論文の内容の要旨

Dynamics and Symmetry Breaking of Collective Neutrino Oscillation in Core-Collapse Supernovae

(超新星爆発におけるニュートリノ集団振動のダイナミクスと非対称性)

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Massive stars experience a core collapse and end their lives at the final stage of the stellar evolution. An enormous amount of neutrinos are released from the center and deposits the energy into the stalled shock wave to help the explosion. Neutrinos have essential roles in the explosion mechanism through neutrino heating. Neutrino observation from nearby core-collapse supernovae will help us to enrich our understanding of supernova physics. However, if neutrino oscillation interchanges different flavors, the flavor-dependent reactions can be modified. This dissertation presents the possibility and the impact of neutrino oscillation, mainly induced by the neutrino-neutrino interactions, inside the core-collapse supernovae.

In environments with high dense neutrino medium, such as core-collapse supernovae, the neutrino self-interaction can not be ignored and induce the nonlinear flavor mixing phenomenon called collective neutrino oscillation. This flavor conversion occurs at $\mathcal{O}(10-100)$ km near the proto-neutron star, and the phase space distribution among each flavor dramatically changes. Therefore, collective neutrino oscillation can potentially affect the neutrino signals, the explosive nucleosynthesis, and the explodability in core-collapse supernovae. However, the neutrino self-interactions are still poorly understood because the system is a complicated seven-dimensional problem. Many studies have adopted a simplified description, called the

bulb model, to relax the complexity. Nevertheless, the flavor conversions demonstrate interesting spectral mixing features in the neutrino energy distribution. The non-trivial behaviors are in the spotlight, and the studies beyond the bulb model progress rapidly. Collective flavor instability is triggered if there exists a spectral crossing that the difference in the phase space distribution between neutrinos and antineutrinos changes the sign at some momentum. Currently, collective neutrino oscillation can be divided into two flavor instabilities: slow and fast modes. Slow flavor conversion is induced by a spectral crossing in the energy distribution, while fast one is by a crossing in the angular distributions.

In this dissertation, we report our studies on the development of slow and fast flavor conversion, respectively. The flavor evolution strongly depends on the assumption in the simulation system, and we focus on the dynamics and the symmetry breaking. First, we introduce the basic bulb model to simplify the neutrino self-interactions and demonstrate the flavor mixing phenomena. Then, we present the impacts beyond the bulb model.

The bulb model requires isotropic neutrino emission but demonstrates the most straightforward slow flavor conversions, called spectral splits that the energy distribution is swapped only above a critical energy. On the other hand, considering the global geometry effects, the collective effects can be suppressed by dense background matter. We find that collective neutrino oscillation is completely suppressed at all time epochs from the neutronization burst to the formation of a black hole under the high matter density profile in a failed supernova model. This model is an extreme case of core-collapse supernovae, but the suppression behaviors are probably general during the accretion phase. The neutrino self-interactions need to overcome the matter-induced phase dispersion to exhibit the collective flavor conversions. The bulb model calls for many assumptions, which inhibit the excitation of some flavor instabilities. Therefore, symmetry breaking induces a new collective instability and gives rise to more precise flavor conversions. Neutrino states are obtained as $\rho_\nu(r; E_\nu, \theta_\nu)$ in the traditional bulb model, but for the extended descriptions axial-symmetry breaking $(r; E_\nu, \theta_\nu, \varphi_\nu)$ and spatio-temporal symmetry breaking $(t; r, \Theta; E_\nu, \theta_\nu)$ are considered. Newly considered flavor instability can potentially overcome the matter suppression and induce the flavor conversions in the region where the complete matter suppression appears in the bulb model. Axial-symmetry breaking in direction provides a multi-azimuthal-angle instability and changes the geometry term of neutrino emission. We perform the first-ever three-flavor calculation of collective neutrino oscillation considering three-dimensional momentum space for an electron-capture supernova model with an $8.8 M_\odot$ progenitor. By employing a realistic supernova model, not parametric neutrino properties, we find that the multi-azimuthal-angle instability partly breaks matter suppression and induces additional collective flavor conversions with three-flavor effects. Also, the translation symmetry breaking raises spatio-temporal instability in time and space. The inhomogeneity in time is the most likely to overcome the matter suppression. Still, we need to investigate the adiabatic growth of collective neutrino oscillation in detail for a realistic supernova model. In addition to the effects of symmetry breaking, the consideration of coherent neutrino-nucleus scattering also provides an impact beyond the bulb model. A small fraction of escaping neutrinos is scattered by the background nuclei and nucleons, changing the propagation direction. The direction-changing scattering generates a neutrino halo and makes intersection angles broader. If inward-scattered neutrinos can not be neglected, it is more challenging to compute the flavor conversion globally. On the other hand, if the contribution is minor compared to that from the outwardly propagating neutrino flux, we can treat it safely by extending the bulb description. We perform the first-ever numerical study of collective neutrino oscillation considering the neutrino halo for a $9.6M_{\odot}$ iron-core progenitor model. In our iron-core collapse supernova model, inwardly directed components can not be neglected in the region where the matter suppression is dominant. On the other hand, the outward contribution is dominant outside the shock front, and we can investigate the effects of the neutrino halo numerically. We find that halo neutrinos do not overcome the matter suppression but provide sharper spectral splits and delay the onset of collective neutrino oscillation.

Above the discussion is within the slow flavor conversion, and the isotropic angular distribution suppresses the fast instability. Fast flavor conversion is induced by a zero crossing in the neutrino lepton flavor number (NLFN) angular distribution. The angular crossings are generated by various supernova dynamics and can locally excite the fast instability. In the preshock region of core-collapse supernovae, coherent neutrino-nucleus scattering forms the angular crossing in the backward direction due to the difference in the averaged energies between neutrinos and antineutrinos. If we consider the identical heavy-leptonic flavors $\nu_X = \bar{\nu}_X$, the electron lepton number (ELN) crossings induce the fast instability. On the other hand, in a realistic supernova model, microphysics breaks the condition, and non-zero μLN and τLN angular distributions appear. Muon production enhances the $\bar{\nu}_\mu$ emission and provides the strongly negative μLN angular distribution. We simulate the nonlinear flavor evolution with fast modes for the six-species angular distributions considering the microphysics. We find that fast instability is excited only in the $e-\tau$ sector and then propagates across the other sectors in the case including the vacuum mixing term. Also, we find for the first time the development of a cascade on spatial Fourier space due to the nonlinear mode coupling. Furthermore, we perform the flavor evolution for three types of angular distributions in a one-dimensional box with the (t, z, v_z) system. We find that a flavor wave excited during the linear phase propagates toward the positive-z direction and interacts with the backward-moving components. The nonlinear interference shifts the flavor waves from larger-scale to smaller-scale structures and establishes flavor equilibrium in space-averaging quantities. The flavor equilibrium is above or below the crossing direction and resembles the spectral splits in the slow flavor conversion. The description can be explained using the asymmetry ratio between neutrinos and antineutrinos. We can categorize the asymptotic behaviors by simulating fast flavor conversion for three types of angular distributions. In the case that the total number density of ν_e exceeds that of $\bar{\nu}_e$, fast flavor conversion seems to transfer the angular distribution from the positive ELN parts to the negative and makes the crossing shallower, following the global electron-family number conservation. In the case of the $\bar{\nu}_e$ excess, the contrary trends occur. If the description is universal, it will provide a crucial hint about incorporating fast flavor conversion to the core-collapse simulations.