

Flavor Oscillations in Core-Collapse Supernovae

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Abstract

Core collapse supernovae are unique laboratories to study many aspects of neutrino physics. The vicinity of the proto-neutron star in a core-collapse supernova is characterized by large matter and neutrino densities. A salient feature of this region is the impact of neutrino-neutrino interactions. Properties of the ensuing non-linear many-neutrino system are examined with a particular emphasis on its collective behavior and its symmetries. The impact of neutrino properties and interactions on the r-process nucleosynthesis that may take place in the supernova environment is discussed.

Keywords: Supernova neutrinos, collective neutrino oscillations

1. Introduction

Core collapse supernovae are unique laboratories to study many aspects of neutrino physics. Following the collapse, almost the entire gravitational binding energy of the progenitor star is emitted in neutrinos. The collapse results in very large values of Fermi energy for electrons and electron neutrinos, about 10^{57} units of electron lepton number. Neutrinos then transport entropy and electron lepton number¹ away from the proto-neutron star. Neutrinos dominate the energetics of core-collapse supernovae; they carry about 10% of the progenitor star's rest mass, 10^{53} ergs, in contrast to the total optical and kinetic energy which about only one percent of this amount. Since the diffusion time of the neutrinos (slightly less than ten seconds) is much longer than typical time scale of weak interactions, the sheer number of neutrinos present in the proximity of the proto-neutron star enable many-body aspects of neutrino physics emerge. Resulting collective neutrino oscillations allow testing a sector of the Standard Model that cannot be tested elsewhere, namely the weak interaction between two neutrinos, as schematically depicted

in Figure 1. There are several excellent review articles which may serve as starting points on the expansive literature exploring physics opportunities with supernova neutrinos [1, 2, 3].

In a supernova, matter-enhanced neutrinos oscillations (the MSW effect) is operational not only for the neutrinos, but, under certain conditions, for antineutrinos as well. However, collective effects (especially non-diagonal neutrino-neutrino interaction terms) dominate the neutrino transport much deeper than the MSW effect.

Core-collapse supernovae are also plausible sites for the r-process nucleosynthesis. The parameter controlling nucleosynthesis, electron fraction or equivalently neutron-to-proton ratio, is determined by the neutrino capture rates. Interactions of the neutrinos and antineutrinos streaming out of the core both with nucleons and seed nuclei determine the neutron-to-proton ratio. Hence to understand core-collapse supernovae and the r-process nucleosynthesis it may host it is crucial to fully understand neutrino properties and interactions [4].

If there are sufficiently energetic electron neutrinos present among the neutrinos emitted from the cooling proto-neutron star, they can convert neutrons into protons. Those neutrons could otherwise initiate the r-

¹Note that since μ and τ neutrinos are pair produced they carry no net muon or tau lepton number.

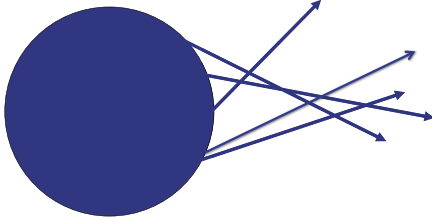


Figure 1: Schematic illustration of the neutrino-neutrino interactions near the neutrinosphere.

process nucleosynthesis. Instead they get bound in helium nuclei, an energetically favorable situation, dropping out of the r-process. This "alpha effect" can cause significant increases in the electron fraction, halting the formation of r-process elements [5].

2. The Mikheyev, Smirnov, Wolfenstein (MSW) effect in a core-collapse supernova

Using the following parameterization of the neutrino mixing matrix:

$$\begin{aligned} \mathbf{T} &= \mathbf{T}_{23} \mathbf{T}_{13} \mathbf{T}_{12} \\ &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & C_{23} & S_{23} \\ 0 & -S_{23} & C_{23} \end{pmatrix} \begin{pmatrix} C_{13} & 0 & S_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -S_{13}e^{i\delta_{CP}} & 0 & C_{13} \end{pmatrix} \\ &\quad \times \begin{pmatrix} C_{12} & S_{12} & 0 \\ -S_{12} & C_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \end{aligned} \quad (1)$$

where $C_{ij} = \cos \theta_{ij}$, $S_{ij} = \sin \theta_{ij}$, and δ_{CP} is the CP-violating phase, the MSW evolution equations can be written as

$$i \frac{\partial}{\partial t} \begin{pmatrix} \Psi_e \\ \Psi_\mu \\ \Psi_\tau \end{pmatrix} = \mathbf{H} \begin{pmatrix} \Psi_e \\ \Psi_\mu \\ \Psi_\tau \end{pmatrix} \quad (2)$$

with

$$\mathbf{H} = \mathbf{T} \begin{pmatrix} E_1 & 0 & 0 \\ 0 & E_2 & 0 \\ 0 & 0 & E_3 \end{pmatrix} \mathbf{T}^\dagger + \begin{pmatrix} V_{e\mu} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & V_{\tau\mu} \end{pmatrix}. \quad (3)$$

In Eq. (3), by dropping a term proportional to the identity, $V_{\mu\mu}$ is chosen to be zero. The non-zero potentials in this equation are the widely used tree-level contribution [6]

$$V_{\mu e}(x) = \sqrt{2} G_F N_e(x), \quad (4)$$

where N_e is the effective electron density, i.e. the difference between electron and positron densities, and the Standard Model loop correction [7],

$$\begin{aligned} V_{\tau\mu} &= -\frac{3\sqrt{2}G_F\alpha}{\pi \sin^2 \theta_W} \left(\frac{m_\tau}{m_W} \right)^2 \\ &\times \left\{ (N_p + N_n) \log \frac{m_\tau}{m_W} + \left(\frac{N_p}{2} + \frac{N_n}{3} \right) \right\}. \end{aligned} \quad (5)$$

Especially when the muon and tau neutrino fluxes emitted from the proto-neutron star differ, loop-correction contributions to the neutrino potential may play an important role [8].

Here we assumed that neutrinos interact with uniform, monotonically-varying background matter, ignoring any background fluctuations. In the presence of fluctuations,

$$N_e = \langle N_e \rangle + \text{fluctuating part}, \quad (6)$$

where $\langle N_e \rangle$ is the fluctuation averaged part of the electron density, one can observe interesting effects [9]. Effects of such random density fluctuations on two-neutrino flavor transformations in the post-core-bounce supernova environment was first examined long ago [10]. Recently there has been renewed interest in exploring the effects of turbulence and density fluctuations in core-collapse supernovae [11].

With three flavors, one has to explicitly include the CP-violating phase in discussing supernova neutrinos. However, it is rather straightforward to show that the CP-violating phase factorizes out in the neutrino evolution Hamiltonian if only the tree level neutrino potential of Eq. (4) is used. This factorization gives us interesting sum rules: Electron neutrino survival probability, $P(\nu_e \rightarrow \nu_e)$ is independent of the value of the CP-violating phase, δ ; or equivalently, in the absence of sterile neutrino mixing, the combination $P(\nu_\mu \rightarrow \nu_e) + P(\nu_\tau \rightarrow \nu_e)$ at a fixed energy is independent of the value of the CP-violating phase [12]. It is possible to derive similar sum rules for other amplitudes [13]. Discussions of the breakdown of this formula when sterile neutrinos are present is given in Ref. [14] and the impact of the CP-violating phase on collective effects in Ref. [15].

The discussion above only pertains to three active flavors, ignoring the possibility of mixing between active

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