論文の内容の要旨

Neutrino oscillations deep inside core-collapse supernovae and their impact on νp-process nucleosynthesis

(重力崩壊型超新星の最深部で起こるニュートリノ振動とνp元素合成過程への影響)

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Large numbers of neutrinos are emitted in core-collapse supernova explosion. Supernova neutrinos are effective tools to understand phenomenology of supernova explosion and properties of neutrinos in extreme environment of core-collapse supernovae. Supernova neutrinos are first discovered in SN1987A, but the number of neutrino event is not enough for detection of neutrino oscillations inside core-collapse supernovae. It is considered that supernova neutrinos are affected by peculiar neutrino oscillations inside medium. Especially, coherent forward scatterings of neutrinos with themselves induce non-linear flavor conversions called "Collective neutrino oscillations" around $100 - 1000$ km from the center. Collective neutrino oscillations change neutrino and antineutrino spectra dramatically and increases high energy ν_e and $\bar{\nu}_e$ through the spectral swap. It is expected that such increased e-flavor neutrinos have influence on observable quantities such as neutrino signals in neutrino

detectors and nuclear abundances of heavy nuclei in core-collapse supernovae. In this thesis, we carry out numerical simulation of collective neutrino oscillations in core-collapse supernovae. Then, we study how collective neutrino oscillations affect neutrino events in neutrino detectors and supernova nucleosynthesis.

First, we perform the three flavor multiangle simulations for precise collective neutrino oscillations by using simulation data of an electron capture supernova whose progenitor mass is $8.8M_{\odot}$. Collective neutrino oscillations are not prevented by the multiangle matter suppression because of the dilute envelop of the progenitor. In inverted mass hierarchy, $e-y$ conversions are dominant in collective neutrino oscillations as represented in previous studies. However, we find dominant $e-x$ conversions in normal mass hierarchy which are totally negligible in previous works. The $e-x$ conversions are sensitive to the baryon density outside the proto-neutron star. Therefore, such $e-x$ conversions would be characteristic behaviors of light mass progenitor such as electron capture supernovae. Furthermore, we discuss the detectability of collective neutrino oscillations in future neutrino detectors such as Hyper-Kamiokande (HK), JUNO and DUNE. We estimate spectra of ν_e and $\bar{\nu}_e$ on the earth. In inverted neutrino mass hierarchy, the spectrum of $\bar{\nu}_e$ on the earth becomes soft owing to the combination of collective neutrino oscillations and MSW H-resonances, so that the value of hardness ratio $R_{\mathrm{H/L}}$ is reduced. Such softening feature is suitable to reveal contributions of collective neutrino oscillations. HK can distinguish this effect within the 1σ Poisson error if the supernova occurs at 15 kpc from the earth. On the other hand, in normal mass hierarchy, the spectrum of ν_e becomes soft. DUNE can probe such softened ν_e spectrum within 4 kpc, but the significant reduction of hardness ratio around 100 ms can be detected even if the supernova occurs at the center of our galaxy ($\sim$ 10 kpc). The behavior of hardness ratio is opposite depending on neutrino mass hierarchies and neutrino species. Therefore, the combination of HK and DUNE is an intriguing opportunity to test the existence of collective neutrino oscillations.

In the second study, we simulate the effect of collective neutrino oscillations on the νp-process nucleosynthesis in proton rich neutrino driven winds. The number flux of energetic $\bar{\nu}_e$ is raised by collective neutrino oscillations in a 1D explosion model of a $40M_\odot$ progenitor. In the later wind trajectory at 1.1 s post bounce, abundances of p-nuclei are enhanced remarkably by $\sim 10 - 10^4$ times in normal mass hierarchy and p-nuclei are synthesized up to ^{124,126}Xe and ^{130}Ba. On the other hand, in the early wind model at 0.6 s, collective neutrino oscillations are prominent in inverted mass hierarchy irrespective of the reverse shock. Thus the νp-process nucleosynthesis is enhanced in inverted mass hierarchy. We simulate both cases with and without the reverse shock in the early wind model. Outside the reverse shock, the wind temperature becomes nearly constant in the temperature region for the νp-process ($T \sim 1.5 - 3.0 \times 10^9$K), which multiplies oscillation effects and results in more abundant p-nuclei. The averaged overproduction factor of p-nuclei is dominant in the later wind model if we remove the reverse shock in the early wind model. However, the contribution of the early wind model becomes large if we take into account the reverse shock. Especially, the averaged overproduction factors of p-nuclei in the range of $A = 84 - 108$ are enhanced in inverted mass hierarchy owing to the reverse shock effect. Our result demonstrates that collective neutrino oscillations can strongly influence on the νp-process, which indicates that they should be included in nuclear network calculations in order to obtain precise abundances of p-nuclei. Our finding would help understand the origin of solar-system isotopic abundances of p-nuclei such as ^{92,94}Mo and ^{96,98}Ru.