NONLINEAR EVOLUTION OF FAST COLLECTIVE NEUTRINO OSCILLATIONS IN CORE-COLLAPSE SUPERNOVAE

MILAD DELFAN AZARI$^{1,2,†}$, HIROKAZU SASAKI$^3$, TOMOYA TAKIWAKI$^4$ AND HIROTADA OKAWA$^5$

$^1$Waseda Research Institute for Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-8555, Japan
$^2$Department of Physics, Graduate School of Advanced Science and Engineering, Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo 169-8555, Japan
$^3$Theoretical Division, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
$^4$Division of Science, National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
$^5$Waseda Institute for Advanced Study, 1-21-1 Nishi-Waseda, Tokyo 169-0051, Japan

E-mail: †milad@heap.phys.waseda.ac.jp

Abstract. According to one of the most promising supernova theories, the neutrino-heating mechanism, neutrinos are responsible for transferring the energy released during the gravitational collapse of massive stars to their surroundings. If neutrino flavors are converted fast in the cores, the efficiency of neutrino heating is enhanced and can change the dynamics of the shock wave in supernovae. In this article, we investigate the dynamics of fast neutrino flavor conversions with collisions under energy-dependent treatment in detail. For the first time, we use a realistic initial condition, which is taken from the results of the self-consistent, realistic Boltzmann simulations in two spatial dimensions under axisymmetry. We report that the neutrino flavor conversion will be significantly enhanced if the energy-dependent collision term is considered in the neutrino transport equation which has been ignored in previous studies. We present the preliminary results of our investigation here, which are consistent with other studies which were conducted under simple treatments. It is believed that such findings may have an impact on the explosion mechanism of core-collapse supernovae, nucleosynthesis and neutrino astronomy.

Keywords: core-collapse supernovae, neutrinos, neutrino oscillations, nucleosynthesis.

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I. INTRODUCTION

Neutrinos are fermions, and they are among the most abundant particles in the universe. They are massive particles, but their masses are much smaller than those of their charged lepton counterparts. Since they are massive particles and their masses are not diagonal with respect to the flavors [1], when propagating through vacuum, they oscillate [2]. When matter exists, weak interactions with surrounding matter alter the dispersion relation in vacuum and induce resonant conversions known as the MSW (Mikheyev-Smirnov-Wolfenstein) effect [3]. Neutrinos also generate their own self-energy through their interactions with one another, and if these neutrinos are highly populated, then they will undergo neutrino flavor conversions. These phenomena are called collective neutrino oscillations. Since the equations underlying the collective neutrino oscillation case are nonlinear, it is difficult to comprehend the so-called collective neutrino oscillations [4].

It is known that the collective neutrino oscillation occurs only where neutrinos are abundant. Core-collapse supernovae (CCSNe) are one of such sites in the universe based on the discovery of about 20 electron-type antineutrinos from the supernova SN1987A in the Large Magellanic Cloud [5]. CCSNe are the energetic deaths of massive stars in the course of their lives, yet at the same time, they are the births of compact objects such as black holes and neutron stars. CCSNe are known to occur when shockwaves generated in the center reach the stellar outer envelopes, but theoretical studies of core bounces caused by hardening of matter at the nuclear density cannot generate shockwaves powerful enough to reach the outer regions. This explosion mechanism is still not fully understood theoretically [6]. It is believed that a deeper study of the initial implosion of the core is needed to initiate an explosion. CCSNe are important agents in the synthesis of heavy nuclei in the universe, emitting copious neutrinos and gravitational waves, therefore being prime targets for nascent neutrino and gravitational wave astronomy.

Neutrinos are regarded as the key players in CCSNe. A neutron star releases almost all of its binding energy during gravitational collapse as neutrinos, and the kinetic energy of the matter released in a supernova explosion is only one percent of this energy. In the currently most popular scenario, which is known as the neutrino heating mechanism, a fraction of $\nu_e$ and $\bar{\nu}_e$ are reabsorbed by the matter between the shock front and the so-called gain radius and deposit their energy to push the stagnated shock again. It is known that $\nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$ have higher energies than $\nu_e$ and $\bar{\nu}_e$ due to the weak interactions of $\nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$ with matters while propagating. If the former neutrinos ($\nu_\mu, \bar{\nu}_\mu, \nu_\tau$ and $\bar{\nu}_\tau$) are converted to the latter neutrinos ($\nu_e$ and $\bar{\nu}_e$), those converted neutrinos will be absorbed by matter. As a result of these neutrino flavor conversions, more neutrino energy will be transferred to the matter behind the shock and it may lead to the successful explosions [7]. In fact, this is one of the main reasons that supernova researchers and particle physicists are both interested in collective neutrino oscillations.

There has been a lot of interest in fast-pairwise collective neutrino oscillations in recent years. It was Sawyer who first proposed that fast flavor conversions might occur near the neutrino sphere [8]. The oscillation length in fast collective oscillation is $\sim 10^{-5}$ km. Fast flavor conversions may occur near neutrino spheres and may have a significant impact on explosion dynamics in astrophysical environments. It is known that there is a strong relationship between fast flavor conversions and the anisotropic angular distribution of neutrinos. So far, the possibility of fast flavor conversions in CCSNe and neutron star mergers using neutrino radiation hydrodynamic
simulations has been studied and it has been pointed out that fast flavor conversions occur as a result of the crossing between the angular distribution of electron neutrinos and that of anti-electron neutrinos, so-called electron-lepton number (ELN) crossing \([9–11]\). The effects of collisions on fast flavor conversions have been under attention these days as well. In some studies, neutral-current collisions enhance fast flavor conversions (e.g., \([12]\)), while others have reported damping effects \([13]\). These results are inconsistent with each other and the role of collisions in fast flavor conversion is unclear.

Our research focuses on calculating fast flavor conversions in a nonlinear regime and the effects of neutrino scatterings on the fast flavor conversions by examining the dynamics of two flavors of neutrinos in the realistic two-dimensional (2D) fully self-consistent Boltzmann-neutrino-radiation-hydrodynamics simulations. This article is organized as follows. In Section II, we briefly describe the numerical models used in this research and summarize the equations that will be used in the analysis. We present our results in Section III, and we summarize our results and conclude the paper in Section IV.

II. MODELS AND FORMULATIONS

II.1. Models

In this article, our analysis is based on the results of the realistic two-dimensional (2D) fully self-consistent Boltzmann-neutrino-radiation-hydrodynamics simulations for the progenitor model of non-rotating 11.2 M\(_\odot\) \([14]\) which were performed on the Japanese K-supercomputers \([15]\). In these simulations, three neutrino species, \(\nu_e\), \(\bar{\nu}_e\) and \(\nu_x\) are considered and their distributions are computed on spherical coordinates \((r, \theta)\) under spatial axisymmetry. As in our previous studies, we used spherical coordinates in momentum space \((E, \theta_\nu, \phi_\nu)\), in which the two angles are measured from the local radial direction. The computational domain covers \(0 \leq r \leq 5000\) km, \(0 \leq \theta \leq \pi\), \(0 \leq E \leq 300\) MeV, \(0 \leq \theta_\nu \leq \pi\) and \(0 \leq \phi_\nu \leq 2\pi\) with \(384(r), 128(\theta), 20(E), 10(\theta_\nu)\) and \(6(\phi_\nu)\) mesh cells. This paper adopts the Furusawa-Shen equation of state (FSEOS) that is based on relativistic mean field theory for nuclear matter \([16]\). In this article, we only present the results of our analysis at the post-bounce time of \(t_{\text{pb}} = 190\) ms.

II.2. Formulations

Similar to the previous works \([17–20]\), we calculate fast neutrino flavor conversions of \(\nu_e\) and \(\nu_x\) with their anti-particles \(\bar{\nu}_e\) and \(\bar{\nu}_x\) considering the collision effects of neutrino scattering. We study neutrino flavor conversions based on neutrino density matrices. The evolution of neutrinos is described as

\[
\frac{d}{dt} \rho = -i[H, \rho] + C[\rho, \bar{\rho}],
\]

\[
\frac{d}{dt} \bar{\rho} = -i[\bar{H}, \bar{\rho}] + \bar{C}[\rho, \bar{\rho}],
\]

where \(H\) and \(C\) are the Hamiltonian and collision terms for neutrinos, respectively and \(\bar{H}\) and \(\bar{C}\) correspond to the Hamiltonian and collision terms for anti-neutrinos. The collision part is similar to Equations 2 and 8 in \([21]\). The Hamiltonian in Eq. 1 is written as

\[
H = H_{\text{vacuum}} + H_{\text{matter}} + H_{\text{collective}},
\]
where the vacuum term is given as
\[ H_{\text{vacuum}} = \frac{M^2}{2E}. \] (4)
where \( M^2 \) is the mass squared matrix in vacuum and is equal to \( \text{diag} (m_1^2, m_2^2, m_3^2) \). Note that in this study, matter potential is ignored for simplicity and the collective part is given as
\[ H_{\nu\nu}(\cos \theta_{\nu}) = \int d\mu' \int d\phi' \int_{-1}^{1} \frac{d \cos \theta'_{\nu}}{2} h_{\nu\nu}, \] (5)
where \( h_{\nu\nu} \) is
\[ h_{\nu\nu} = (\rho(E', \theta'_{\nu}, \phi'_{\nu}) - \bar{\rho}(E', \theta'_{\nu}, \phi'_{\nu})) (1 - \cos \theta_{\nu} \cos \theta'_{\nu} - \sin \theta_{\nu} \sin \theta'_{\nu} (\cos \phi_{\nu} \cos \phi'_{\nu} + \sin \phi_{\nu} \sin \phi'_{\nu})). \] (6)
In this study, we use 200 grid points for \( \theta_{\nu} \) and 20 grid points for energy. These grid numbers are comparable with the previous studies [21, 22].

III. RESULTS

We start showing our results by illustrating the initial condition of energy integrated simulation in Fig. 1. The density matrix of \( \nu_e, \bar{\nu}_e, \nu_x \) and \( \bar{\nu}_x \) are represented as \( \rho_{11} \) (red), anti-\( \rho_{11} \) (green), \( \rho_{22} \) (blue) and anti-\( \rho_{22} \) (yellow), respectively. Note that the density matrix of \( \nu_x \) is covered up by \( \bar{\nu}_x \) and is not visible in the figure. The black circle indicates the electron-lepton number (ELN) crossing. Figure 2 shows the initial condition of energy dependent simulation. Similar to the previous figure, the density matrix of \( \nu_e, \bar{\nu}_e, \nu_x \) and \( \bar{\nu}_x \) are represented as \( \rho_{11} \) (red), anti-\( \rho_{11} \) (green), \( \rho_{22} \) (blue) and anti-\( \rho_{22} \) (yellow), respectively, and the black circle indicates the electron-lepton number (ELN) crossing. Figures 3 and 4 show the density profiles of \( \rho_{11} \) and anti-\( \rho_{11} \). At low energy, the densities \( \rho \) are largely deviated from unity but they do not contribute to the integrated profile. In the intermediate energy range, 10-50 MeV, the profile is similar to the integrated profile.

![Fig. 1. Initial condition of energy integrated simulation. \( \rho_{11} \) (red), anti-\( \rho_{11} \) (green), \( \rho_{22} \) (blue) and anti-\( \rho_{22} \) (yellow) correspond to the density matrix of \( \nu_e, \bar{\nu}_e, \nu_x \) and \( \bar{\nu}_x \), respectively. The electron-lepton number crossing is indicated as black circle.](image1)

![Fig. 2. Initial condition of energy dependent simulation. \( \rho_{11} \) (red), anti-\( \rho_{11} \) (green), \( \rho_{22} \) (blue) and anti-\( \rho_{22} \) (yellow) correspond to the density matrix of \( \nu_e, \bar{\nu}_e, \nu_x \) and \( \bar{\nu}_x \), respectively. The electron-lepton number crossing is indicated as black circle.](image2)
Figure 5 represents the overall evolution for energy integrated (blue) and energy dependent (red) transition probabilities. It is seen that overall evolution is almost the same and the conversion probability is 2% and the initial profile does not change significantly. Figure 6, shows the evolution for energy dependent (ED) and energy dependent with neutral current scattering (ED-NC) transition probabilities. This is clearly seen that the neutral current (NC) effect is very significant, and it dramatically changes the nature of the evolution. We found that without collision, the transition probability is 0.02, while with collision, it is 0.6. This means that with collision, the transition probability is 30 times greater than without collision.

IV. SUMMARY

We calculate fast flavor conversions with collision effects of neutrino scatterings based on the realistic two-dimensional (2D) fully self-consistent Boltzmann-neutrino-radiation-hydrodynamics
simulations for the progenitor model of non-rotating $11.2\,M_{\odot}$ which were performed on the Japanese K-supercomputers at the post-bounce time of $t_{pb} = 190$ ms. As a result, we find that if the energy-dependent collision term is considered in the neutrino transport equation, the neutrino flavor conversions will be significantly enhanced in supernova cores. These findings are in agreement with previous works which were conducted by some approximations. The results presented in this paper are preliminary, and the rest will be presented elsewhere soon.

REFERENCES