Identifying the neutrino mass hierarchy with supernova neutrinos

Ricard Tomàs
AHEP Group, Institut de Física Corpuscular - C.S.I.C/Universitat de València
Edifici Instituts d’Investigació, Apt. 22085, E-46071 València, Spain
E-mail: ricard@ific.uv.es

Abstract. We review how a high-statistics observation of the neutrino signal from a future galactic core-collapse supernova (SN) may be used to discriminate between different neutrino mixing scenarios. We discuss two complementary methods that allow for the positive identification of the mass hierarchy without knowledge of the emitted neutrino fluxes, provided that the $13$-mixing angle is large, $\sin^2 \theta_{13} \gg 10^{-5}$. These two approaches are the observation of modulations in the neutrino spectra by Earth matter effects or by the passage of shock waves through the SN envelope. If the value of the $13$-mixing angle is unknown, using additionally the information encoded in the prompt neutronization $\nu_e$ burst—a robust feature found in all modern SN simulations—can be sufficient to fix both the neutrino hierarchy and to decide whether $\theta_{13}$ is “small” or “large.”

1. Introduction
Despite the enormous progress of neutrino physics in the last decade, many open questions remain to be solved. Among them are two, the mass hierarchy and the value of the $13$-mixing angle $\theta_{13}$, where the observation of neutrinos from a core-collapse supernova (SN) could provide important clues [1, 2, 3]. Schematically, the neutrino emission by a SN can be divided into four stages: Infall phase, neutronization burst, accretion, and Kelvin-Helmholtz cooling phase. Most SN neutrinos are emitted during the last two stages, in all flavors with only small differences between the $\bar{\nu}_e$ and $\bar{\nu}_{\mu,\tau}$ spectra. Moreover, the absolute values of the average neutrino energies as well as the relative size of the luminosities during the accretion and cooling phases cannot be determined with sufficient precision, especially if the SN is optically obscured and the progenitor type remains unknown. Therefore, a straightforward extraction of oscillation parameters from the bulk of the SN neutrino signal seems hopeless. Only features in the detected neutrino spectra that are independent of unknown SN parameters should be used in such an analysis.

The two most promising sources for such features are the modulations in the neutrino spectra caused by the Earth matter or by the passage of shock waves through the SN envelope. Moreover, the detection of the neutronization $\nu_e$ peak could help to break possible degeneracies in the case that $\theta_{13}$ is still unknown, see Tab. 1.

2. Identifying signatures of the SN shock wave propagation
The neutrino spectra arriving at the Earth are determined by the primary neutrino spectra as well as the neutrino survival probabilities. These in turn are determined by the number of
Table 1. The presence of Earth-matter and shock wave effects in the $\bar{\nu}_e$ spectra and of the $\nu_e$ burst for different neutrino mixing scenarios.

| Case | Hierarchy $\sin^2 \theta_{13}$ | Earth | Shock | $\nu_e$ burst |
|------|-------------------------------|-------|-------|--------------|
| A    | Normal $\gg 10^{-3}$          | Yes   | No    | No           |
| B    | Inverted $\gg 10^{-3}$        | No    | Yes   | Yes          |
| C    | Any $\ll 10^{-5}$             | Yes   | No    | Yes          |

Resonances that the neutrinos traverse and their adiabaticity. Both are directly connected to the neutrino mixing scheme.

During approximately the first two seconds after core bounce, the neutrino survival probabilities are constant in time and in energy for all three cases A, B, and C, see Tab. 1. However, at $t \approx 2$ s the H-resonance layer, corresponding to $\Delta m^2_{\text{atm}}$ and located at a density $\rho_H$, is reached by the outgoing shock wave, see left panel of Fig. 1. The way the shock wave passage affects the neutrino propagation strongly depends on the neutrino mixing scenario [4]. In particular, in scenario B, the sudden change in the density breaks the adiabaticity of the H resonance, leading to a time and energy dependence of the $\bar{\nu}_e$ survival probability, and thus observable consequences in the $\bar{\nu}_e$ spectrum. These effects are clearly visible in $\langle E_{\bar{\nu}_e} \rangle$, see right panel of Fig. 1, and are independent of the assumptions about the initial neutrino spectra [5].

Figure 1. Left: Shock and reverse-shock propagation. Right: The average energy of $\bar{\nu}_e p \rightarrow n e^+$ events binned in time for a static density profile, a profile with only a forward shock and with forward and reverse shock, from Ref. [5]. A megaton water Cherenkov detector and a SN at 10 kpc is assumed.

3. Earth-matter effects
If neutrinos cross the Earth before reaching the detector, the conversion probabilities may become energy-dependent and induce modulations in the neutrino energy spectrum. These modulations arise in the antineutrino channel only in cases A and C [6]. The frequencies $k_i$ characterizing this modulation are completely independent of the primary neutrino spectra, and can be determined to a good accuracy from the knowledge of the solar oscillation parameters, the Earth matter density, and the position of the SN in the sky [7].

Identifying Earth effects is equivalent to observing excess power in $G(k) \equiv \left| \sum_{i=1}^{N} e^{iky_i} \right|^2 / N$ around the known frequencies $k_i$. In particular the Earth effect peaks tend to increase the
Figure 2. Comparison of $p_{95}$ as a function of nadir angle $\eta$ for a 32 kton scintillator (SC) and a megaton water Cherenkov (HK) detector, from Ref. [7].

Figure 3. Number of events per time bin in a megaton water Cherenkov detector for a SN at 10 kpc for cases A and C, and for different progenitor masses, from Ref.[8].

area under the power spectrum between two fixed frequencies. The confidence level of peak identification, $p_\alpha$, may then be defined as the fraction of the area of the background distribution that is less than the actual area measured, see Fig. 2.

4. Neutronization $\nu_e$ burst

If the value of $\theta_{13}$ is unknown, a degeneracy exists between case A and C. In this case, the additional information encoded in the $\nu_e$ neutrinos emitted during the neutronization burst can fix the range of $\theta_{13}$ as well as the neutrino mass hierarchy.

In Fig. 3 we show the expected neutrino signal from $t = -5$ to 18 ms for different progenitor masses, and for the mixing scenarios A and C. The peak structure can be clearly seen in case C, independently of the progenitor mass, but not in case A [8]. Including recent improvements of the electron capture rates or uncertainties in the nuclear equation of state has only little effect on the neutronization peak compared to the size of the statistical fluctuations. Therefore the observation of a peak in the first milliseconds of the neutrino signal would rule out the normal mass hierarchy with “large” $\theta_{13}$ (case A).

Acknowledgments

I would like to thank the co-authors R. Buras, A. S. Dighe, H.-Th. Janka, M. Kachelrieß, A. Marek, G. G. Raffelt, M. Rampp and L. Scheck. This work was supported by a Marie-Curie-Fellowship of the European Community, and the Juan de la Cierva programme.

References
[1] Dighe A S and Smirnov A Y 2000 Phys. Rev. D 62 033007
[2] Lunardini C and Smirnov A Y 2003 JCAP 0306 009
[3] Takahashi K and Sato K 2003 Nucl. Phys. A 718 455
[4] Schirato R C and Fuller G M Preprint astro-ph/0205390
   Fogli G L, Lisi E, Montanino D and Mirizzi A 2003 Phys. Rev. D 68 033005
   Lunardini C and Smirnov A Y 2003 JCAP 0306 009
[5] Tom`as R, Kachelrieß M, Raffelt G G, Dighe A S, Janka H T and Scheck L 2004 JCAP 0409 015
[6] Lunardini C and Smirnov A Y 2001 Nucl. Phys. B 616 307
   Dighe A S, Keil M T and Raffelt G G 2003 JCAP 0306 006
   Dighe A S, Kachelrieß M, Raffelt G G and Tom`as R 2004 JCAP 0401 004
[7] Kachelrieß M, Tom`as R, Buras R, Janka H T, Marek A and Rampp M 2005 Phys. Rev. D 71 063003