average energies (see [2] for details). We analyze the detection of the above signal using two large water Cherenkov detectors A and B of fiducial mass 0.4 megaton each, as proposed for upcoming experiments. We compare the number of events in detector A, where neutrinos arrive after traversing $L = 8000$ km in Earth mantle with an approximately constant density $\rho = 4.5$ g/cm^3, with another detector B for which the supernova is not shadowed by the Earth ($L = 0$).

We define

$$R \equiv (N_A - N_B)/N_B \tag{3.3}$$

as the difference between the number of $\bar{\nu}_e$ events at the shadowed detector and the unshadowed detector, normalized to the number of events at the unshadowed detector. In Figure 1, we plot the ratio R as a function of the measured positron energy $E_{\rm pos}$ for $\bar{\nu}_e$ in normal hierarchy (left panel) and inverted hierarchy (right panel) for $\sin^2\theta_{13} < 10^{-5}$. The error bars show the statistical error in R. In the other extreme case of $\sin^2\theta_{13} > 10^{-3}$, both the normal and inverted hierarchy would correspond to the left panel.

Let us consider the scenario where θ_{13} is known to be small. From the figure, in normal hierarchy the ratio R is positive for $E_{\rm pos} \lesssim 25$ MeV and negative at higher energy. The low energy spectrum is dominated by statistical error, but for $E_{\rm pos} \gtrsim 30$ MeV the depletion of the signal with respect to the unshadowed detector is clearly visible, with $|R| \gtrsim 5\%$. On the other hand, in inverted hierarchy we find $R = 0$. The difference in the predictions of two hierarchies is significant and should be observable.

We emphasize that our method is based on a model independent signature which does not rely on fitting or extracting any parameters. Therefore, one can make the following statements: (i) Observation of Earth matter effects cannot be explained in inverted hierarchy (ii) Nonobservation of Earth matter effects cannot be explained in normal hierarchy (unless the primary fluxes are almost identical). Our proposed method is thus quite robust, and would be able to identify the mass hierarchy.

4. Conclusions

The determination of the leptonic mixing angle θ_{13} and the neutrino mass hierarchy represent two of the next frontiers of neutrino physics. We have proposed a new possibility for identifying the neutrino mass hierarchy that works for extremely small values of θ_{13}, far beyond the sensitivity of current and future terrestrial neutrino experiments. The sensitivity of supernova neutrino oscillations to the mass hierarchy, for incredibly small values of θ_{13}, is a consequence of the collective neutrino oscillations that take place near the supernova core. These effects interchange the initial $\bar{\nu}_e$ and $\bar{\nu}_y$ spectra in the inverted hierarchy, which are then further processed by MSW effects in the SN envelope. This spectral swap can be revealed by comparing the event rate at a shadowed detector with that at an unshadowed detector. If neutrino oscillation experiments fail to determine the mass hierarchy, then this proposed method could represent the last hope to resolve this issue, provided that large water Cherenkov detectors are available at the time of the next galactic SN explosion. Moreover, if a large Liquid Argon detector will be built, Earth matter signatures on the SN ν_e spectrum could also be detected [5]. This perspective should be considered when choosing optimal detector locations for upcoming large neutrino detectors [6].

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