Neutrino and antineutrino spectral splits from collective effects in supernovae

Irene Tamborra\textsuperscript{1,2}
\textsuperscript{1} Dipartimento Interateneo di Fisica “Michelangelo Merlin,”
Via Amendola 173, 70126 Bari, Italy
\textsuperscript{2} Istituto Nazionale di Fisica Nucleare, Sezione di Bari,
Via Orabona 4, 70126 Bari, Italy
E-mail: irene.tamborra@ba.infn.it

Abstract. In core-collapse supernovae, $\nu - \nu$ interactions affect appreciably the evolution of flavor. Collective effects are discussed in the case of supernova luminosities which are different for different flavors. The observable spectral split features of $\nu$ and $\bar{\nu}$ are highlighted. Detection of such effects could provide a handle on two unknown: the neutrino mass hierarchy and the mixing angle $\theta_{13}$.

1. Introduction and supernova framework
Neutrino flavor states ($\nu_e, \nu_\mu, \nu_\tau$) are related to the mass states ($\nu_1, \nu_2, \nu_3$) by means of a unitary matrix that is a function of the mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and of a possible CP-violating phase $\delta$. Although the squared mass differences ($\delta m^2 \ll \Delta m^2$) are precisely known, the sign of $\Delta m^2$ (i.e., the mass hierarchy) is unknown, as well as $\theta_{13}$. Hints about these two unknowns might come from core-collapse supernova (SN) neutrinos.

In the SN matter, the $\nu_e - \nu_\mu, \nu_\tau$ interaction energy difference is described by the Mikheev-Smirnov-Wolfenstein (MSW) matter potential $\lambda(r) = \sqrt{2} G_F N_e(r)$ where $N_e(r)$ is the electron number density (see [1] for a review). Moreover, $\nu - \nu$ interactions induce collective flavor changes. The corresponding self-interaction potential is given by

$$\mu = \sqrt{2} G_F (N + \bar{N}) ,$$

as a function of the total effective density of neutrinos ($N = N_e + N_\mu + N_\tau$) and antineutrinos ($\bar{N}$) per unit volume. For sake of simplicity we focus on $\mu$-induced collective effects. Since $\nu_\mu$ and $\nu_\tau$ behave similarly at typical SN energies, we call each of them as $\nu_x$. We can reduce the full $3\nu$ evolution to an effective $2\nu$ one, namely: $3\nu = (\nu_e, \nu_x) \oplus (\nu_\mu, \nu_\tau)$, one $\nu_x$ acts as “spectator.” The relevant $2\nu$ subspace ($\nu_e, \nu_x$) is governed by ($\pm \Delta m^2, \theta_{13}$)[2]. We choose as default values: $\sin^2 \theta_{13} = 10^{-6}$ and $\Delta m^2 = 2 \times 10^{-3}$ eV$^2$.

The total energy luminosity, $L_{tot}$, is distributed over six ($3\nu + 3\bar{\nu}$) species. One spectator neutrino family $\nu_x$ only shares a fraction of luminosity, but does not take part to oscillations. The fractional luminosities ($l_\alpha = L_\alpha/L_{tot}$ for $\alpha = e, \bar{\nu}, x$, and with $l_x \equiv l_\bar{\nu}$) obey the constraint:

$$1 = l_e + l_\nu + 4l_x .$$

© 2010 IOP Publishing Ltd
Figure 1. Equipartition case in inverted hierarchy. Left upper panel: flux of $\nu_e$ (black, solid) and of $\nu_x$ (red, solid) at the end of collective effects; dotted lines indicate initial spectra. Left lower panel: electron flavor survival probability $P_{ee}$. Right upper panel: as before, but for $\bar{\nu}$. Vertical green lines mark the crossing energies where the $\nu_e$ (or $\bar{\nu}_e$) and $\nu_x$ fluxes are equal.

Our purpose is to go beyond the usual assumption of “energy equipartition” among flavors, which amounts to take $l_e = l_{\bar{\nu}} = l_x$.

We assume a total luminosity $L_{\text{tot}} = 10^{53}$ erg/s, and average energies as

$$\langle E_e \rangle = 10 \text{ MeV}, \quad \langle E_{\bar{\nu}} \rangle = 12 \text{ MeV}, \quad \langle E_x \rangle = 15 \text{ MeV}. \quad (3)$$

The densities for unit of volume and energy are then [3]:

$$n_\alpha(r, E) = \frac{L_{\text{tot}}}{4\pi R^2_\nu} \frac{\Phi_\alpha(E)}{\langle E_\alpha \rangle} g(r), \quad (4)$$

where $g(r)$ is a damping factor (decreasing as $\sim 1/r^4$), $\Phi_\alpha(E)$ are thermal $\nu$ spectra, and $R_\nu = 10 \text{ km}$ is the $\nu$-sphere radius.

In Fig. 1, oscillated spectra for the equipartition case in inverted hierarchy $(-\Delta m^2)$ are shown [2, 4, 5, 6]. In this case, above a critical energy neutrinos swap their flavors, and similarly for $\bar{\nu}$ (but at lower energy).

2. Ternary Luminosity Diagram

The constraint in Eq. 2 can be represented in terms of a ternary diagram with fractional luminosities on each side. Each internal point of the triangle corresponds to different initial luminosity distributions. The equipartition case, described in Fig. 1, corresponds to $(l_e, l_{\bar{\nu}}, 4l_x) = (1/6, 1/6, 4/6)$. Variations from this case induce dramatic spectral changes [7].

Fig. 2 shows the qualitative spectral split patterns emerging from our numerical exploration of the ternary luminosity diagram, in the case of inverted hierarchy $[7]$. We use different markers for different split patterns, as indicated in the legend of Fig. 2. In the lower half of the diagram, corresponding to relatively low $\nu_x$ luminosity $(4l_x < 0.5)$, we always find one $\nu$ and one $\bar{\nu}$ split. More precisely, the blue triangles on the right correspond to one dominant $\nu$ split at high energy (HE) plus a minor $\bar{\nu}$ split at low energy (LE), qualitatively similar to the equipartition case shown in Fig. 1; for the yellow triangles on the left, the situation is reversed for $\nu$ and $\bar{\nu}$. As the $\nu_x$ luminosity increases, some $1\nu$ (HE) + $1\bar{\nu}$ (LE) split cases survive (blue triangles), including the equipartition point. However, these cases are now flanked, on the left, by a couple of points where a double $\nu$ split occurs (blue squares) and, on the right, by two points with a double $\bar{\nu}$ split (yellow squares) plus two points with a double split for both $\nu$ and $\bar{\nu}$ (red circles). One of these two last cases is shown in Fig 3.
**Figure 2.** Spectral split patterns in inverted hierarchy. Blue (yellow) triangles: one HE $\nu$ split and one LE $\bar{\nu}$ split (one LE $\nu$ split and one HE $\bar{\nu}$ split). Blue (yellow) squares: two $\nu$ splits and no $\bar{\nu}$ split (two $\bar{\nu}$ splits and no $\nu$ split). Red circles: two splits for both $\nu$ and $\bar{\nu}$.

In conclusion, the luminosity equipartition scenario ($1\nu$ HE $+ 1\bar{\nu}$ LE splits) is somewhat “special.” In many other cases, the spectral split pattern may be significantly different [7, 8]. This must be taken into account in the analysis of prospective SN signals. For each different luminosity distribution if a double or a single split should take place, could be understood in terms of the initial conditions of the global vectors.

**3. Conclusions**

In a core-collapse supernova the $\nu$ density is high, and $\nu - \nu$ interactions are not negligible. They induce collective flavor conversion, typically leading to spectral splits/swaps. We have analyzed different luminosity distribution scenarios, embedding the equipartition scenario as a particular case. We find that several split patterns emerge in the luminosity diagram.

**Acknowledgments**

This work is supported in part by the Italian “Istituto Nazionale di Fisica Nucleare” (INFN) and “Ministero dell’Istruzione, dell’Università e della Ricerca” (MIUR) through the “Astroparticle Physics” research project. The results presented here have been obtained in Ref. [7] in collaboration with G.L. Fogli, E. Lisi, A. Marrone. I.T. is grateful to TAUP 2009 organizers for kind hospitality.

**References**

[1] T. K. Kuo, J. Pantaleone, *Rev. Mod. Phys.* 61, 937 (1989).
[2] G. L. Fogli, E. Lisi, A. Marrone and I. Tamborra, *JCAP* 0904, 030 (2009).
[3] H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, *Phys. Rev.* D 74, 105014 (2006).
[4] G. L. Fogli, E. Lisi, A. Marrone, A. Mirizzi and I. Tamborra, *Phys. Rev.* D 78, 097301 (2008).
[5] S. Hannestad, G. G. Fuller, J. Carlson and Y. Y. Y. Wong, *Phys. Rev.* D 74, 105010 (2006) [Erratum-ibid. D 76, 029901 (2007)].
[6] G. G. Raffelt and A. Y. Smirnov, *Phys. Rev.* D 76, 125008 (2007).
[7] G. Fogli, E. Lisi, A. Marrone and I. Tamborra, arXiv:0907.5115 [hep-ph], to appear in *JCAP* (2009).
[8] B. Dasgupta, A. Dighe, G. G. Raffelt and A. Y. Smirnov, *Phys. Rev. Lett.* 103 (2009) 051105.