Resonant Spin-Flavor Conversion of Supernova Neutrinos

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Abstract

We investigate resonant spin-flavor (RSF) conversions of supernova neutrinos which are induced by the interaction of neutrino magnetic moment and supernova magnetic fields. With a new diagram we propose, it is found that four conversions occur in supernovae, two are induced by the RSF effect and two by the pure Mikheyev-Smirnov-Wolfenstein (MSW) effect. The realistic numerical calculation of neutrino conversions indicates that the RSF-induced $\bar{\nu}_e \leftrightarrow \nu_\tau$ transition occurs efficiently, when $\mu_\nu > 10^{-12}\mu_B(B_0/5 \times 10^9 \text{ G})^{-1}$, where B_0 is the strength of the magnetic field at the surface of iron core. We also evaluate the energy spectrum as a function of $\mu_\nu B_0$ at the Super-Kamiokande detector using the calculated conversion probabilities, and find that the spectral deformation might have possibility to provide useful information on the neutrino magnetic moment as well as the magnetic field strength in supernovae.

1. Introduction

The properties of neutrinos attract a lot of attention since neutrinos alone are the elementary particles showing evidence of new physics beyond the standard model. In addition to the neutrino mass and nonzero mixings which have been proven to exist by recent experiments, the nonzero magnetic moment is another nature of neutrinos beyond the standard model. The most stringent upper bound of the neutrino magnetic moment is obtained from the stellar cooling argument, which gives $\mu_\nu < (1-4) \times 10^{-12}\mu_B$, where μ_B is the Bohr magneton.

If neutrinos have the nonzero magnetic moment, it leads to precession between left- and right-handed neutrinos in sufficiently strong magnetic fields expected in the inner region of the core-collapse supernova. In general, nondiagonal elements of the magnetic moment matrix are possible and neutrinos can be changed into different flavors and chiralities. Furthermore, with the additional effect of the coherent forward scattering by matter, neutrinos can be resonantly converted into those with different chiralities by a mechanism similar to the well-

pp. 1451–1454

known Mikheyev-Smirnov-Wolfenstein (MSW) effect.

In this paper, we study this resonant spin-flavor (RSF) effect in detail, including three-flavor neutrinos and antineutrinos. Particularly, a new crossing diagram, which deals with both MSW and RSF effects, is given. From the diagram, we find that the combination of the MSW and the RSF effects makes crossing schemes very interesting to investigate, and the expected flux would be different from that obtained in the case of the pure MSW or pure RSF effect. In addition, we calculate numerically the conversion probabilities of neutrinos and antineutrinos in the supernova using the three-flavor formulation. In the calculations, we adopt the latest neutrino mixing parameters, which are constrained by the solar and the atmospheric neutrino experiments, and assume the normal mass hierarchy and that the neutrino is the Majorana particle.

2. Formulation and Level Crossing Scheme

The interaction of the magnetic moment of neutrinos and magnetic fields is described by

$$\langle(\nu_i)_R|H_{\rm int}|(\nu_j)_L\rangle = \mu_{ij}B_\perp, \tag{1}$$

where μ_{ij} is the component of the neutrino magnetic moment matrix, $B_\perp$ is the magnetic field transverse to the direction of propagation, $(\nu)_R$ and $(\nu)_L$ are the right- and left-handed neutrinos, respectively, and i and j denote the flavor eigenstate of neutrinos, i.e., e, μ, and τ. If neutrinos are the Majorana particles as we assume in this paper, ν_R's are identical to antiparticles of ν_L's and interact with matter. The diagonal magnetic moment is forbidden for the Majorana neutrinos, and therefore only the conversion between different flavors is possible, e.g., $(\bar{\nu}_e)_R \leftrightarrow (\nu_{\mu,\tau})_L$.

We solve the three-flavor (six-component) Schrödinger equation, numerically. In this section, however we give a qualitative discussion, using a new level crossing diagram shown in Fig. 1. The figure clearly includes not only ordinary MSW resonances but also the RSF effects, and it is expected that the combination effect of MSW and RSF makes this scheme very interesting to investigate. From the earlier publications on the MSW effect, we know that the MSW-L is adiabatic for the LMA solution, and MSW-H is adiabatic for large θ_{13} and nonadiabatic for small θ_{13}. Here, adiabatic resonance means that the flavor conversion takes place very efficiently. The adiabaticity parameter of the RSF-L and RSF-H depends on the magnetic field strength and the density profile at the resonance point. For instance, when MSW-L and RSF-H are adiabatic and the others are nonadiabatic (this case is actually expected if θ_{13} is small and magnetic field is sufficiently strong), the conversions such as $\nu_e \to \nu_2, \nu'_\mu \to \nu_1, \nu'_\tau \to \bar{\nu}_1, \bar{\nu}_e \to \nu_3, \bar{\nu}'_\mu \to \bar{\nu}_2$, and $\bar{\nu}'_\tau \to \bar{\nu}_3$ occur. We can easily predict this sort of conversion schemes from Fig. 1., in the case all the resonances are either completely adiabatic or completely nonadiabatic; for the intermediate cases we have no choice but to trust numerical calculations.

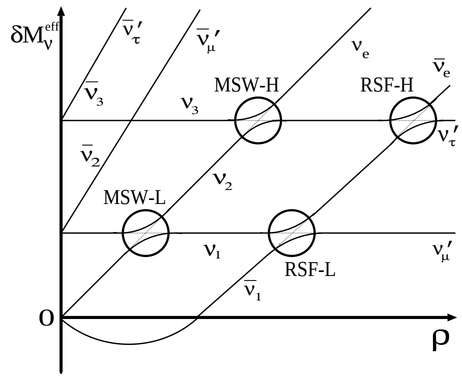

Fig. 1. The schematic illustration of level crossings, where $\nu_{1,2,3}$ and $\bar{\nu}_{1,2,3}$ represent the mass eigenstates of neutrinos and antineutrinos in matter, respectively, and $\nu'_{\mu,\tau}$ and $\bar{\nu}'_{\mu,\tau}$ the mass eigenstates at production, which are superpositions of ν_μ and ν_τ or $\bar{\nu}_\mu$ and $\bar{\nu}_\tau$. There are four resonance points, MSW-L, MSW-H, RSF-L, and RSF-H. The adiabatic conversion means that the neutrinos trace the solid curve at each resonance point (i.e., the mass eigenstate does not flip), while the nonadiabatic conversion is shown by the dotted line.

3. Results of Numerical Calculation

In solving the six-component Schrödinger equation numerically, we have adopted presupernova profiles by Woosley and Weaver [6] and assumed the dipole structure of a magnetic field. The field strength is normalized at the surface of the iron core with the value B_0; as B_0 we take to $\sim 10^{10}$ G, motivated by the observations of the surface magnetic field of white dwarfs.

With the numerically calculated conversion probabilities, the spectrum at the SK detector is obtained. Figure 2. shows a event ratio of high-energy tail ($E_e > 25$ MeV) compared to low-energy events ($E_e < 20$ MeV); here, as original neutrino spectra we have adopted the result of numerical simulation of supernova explosion by the Lawrence Livermore group [5]. From this figure, it is shown that when we increase the value of B_0, the energy spectrum shifts to the higher energy region and the shift saturates at $B_0 \sim 10^{10}$ G. This is because at $B_0 > 10^9$ G the RSF-H conversion starts to become adiabatic and it achieves a completely adiabatic transition at $B_0 \sim 10^{10}$ G. This result does not depend on the value of θ_{13}. More detailed discussion is given in Ref. [1].

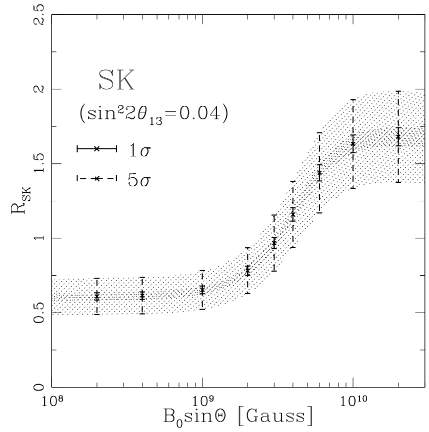

Fig. 2. Ratio of high energy events to low energy events at SK, $R_{\rm SK}$, as a function of B_0 for $\sin^2 2\theta_{13} = 0.04$, where error bars include only statistical errors. The solid error bars are at 1σ level and the dashed ones at 5σ level. The thick and thin bands are the cubic spline interpolations of 1σ and 5σ error bars, respectively.

4. Discussion

The effective matter potential for the RSF conversion is given in the form proportional to the value of $(1-2Y_e)$, where Y_e is the electron number fraction per nucleon. Thus, the deviation of the value of Y_e from 0.5 in the stellar envelope is quite important, and this value is strongly dependent on the isotopic composition. Since this deviation is determined by rarely existent nuclei, the accurate estimate of this deviation is quite difficult. Therefore, the astrophysical uncertainty in $(1-2Y_e)$ should be discussed. We have also investigated this point in detail [2].

In addition to the next galactic supernovae, the observation of the supernova relic neutrino (SRN) background would be available to obtain information on the flavor conversion mechanism in supernovae [3,4]. However, the SRN prediction including the RSF mechanism is difficult at present, and thus it is slated for future work.

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