PROCEEDINGS OF SCIENCE

Distinguishing SNν equalization from a pure MSW

Francesco Capozzi*
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Föhringer Ring 6, 80805 München, Germany
E-mail: capozzi@mpp.mpg.de

Basudeb Dasgupta
Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400005, India

Alessandro Mirizzi
Dipartimento Interateneo di Fisica "Michelangelo Merlin", and Istituto Nazionale di Fisica Nucleare - Sezione di Bari, Via Amendola 173, 70126 Bari, Italy

Among the theoretically possible flavor conversion scenarios of supernova neutrinos there are flavor equalization and the well known Mikheyev-Smirnov-Wolfenstein effect. We present a simple method to distinguish experimentally between them, using the combination of three detection channels: charged-current neutrino interaction on Argon, neutrino elastic scattering on protons and inverse β decay.

Neutrino Oscillation Workshop (NOW2018)
9 - 16 September, 2018
Rosa Marina (Ostuni, Brindisi, Italy)

*Speaker.

PoS(NOW2018)049

1. Introduction

Neutrino flavor conversions in the context of a core collapse supernova are still under theoretical investigation. It is well established that the conditions for the Mikheyev-Smirnov-Wolfenstein (MSW) effect [1, 2] are satisfied when neutrinos are propagating in the outer layers of the exploding star ($r \gtrsim 1000$ km). Recently, most of the attention has been devoted to the less understood self induced flavor conversions, which stem from the neutrino-neutrino forward scattering potential and occur closer to the core ($r < 1000$ km). Under specific conditions, such effects have been shown to induce spectral swaps and splits [3, 4, 5, 6]. In other cases neutrinos might undergo complete decoherence leading to equalization of fluxes and spectra for the different species [7, 8]. If this happens, matter effects occurring at larger distances would not introduce further conversions. Furthermore, the possibility of an early flavor equalization might have an impact on both the shock revival and the nucleosynthesis processes. It is thus timely to investigate whether experimental measurements of supernova neutrinos might shed light on the nature of flavor conversions. In particular, we propose a method to experimentally distinguish between the two extreme scenarios, i.e. MSW and flavor equalization, without making any assumption on the functional form of neutrino energy fluxes. A more detailed presentation can be found in [9].

2. Distinguishing MSW and flavor equalization

We consider three detection channels: neutrino elastic scattering on proton (pES) [10, 11], inverse β decay (IBD) [12] and neutrino charged current scattering on ^{40}Ar (ArCC) [13, 14], in the context of JUNO [15], Hyper-Kamiokande (HyperK) [16] and DUNE [17, 18, 19, 20], respectively. The first is a neutral current channel and it is thus not sensitive to flavor conversions, whereas the others are sensitive to $\bar{\nu}_e$ and ν_e respectively. The neutrino flux at each detector is given by

$$\frac{dF_{\text{pES}}}{dE_\nu} = \frac{dF^0_{\nu_e}}{dE_\nu} + \frac{dF^0_{\bar{\nu}_e}}{dE_\nu} + 4\frac{dF^0_{\nu_x}}{dE_\nu}\,, \tag{2.1}$$

$$\frac{dF_{\text{IBD}}}{dE_\nu} = \frac{dF^0_{\bar{\nu}_e}}{dE_\nu}\bar{P}_{ee} + \frac{dF^0_{\nu_x}}{dE_\nu}(1-\bar{P}_{ee})\,, \tag{2.2}$$

$$\frac{dF_{\text{ArCC}}}{dE_\nu} = \frac{dF^0_{\nu_e}}{dE_\nu}P_{ee} + \frac{dF^0_{\nu_x}}{dE_\nu}(1-P_{ee})\,, \tag{2.3}$$

where F^0 represents the flux at production (without flavor conversions), P_{ee} and $\bar{P}_{ee}$ are the survival probabilities for electron neutrino and antineutrinos, respectively, and we are assuming that $F^0_{\nu_x} = F^0_{\nu_\mu} = F^0_{\nu_\tau} = F^0_{\bar{\nu}_\mu} = F^0_{\bar{\nu}_\tau}$. The following table reports the values of P_{ee} and $\bar{P}_{ee}$ for the flavor conversion scenarios under consideration.

Scenario	Mass Ordering	P_{ee}	$\bar{P}_{ee}$
MSW	NO	0	$\cos^2\theta_{12} \simeq 0.7$
MSW	IO	$\sin^2\theta_{12} \simeq 0.3$	0
FE	either	$1/3 \simeq 0.33$	$1/3 \simeq 0.33$

Experimentally one measures a distribution of events as a function of energy, which is the convolution of Eq. 2.1-2.3 with cross section, energy resolution and the detector efficiency. In order to extract the neutrino fluxes from the data, some techniques have been proposed in [11, 21] for pES and IBD, and they can be extended also to ArCC. In our work we use the simplest technique proposed in [21]. More time consuming and precise approaches are beyond the scope of this work, but they must be used when dealing with real data. The direct extraction of neutrino fluxes makes our method completely independent from any assumption on their functional form.

Once neutrino fluxes are extracted, we calculate the ratios

$$R = \frac{F_{\mathrm{pES}}}{F_{\mathrm{ArCC}}} = \frac{4+x+\bar{x}}{P_{ee}x+(1-P_{ee})}, \qquad \bar{R} = \frac{F_{\mathrm{pES}}}{F_{\mathrm{IBD}}} = \frac{4+x+\bar{x}}{\bar{P}_{ee}\bar{x}+(1-\bar{P}_{ee})}, \tag{2.4}$$

where $x \equiv \frac{F^0_{\nu_e}}{F^0_{\nu_x}} \lesssim 1$ and $\bar{x} \equiv \frac{F^0_{\bar{\nu}_e}}{F^0_{\nu_x}} \lesssim 1$. According to current supernova simulations, the following hierarchy is usually realized: $x \lesssim \bar{x} \lesssim 1$. The final step of our method consist in comparing the measured values of R and $\bar{R}$ with the expectations for a specific scenario. Below we discuss more carefully this step in the context of normal and inverted mass ordering.

2.1 Normal Ordering

Let us assume the mass ordering is known to be normal (e.g. from neutrino oscillation experiments). One then finds the limiting values for MSW and FE in the case of R:

$$R_{\mathrm{MSW}} = \begin{cases} 4 & x,\bar{x} \ll 1 \\ 5 & x \ll 1, \text{and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}, \qquad R_{\mathrm{FE}} = \begin{cases} 6 & x,\bar{x} \ll 1 \\ 7.5 & x \ll 1, \text{and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}. \tag{2.5}$$

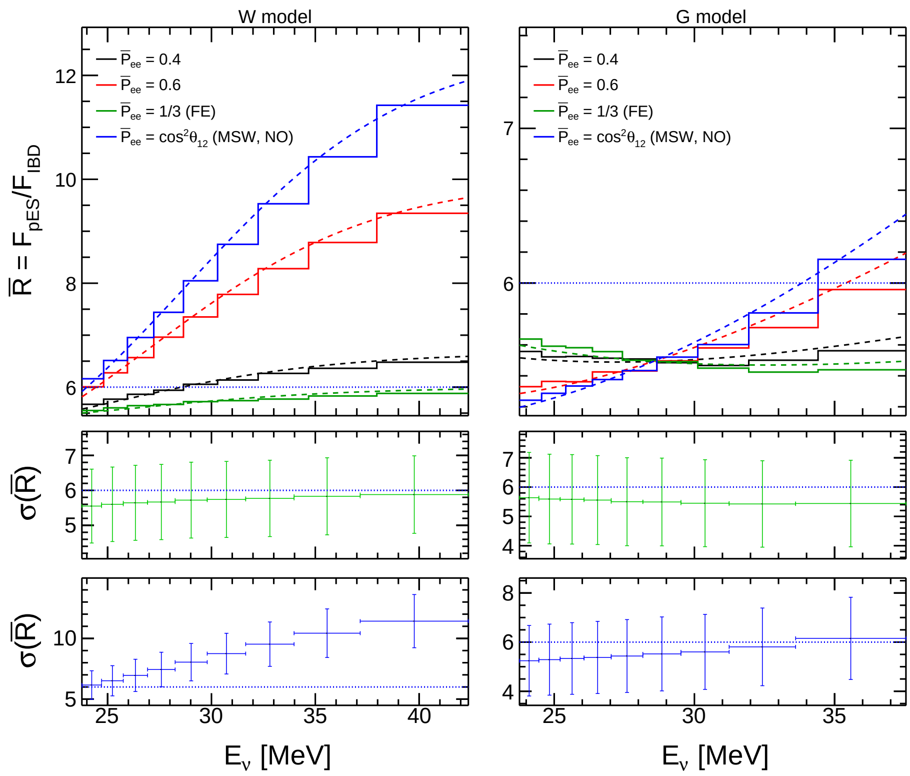
Similarly, for $\bar{R}$ one obtains

$$\bar{R}_{\mathrm{ME}} = \begin{cases} 13.3 & x,\bar{x} \ll 1 \\ 5 & x \ll 1, \text{and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}, \qquad \bar{R}_{\mathrm{FE}} = \begin{cases} 6 & x,\bar{x} \ll 1 \\ 5 & x \ll 1, \text{and } \bar{x} \lesssim 1 \\ 6 & x \lesssim \bar{x} \lesssim 1 \end{cases}. \tag{2.6}$$

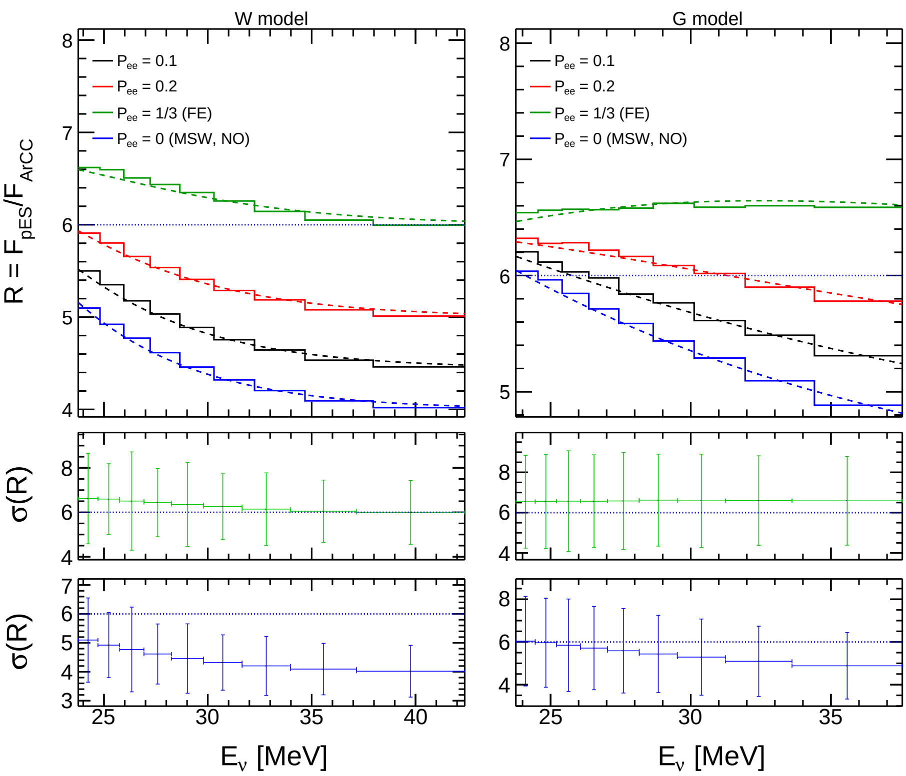
Thus, one has the following options:

- $R > 6$: excludes pure matter effects,
- $R \lesssim 6$: excludes complete flavor equalization,
- $\bar{R} > 6$: excludes complete flavor equalization,
- $\bar{R} \sim 5-6$: degeneracy between pure matter effects and complete or partial flavor equalization, which might be removed in combination with R.

Let us now apply the previous considerations to simulated data. We assume the functional form in [22] for neutrino fluxes at production, with the correspondent parameters taken either from [23] (W model) or [24] (G model). The key difference between the two models is that the former exhibits larger differences in the spectral features of the different species, while the latter shows more similar neutrino spectra.



(a) $\bar{R}$ for NO and $d = 10$ kpc



(b) R for NO and $d = 10$ kpc

Figure 1: Ratios $\bar{R}$ (a) and R (b) for different values of $\bar{P}_{ee}$. Statistical errors for complete flavor equalization and pure matter effects are also reported.

Figure 1a and 1b show the simulated values of $\bar{R}$ and R, respectively, as a function of neutrino energy and for four flavor conversion scenarios: MSW, flavor equalization and two intermediate cases. One sigma statistical errors are shown in the middle panels for complete flavor equalization, and in the lower panels for MSW, assuming a distance of 10 kpc for the supernova. In the case of MSW and W model this method disfavours flavor equalization at a few sigma confidence level. A smaller significance is obtained when considering flavor equalization and the G model.

2.2 Inverted ordering

R is not relevant in this case since its values are basically indistinguishable for MSW and flavor equalization (in both cases we have $P_{ee} \simeq 0.3$). However, if $\bar{R} < 5$ we are able to disfavour flavor equalization with a few sigma confidence level, assuming a 10 kpc supernova and the W model (not shown).

3. Conclusions

A complete understanding of the flavor conversions for supernova neutrinos is still missing. We have introduced a simple technique to distinguish experimentally among two extreme scenarios: pure MSW and flavor equalization. Such method is based on three detection channels: inverse β decay, neutrino elastic scattering on protons and charged current scattering on Argon. From each channel we extract the neutrino fluxes. Then we calculate ratios between fluxes: R and $\bar{R}$. Depending on the measured value for these ratios, the distance of the supernova and the similarity of the original fluxes we might be able to reject the presence of one scenario. We stress that our procedure is really model-independent, in the sense that it does not rely fitting or modelling the spectral shape of the neutrino fluxes.

References

[1] L. Wolfenstein, Phys. Rev. D **17** (1978) 2369.

[2] S. P. Mikheyev and A. Y. Smirnov, Sov. J. Nucl. Phys. **42** (1985) 913 [Yad. Fiz. **42** (1985) 1441].

[3] H. Duan, G. M. Fuller, J. Carlson and Y. Z. Qian, Phys. Rev. D **74** (2006) 105014.

[4] S. Hannestad, G. G. Raffelt, G. Sigl and Y. Y. Y. Wong, Phys. Rev. D **74** (2006) 105010 Erratum: [Phys. Rev. D **76** (2007) 029901].

[5] G. L. Fogli, E. Lisi, A. Marrone and A. Mirizzi, JCAP **0712** (2007) 010.

[6] B. Dasgupta, A. Dighe, G. G. Raffelt and A. Y. Smirnov, Phys. Rev. Lett. **103** (2009) 051105.

[7] R. F. Sawyer, Phys. Rev. D **79** (2009) 105003.

[8] R. F. Sawyer, Phys. Rev. Lett. **116** (2016) no.8, 081101.

[9] F. Capozzi, B. Dasgupta and A. Mirizzi, Phys. Rev. D **98** (2018) no.6, 063013.

[10] J. F. Beacom, W. M. Farr and P. Vogel, Phys. Rev. D **66** (2002) 033001.

[11] B. Dasgupta and J. F. Beacom, Phys. Rev. D **83** (2011) 113006.

[12] A. Strumia and F. Vissani, Phys. Lett. B **564** (2003) 42.

PoS(NOW2018)049

[13] M. Bhattacharya, C. D. Goodman and A. Garcia, Phys. Rev. C **80** (2009) 055501.

[14] F. Capozzi, S. W. Li, G. Zhu and J. F. Beacom, arXiv:1808.08232 [hep-ph].

[15] F. An *et al.* [JUNO Collaboration], J. Phys. G **43** (2016) no.3, 030401.

[16] K. Abe *et al.* [Hyper-Kamiokande Collaboration], arXiv:1805.04163 [physics.ins-det].

[17] R. Acciarri *et al.* [DUNE Collaboration], arXiv:1512.06148 [physics.ins-det].

[18] J. Strait *et al.* [DUNE Collaboration], arXiv:1601.05823 [physics.ins-det].

[19] R. Acciarri *et al.* [DUNE Collaboration], arXiv:1601.02984 [physics.ins-det].

[20] J. Migenda [DUNE Collaboration], arXiv:1804.01877 [physics.ins-det].

[21] H. L. Li, Y. F. Li, M. Wang, L. J. Wen and S. Zhou, Phys. Rev. D **97** (2018) no.6, 063014.

[22] M. T. Keil, G. G. Raffelt and H. T. Janka, Astrophys. J. **590** (2003) 971.

[23] T. Fischer, S. C. Whitehouse, A. Mezzacappa, F.-K. Thielemann and M. Liebendorfer, Astron. Astrophys. **517** (2010) A80.

[24] P. D. Serpico, S. Chakraborty, T. Fischer, L. Hudepohl, H. T. Janka and A. Mirizzi, Phys. Rev. D **85** (2012) 085031.

PoS(NOW2018)049