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Physics of neutrino flavor transformation through matter–neutrino resonances

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ABSTRACT

In astrophysical environments such as core-collapse supernovae and neutron star–neutron star or neutron star–black hole mergers where dense neutrino media are present, matter–neutrino resonances (MNRs) can occur when the neutrino propagation potentials due to neutrino–electron and neutrino–neutrino forward scattering nearly cancel each other. We show that neutrino flavor transformation through MNRs can be explained by multiple adiabatic solutions similar to the Mikheyev–Smirnov–Wolfenstein mechanism. We find that for the normal neutrino mass hierarchy, neutrino flavor evolution through MNRs can be sensitive to the shape of neutrino spectra and the adiabaticity of the system, but such sensitivity is absent for the inverted hierarchy.

1. Introduction

Neutrino flavor oscillations observed by experiments on solar, atmospheric, reactor and accelerator neutrinos have led to the understanding that neutrinos are massive and their vacuum mass eigenstates are distinct from the weak-interaction states or flavor states, which causes neutrinos to oscillate in vacuum. Remarkable advances have been made in recent years to measure the parameters for neutrino mixing: all the parameters have been measured now except for the neutrino mass hierarchy and the CP-violating phase(s) [1].

When neutrinos propagate through a dense matter, e.g., inside the sun, they can experience a matter potential which stems from the coherent forward scattering by the ordinary matter and leads to the Mikheyev–Smirnov–Wolfenstein (MSW) flavor transformation [2,3]. In the early universe and near hot, compact objects where dense neutrino media are present, neutrinos can also experience a neutrino potential which arises from the neutrino–neutrino forward scattering or neutrino self-interaction [4–6]. The whole neutrino medium can experience collective oscillations when the neutrino potential dominates (e.g., [7–19]; see also Ref. [20] for a review). There can also be interesting interplay between the matter and neutrino potentials when both are significant [21–27].

Recently, a novel phenomenon of neutrino flavor oscillations, which may occur outside a black-hole accretion disk emitting a larger flux of $\bar{\nu}_e$ than ν_e, was discovered and termed the "matter–neutrino resonance" or MNR [28–30]. This phenomenon can be illustrated by the example of a homogeneous and isotropic neutrino gas which initially consists of mono-energetic ν_e and $\bar{\nu}_e$ only. If initially the antineutrino–neutrino density difference $n_{\bar{\nu}_e} - n_{\nu_e}$ is larger than the electron density n_e and it becomes smaller than n_e later, then the matter and neutrino potentials can (nearly) cancel each other, which results in a resonance [28]. Through MNRs the neutrinos can experience an almost full flavor conversion in both the normal and inverted (neutrino mass) hierarchies (NH and IH), but the antineutrinos will eventually return to the electron flavor (see Fig. 1). It is intriguing that the simple criterion of the cancellation of the matter and neutrino potentials can be used not only to identify the regime where MNRs occur but also to solve for the flavor evolution of both the neutrino and antineutrino [28]. The physical nature of MNRs, especially why the matter and neutrino potentials should remain nearly equal over a wide range of neutrino densities, is still not completely understood. Similar phenomena have also been found in core-collapse supernovae when neutrino spin coherence is included [31] or active–sterile neutrino mixing is considered [32].

In this paper we investigate the nature of MNRs. We show that neutrino flavor transformation through MNRs can be explained

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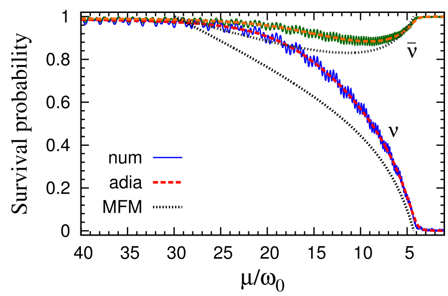

Fig. 1. Neutrino survival probabilities as functions of the neutrino-potential strength $\mu=\sqrt{2}G_F n_\nu$ in a slowly expanding, isotropic and homogeneous gas which consists of mono-energetic ν_e and $\bar{\nu}_e$ of vacuum oscillation frequencies $\pm\omega_0$ in the beginning. The solid curves are obtained by solving the flavor-evolution equations numerically ("num") with $\mu(t)=100\,\omega_0 e^{-\omega_0 t/20}$. The dotted curves are obtained by applying the simple MNR criterion proposed by Malkus et al. [28] ("MFM"). The dashed curves represent the fully adiabatic flavor transformation through an MSW-like mechanism ("adia"). All the calculations assume an antineutrino–neutrino ratio $\alpha=n_{\bar{\nu}}/n_\nu=4/3$, a constant matter potential $\lambda=\sqrt{2}G_F n_e=10\,\omega_0$, vacuum mixing angle $\theta_v=0.15$, and the normal neutrino mass hierarchy.

by an intuitive physical mechanism similar to the standard MSW flavor transformation as first discussed in Ref. [21] and later formulated more explicitly in Ref. [25].

2. Matter–neutrino resonances

2.1. Generalized adiabatic MSW solutions

To elucidate the underlying physics of MNRs, we will again consider the simple example of a homogeneous and isotropic neutrino gas initially consisting of ν_e and $\bar{\nu}_e$ only. As in Ref. [28] we will assume that the neutrino mixing occurs between two active flavors, e and x. We will use the neutrino flavor-isospin (NFIS) $\mathbf{s}_\omega$ to represent the flavor quantum state of a neutrino of vacuum oscillation frequency $\omega=\delta m^2/2E$ [24], where $\delta m^2>0$ and E are the mass-squared difference and energy of the neutrino, respectively. The NFIS of a neutrino is the expectation value of the flavor-isospin operator $\boldsymbol{\sigma}/2=\sum_i \mathbf{e}_i\sigma_i/2$ with respect to the (two-component) neutrino flavor wavefunction ψ, where $\mathbf{e}_i$ $(i=1,2,3)$ are the orthonormal unit vectors in flavor space, and σ_i are the Pauli matrices. The weak-interaction states $|\nu_e\rangle$ and $|\nu_x\rangle$ are represented by the NFISes in the $+\mathbf{e}_3$ and $-\mathbf{e}_3$ directions, respectively. The vacuum mass eigenstates $|\nu_1\rangle$ and $|\nu_2\rangle$ are represented by the NFISes in the directions of $+\mathbf{B}$ and $-\mathbf{B}$, respectively, where

$$\mathbf{B}=-\mathbf{e}_1\sin 2\theta_v+\mathbf{e}_3\cos 2\theta_v. \tag{1}$$

In this paper we will take vacuum mixing angle $\theta_v=0.15$ and $\pi/2-0.15$ for NH and IH, respectively. Also in the NFIS notation the flavor quantum state of an antineutrino is represented by a NFIS of a negative frequency $\omega=-\delta m^2/2E$. A NFIS of a negative ω and in the $+\mathbf{e}_3$ $(-\mathbf{e}_3)$ directions represents the weak-interaction state $|\bar{\nu}_x\rangle$ $(|\bar{\nu}_e\rangle)$.

The equation of motion of a NFIS $\mathbf{s}_\omega$ in a homogeneous, isotropic neutrino gas without collision is [33]

$$\dot{\mathbf{s}}_\omega=\mathbf{s}_\omega\times\mathbf{H}_\omega=\mathbf{s}_\omega\times(\omega\mathbf{B}-\mathbf{V}), \tag{2}$$

where $\mathbf{V}$ represents the neutrino propagation potential in the dense medium.

Neutrino flavor transformation obtains a geometric meaning in the NFIS notation. In vacuum $\mathbf{V}=\mathbf{0}$ and NFIS $\mathbf{s}_\omega$ simply precesses about $\mathbf{H}_\omega$ with frequency ω. As a result, the probability of the neutrino to be in the electron flavor, which is

$$|\langle\nu_e|\psi\rangle|^2=\frac{1}{2}+\mathbf{e}_3\cdot\mathbf{s}_{\omega>0} \tag{3}$$

in the NFIS notation, oscillates with time. This is the vacuum oscillation.

The neutrino propagation potential in an environment of a large matter density but a negligible neutrino density is

$$\mathbf{V}=\lambda\mathbf{e}_3=\sqrt{2}G_F n_e\mathbf{e}_3, \tag{4}$$

where G_F is the Fermi coupling constant, and n_e is the electron number density. If a ν_e is produced at a high matter density such that $\lambda\gg\omega$ and subsequently the density slowly decreases, then the corresponding NFIS $\mathbf{s}_{\omega>0}$ will stay anti-aligned with $\mathbf{H}_\omega$, which is almost in the $-\mathbf{e}_3$ direction initially and becomes $\mathbf{B}$ when $\lambda\to 0$. This process describes an adiabatic MSW flavor transformation [34].

When both the matter and neutrino densities are large, the total potential becomes

$$\mathbf{V}=\lambda\mathbf{e}_3+2\mu\mathbf{S}=\lambda\mathbf{e}_3+2\sqrt{2}G_F n_\nu\mathbf{S}, \tag{5}$$

where n_ν is the total number density of the neutrino, and

$$\mathbf{S}=\int_{-\infty}^{\infty} f_\omega\mathbf{s}_\omega\,\mathrm{d}\omega \tag{6}$$

is the total NFIS. Here we normalize the (constant) neutrino spectrum f_ω with the condition

$$\int_0^{\infty} f_\omega\,\mathrm{d}\omega=1. \tag{7}$$

In the spirit of the adiabatic MSW flavor transformation it was proposed in Ref. [25] that, if both the matter and neutrino densities vary slowly and if the NFIS $\mathbf{s}_\omega$ initially is aligned (anti-aligned) with the Hamilton vector $\mathbf{H}_\omega$, then the NFIS should keep its alignment (anti-alignment) with $\mathbf{H}_\omega$, i.e.,

$$\mathbf{s}_\omega=\frac{\epsilon_\omega}{2}\frac{\mathbf{H}_\omega}{H_\omega}, \tag{8}$$

where $\epsilon_\omega=+1$ (-1) for the aligned (anti-aligned) configuration. Integrating Eq. (8) one obtains a self-consistent equation

$$\mathbf{S}=\frac{1}{2}\int_{-\infty}^{\infty}\frac{\mathbf{H}_\omega}{H_\omega}\epsilon_\omega f_\omega\,\mathrm{d}\omega, \tag{9}$$

which can be used to solve for the adiabatic solutions. As noted in Ref. [25],

$$\mathbf{s}_\omega\cdot\mathbf{e}_2=\mathbf{S}\cdot\mathbf{e}_2=0 \tag{10}$$

in the adiabatic solution because $\mathbf{B}$ is in the $\mathbf{e}_1$–$\mathbf{e}_3$ plane.

2.2. Monochromatic neutrino gases

As in Ref. [28] we will first consider a neutrino gas consisting of mono-energetic ν_e and $\bar{\nu}_e$ at time $t=0$ and with the spectrum

$$f_\omega=\alpha\delta(-\omega_0)+\delta(\omega_0), \tag{11}$$

where $\alpha=n_{\bar{\nu}}/n_\nu$ is the ratio of the number density $n_{\bar{\nu}}$ of the antineutrino to the density n_ν of the neutrino. For this system Eq. (2) becomes

$$\dot{\mathbf{s}}_{\pm\omega_0}=\mathbf{s}_{\pm\omega_0}\times\mathbf{H}'_{\pm\omega_0}, \tag{12}$$

where

$$\mathbf{H}'_{\omega_0}=\omega_0\mathbf{B}-\lambda\mathbf{e}_3-2\mu\alpha\mathbf{s}_{-\omega_0}, \tag{13a}$$

$$\mathbf{H}'_{-\omega_0}=-\omega_0\mathbf{B}-\lambda\mathbf{e}_3-2\mu\mathbf{s}_{\omega_0}. \tag{13b}$$