Graduate School of Advanced Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論　文　題　目
Thesis Theme
New features of collective neutrino oscillations and their occurrence conditions in core-collapse supernovae

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Neutrinos are subatomic particles and one of the most abundant particles in our universe. They are amongst fermions and are massive, although their masses are smaller than those of the charged lepton counterparts. Neutrinos mass eigenstates are not diagonal with their flavor eigenstate and therefore, they oscillate in their three flavors (electron-type, muon-type and tau-type) while propagating in vacuum. When neutrinos propagate through a medium, weak interactions with surrounding matter modify the dispersion relation in vacuum and induce resonant conversions of flavors which originates a phenomenon called Mikheyev-Smirnov-Wolfenstein (MSW) effect and it is believed to be the solution of the solar neutrino problem. The neutrino self-energy induced by weak interactions which is the origin of the MSW effect is generated by the interactions with other neutrinos too and if the neutrinos are highly populated in the environment, flavor conversion occurs which is called as the collective neutrino oscillation. Understanding the physics of collective neutrino oscillation is not an easy task since the equations that explain the neutrinos propagation, become nonlinear.

As mentioned above, the collective neutrino oscillation occurs when they are highly abundant. One of the environments in our universe which is neutrino rich are core-collapse supernovae (CCSNe). CCSNe are the energetic deaths of massive stars at the end of their lives and at the same time they are the birth of compact objects such as black holes and neutron stars. Understanding the physics of CCSNe is very important for a couple of reasons: firstly, its understanding fills the last piece of stellar evolution theory; secondly, CCSNe are the main agents in cosmic synthesis of heavy nuclei; they emit copious neutrinos as well as gravitational waves, hence being one of the chief targets for nascent neutrino and gravitational wave astronomies.

Although the CCSNe explosion mechanism is still not understood well theoretically, but it is believed that the initial implosion of the core should be studied further to produce an explosion. It is known that the supernova explosions happen when the shockwave formed at the center, reaches the stellar outer envelopes. But unfortunately, the theoretical studies of core bounce induced by hardening of matter at the nuclear density cannot generate a powerful shockwave to eject to the outer envelopes. This problem became an unsolved problem for many years for astrophysicists. Supernova researchers are trying to find a way to regenerate the stalled shock inside the core.

Neutrinos are believed to be the key players in the shock revival. They carry most of the energy relieved by the gravitational collapse of massive star cores. If only one percent of their energy is transferred to stellar matter, CCSNe will be produced. In the most popular CCSNe explosion mechanism scenario, neutrino heating mechanism, a fraction of the electron-type neutrinos and antineutrinos are absorbed by the matter between the shock front and gain radius and deposit their energy to push the stalled shock to the outer envelopes. If the neutrinos are absorbed by matter efficiently, the so-called neutrino heating mechanism is successful. It is also believed that muon-type neutrinos and tau-type neutrinos and their anti-particles have higher energies than electron-type neutrinos and anti-electron neutrinos. If the neutrino oscillations occur and absorbed by matter, more energy will be transferred to matter and it may lead to the successful explosions. This is one of the main reasons that understanding the physics of the collective neutrino oscillations is important for astrophysicists. Recently, a mechanism called, fast collective neutrino oscillation is reported. It is known that these fast neutrino flavor conversions occur when the electron-lepton-number (ELN) crossing exist. Crossing means that the sign of the difference between the energy integrated electron-type neutrinos and anti-electron neutrinos distribution functions change as a function of propagation direction. More interestingly, it is known that the occurrence of the fast collective neutrino oscillation near the neutrino sphere, which has a radius that corresponds to the optical depth of one and the neutrinos are copiously emitted, has the highest impact on the explosion mechanism of CCSNe.

The above explanations are the reasons why collective neutrino oscillations are important in the field of particle physics and astrophysics. As mentioned earlier, understanding the physics of collective neutrino oscillation is very difficult due to the nonlinear equations but investigation of the more realistic settings such as studying them in the core of the massive stars are much more difficult since the kinetic equations that describe the neutrino transfer in non-uniform matter should be solved. Even it is very difficult to study them in spherical symmetry cases. Due to these reasons, the previous studies were limited to the simplified one-dimensional models and approximated situations.

Recently, the idea based on the fact that the neutrinos are almost all in the flavor eigenstates at the beginning of the conversions is proposed. By linear analysis, the linearized equations can be used to study where and when the collective neutrino oscillation is triggered. The neutrino flavor conversions can be regarded as the instability of the flavor eigenstate.

In my thesis, I mainly investigate the phenomenon called fast collective neutrino oscillations in core-collapse supernovae as it is believed these so-called fast neutrino flavor conversions may occur near the neutrino sphere. In the beginning, we conducted the linear analysis for some selected neutrino distributions obtained in our fully self-consistent simulations of CCSN in two spatial dimensions under axisymmetry with our Boltzmann- radiation-hydrodynamics code. Computing neutrino transport in situ together with hydrodynamics in which they are in five dimensions (2 spatial and 3 momentum space) and hence fully consistent with matter dynamics. At first, we paid attention to the vicinity of the neutrino sphere only because the neutrino distributions are not axisymmetric with respect to the radial direction in contrast with the one-dimensional models and the different neutrino species fluxes are non-radial and not aligned with each other. Another reason that we started our project based on the mentioned radius is if the fast collective neutrino oscillation occurs near the neutrino sphere, it will have the largest impact on the explosion mechanism of supernovae as mentioned earlier. Since it is remaining to be understood well that the crossing is the really necessary condition for the fast neutrino flavor conversions, we did not just focus on the crossing in the angular distributions of electron-type and anti-electron neutrinos. We hence conducted linear analysis for highly non-radial angular distribution of neutrinos without considering whether the crossing occurs or not. As a matter of fact, when the original neutrinos angular distributions fail to give conversions, we modified them by multiplying the original distribution by some factors until we find conversions and then studied the condition for the successful conversions.

We applied the linear stability analysis to a few data selectively extracted from our fully self-consistent realistic data for a non-rotating progenitor mass of 11.2 solar mass. We have obtained the neutrino distributions at the point near the neutrino sphere for ($r = 44.8$ km and $\theta = 2.36$ rad) from the numerical data at three different post-bounce times: $t_{pb} = 15$, 190.4 and 275.9 ms. The reason we choose this region is we found the highest misalignment between the fluxes of electron-neutrinos and anti-electron neutrinos at $t_{pb} = 15$ ms. This misalignment occurs due to the convective motions and is treated consistently with hydrodynamics in our Boltzmann code. Then we have conducted linear analysis, solving the equation for the dispersion relation to obtain complex solutions, which are supposed to indicate the instability. We didn't find any unstable mode for these cases mentioned earlier which means there is no sign of the instability for the original distributions. As mentioned earlier, after not finding any sign of instability, we have modified the original anti-electron neutrinos angular distributions by arbitrary factors, and we have repeated it until we find that the unstable modes start to exist once the crossing occurs for the electron-type neutrinos and anti-electron neutrinos angular distributions. We confirm that the crossing is the condition for the fast collective neutrino oscillation. We also explored in detail the dispersion relations and how they are related to the wave vector of the perturbation.

As the first work was the pilot study for further thorough and systematic explorations of the possibility of the fast collective neutrino oscillations, on the next step, I conducted a more thorough survey of the ELN crossing in our fully self-consistent, realistic simulations of CCSN in two dimensions under axisymmetry with our Boltzmann-neutrino-radiation-hydrodynamics code that computes neutrino transport together with hydrodynamics. As a result, we find positive detection of the crossing in the region of r = 16-18 km at t_{pb} = 190 ms. This crossing continues to exist in the later times of t_{pb} = 275 ms even for a wider region. It should be stressed that the regions which we find positive results of the crossings are located inside the neutrino sphere and the fast flavor conversion occurrence in these regions may influence on the observations of supernova neutrinos, nucleosyntheses and supernova explosion itself. By applying the same analysis done for the previous work, we confirm that the unstable modes exist at these regions which lead to the fast collective neutrino oscillation.

These new results are in contrast with the claim in my previous results, that the crossings are not likely to occur for the realistic angular distributions of the electron-type and anti-electron neutrinos since the angular distributions of the electron-type neutrinos and anti-electron neutrinos are larger as we go deeper where neutrinos are coupled with matter and their distributions are affected by matter motions, but the population of anti-electron neutrinos will be suppressed by stronger Fermi degeneracy of electron type-neutrino and vice versa at larger radii where anti-electron neutrinos is more abundant but the angular distributions become not much different between electron-neutrinos and anti-electron neutrinos. These results helped us to reach to an interesting interpretation that, the regions where the crossings occur, anti-electron neutrinos are not suppressed and populated in almost equal numbers with the electron-type neutrinos. As time passes the ratio of the anti-electron neutrinos to that of electron-neutrinos increases at some points but still the crossings occur when the ratio is very close to the unity.

As a conclusion, my thesis is structured as follows. Firstly, the equations of motion (EOM) for neutrino flavors are studied in details and linear stability analysis based on the dispersion relation are formulated. Secondly, the numerical models of our realistic simulations of CCSN in this study are explained. Thirdly, the results on the occurrence and the conditions of the fast collective neutrino oscillations are discussed in details and finally, I conclude the thesis and discuss about the future works.

No.1

早稲田大学　博士（理学）　学位申請　研究業績書

(List of research achievements for application of doctorate (Dr. of Science), Waseda University)

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Papers	○ Title: Fast collective neutrino oscillations inside the neutrino sphere in core-collapse supernovae Journal: PHYSICAL REVIEW D Publication date: In press Authors: <u>**Milad Delfan Azari**</u>, Shoichi Yamada, Taiki Morinaga, Hiroki Nagakura, Shun Furusawa, Akira Harada, Hirotada Okawa, Wakana Iwakami and Kohsuke Sumiyoshi ○ Title: Investigations of Fast-Pairwise Collective Neutrino Oscillations in Core-Collapse Supernovae based on the Results of Boltzmann Simulations Journal: The Physical Society of Japan Conference Proceedings Publication date: In press Authors: <u>**Milad Delfan Azari**</u>, Shoichi Yamada, Taiki Morinaga, Wakana Iwakami, Hirotada Okawa, Hiroki Nagakura and Kohsuke Sumiyoshi ○ Title: Linear analysis of fast-pairwise collective neutrino oscillations in core-collapse supernovae based on the results of Boltzmann simulations Journal: PHYSICAL REVIEW D **99**, 103011 Publication date: May 2019 Authors: <u>**Milad Delfan Azari**</u>, Shoichi Yamada, Taiki Morinaga, Wakana Iwakami, Hirotada Okawa, Hiroki Nagakura and Kohsuke Sumiyoshi Title: Pre-supernova neutrino emissions from ONe cores in the progenitors of core-collapse supernovae: are they distinguishable from those of Fe cores? Journal: The Astrophysical Journal, Volume 808, article id. 168,20 pp. Publication date: July 2015 Authors: Chinami Kato, <u>**Milad Delfan Azari**</u>, Shoichi Yamada, Koh Takahashi, Hideyuki Umeda, Takashi Yoshida and Koji Ishidoshiro
Presentations	○ Title: Fast neutrino flavor conversions inside the neutrino sphere in the core-collapse supernovae Conference: Multi-dimensional Modeling and Multi-Messenger observations from Core-Collapse Supernovae (4M-COCOS) Date: October 2019 Authors: <u>**Milad Delfan Azari**</u>, Shoichi Yamada, Taiki Morinaga, Hiroki Nagakura, Shun Furusawa, Akira Harada, Hirotada Okawa, Wakana Iwakami and Kohsuke Sumiyoshi

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	○ Title: Linear analysis of fast-pairwise neutrino flavor conversion in CCSNe based on the results of the realistic Boltzmann-Neutrino-Radiation-Hydrodynamics code Conference: 10th DTA Symposium, Stellar Death and their diversity Date: January 2019 Authors: **<u>Milad Delfan Azari</u>**, Shoichi Yamada, Taiki Morinaga, Wakana Iwakami, Hirotada Okawa, Hiroki Nagakura and Kohsuke Sumiyoshi ○ Title: Linear analysis of fast-pairwise neutrino flavor conversion in CCSNe based on the realistic data Conference: 31st Symposium of the Association of the Theoretical Astrophysicists of Japan (Rironkon) Date: December 2018 Authors: **<u>Milad Delfan Azari</u>**, Shoichi Yamada, Taiki Morinaga, Wakana Iwakami, Hirotada Okawa, Hiroki Nagakura and Kohsuke Sumiyoshi ○ Title: Linear analysis of fast-pairwise neutrino flavor conversion in CCSNe based on the realistic simulations with Boltzmann solver Conference: International Conference on Deciphering multi-Dimensional nature of core-collapse supernovae via Gravitational-Wave and neutrino signatures (SNeGWv2018) Date: October 2018 Authors: **<u>Milad Delfan Azari</u>**, Shoichi Yamada, Taiki Morinaga, Wakana Iwakami, Hirotada Okawa, Hiroki Nagakura and Kohsuke Sumiyoshi ○ Title: Linear analysis of fast-pairwise neutrino flavor conversion in CCSNe by Boltzmann-Hydro code Conference: International Conference on Physics of Core-Collapse Supernovae and Compact Star Formations Date: March 2018 Authors: **<u>Milad Delfan Azari</u>**, Shoichi Yamada, Taiki Morinaga, Wakana Iwakami, Hirotada Okawa, Hiroki Nagakura and Kohsuke Sumiyoshi ○ Title: Neutrino Oscillations in Core-Collapse Supernova Conference: Summer School of the Astronomical Society of Japan Date: July 2015 Authors: **<u>Milad Delfan Azari</u>**, Shoichi Yamada