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Collective Neutrino Flavor Oscillations And Supernova Nucleosynthesis In Proton-rich Gas Flows

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In core-collapse supernovae, non-linear effects are caused by self-interacting neutrinos emitted from the proto-neutron star. These many-body effects induce collective neutrino oscillations and dramatic flavor changes in neutrino fluxes which will have crucial effects on ν-process in outer layers or explosive nucleosynthesis such as r-process and νp-process in neutrino-driven winds. We have studied collective neutrino oscillations in the realistic 3 flavor multi-angle calculation using the simulation data of 1D explosion model. We have also applied these oscillation results to the nucleosynthesis in a proton-rich gas trajectory consistently. Especially, in normal neutrino mass hierarchy, we find the enhancement of the $\bar{\nu}_e$ flux caused by collective neutrino oscillations before νp-process proceeds actively. Therefore, νp-process is triggered by more free neutrons produced by the $\bar{\nu}_e$ absorption on protons and this nucleosynthesis is successful to raise up the abundances of lighter p-nucleus such as Se, Kr, and Sr greatly. Heavier p-nucleus like ^{92}Mo and ^{96}Ru are expected to enhanced by collective neutrino oscillations in more proton-rich and slower gas flows.

1. Introduction

There are several high energy astrophysical and cosmological sites where tremendous numbers of energetic neutrinos are produced such as core-collapse supernovae, neutron star mergers, and the early universe. In such extreme celestial systems, non-linear neutrino flavor oscillations are caused by coherent scatterings of self-interacting neutrinos [1][2][3][4][5][6]. These non-linear effects seem to induce dramatic flavor transitions which play significant roles in the dynamics and the nucleosynthesis in the system.

In core-collapse supernovae, after core-bounce, energetic neutrinos are emitted from the proto-neutron star carrying away the 99 percents of gravitational binding energy of the inner core [7][8]. In cooling phase ($\sim$ 1-10 s after bounce), all species of 3 flavor neutrinos and their anti-neutrinos ($\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$) propagate outwards experiencing the neutrino self-interactions. Around 100 km from the center, all species of neutrinos begin to oscillate coherently and collectively in flavor space irrespective of their momentum [9][10][11][12]. These collective neutrino oscillations cause prominent flavor transitions. These many-body effects will contribute to the explosive nucleosynthesis such as r-process [13][14][15] and νp-process [16][17][18] in neutrino-driven winds stripped from the proto-neutron star. Current numerical simulations employing the sophisticated Boltzmann neutrino transports [19][20] suggest that neutrino-driven winds tend to be proton-rich gas flows ($Y_e > 0.5$) rather than neutron-rich gas flows ($Y_e < 0.5$). Y_e is the electron fraction which represents the number of electrons per one nucleon. In proton-rich gas flows, νp-process is triggered by $\bar{\nu}_e$ absorption on protons:

$$\bar{\nu}_e + p \to n + e^+ \tag{1.1}$$

Free neutrons produced through Eq.(1.1) induce ^{64}Ge$(n,p)^{64}$Ga instead of β^+ reaction even though the life time of ^{64}Ge is larger than the expansion time scale of the gas flow. νp-process is expected to produce p-nucleus especially ^{92}Mo and ^{96}Ru whose origins are still poorly unknown. Eq.(1.1) is a charged current reaction, so that νp-process will be enhanced by collective neutrino oscillations and heavier elements are synthesized in the proton-rich side towards the line of β stability.

2. Methods

2.1 Setup for neutrino oscillations

We adopt calculation results of a 1D explosion simulation based on the 15 $M_\odot$ progenitor model "s15s7b2"[21] and the simulation setup discussed in [22]. We assume that the system remains steady and neutrinos are emitted outwards half-isotropically. As the gas properties and neutrino initial conditions, the time profile of 1.2 s after bounce is used. We define the radius of neutrino sphere $R_\nu = 18$ km and employ the "bulb" model [9]. Table.1 represents the initial neutrino parameters. The normalized neutrino spectra $f_{\nu_\beta}(E)$ are characterized by these parameters [24]:

$$f_{\nu_\beta}(E) = \frac{E^\alpha}{\Gamma(\alpha+1)}\left(\frac{\alpha+1}{A}\right)^{\alpha+1} \exp\left[-\frac{(\alpha+1)E}{A}\right] \tag{2.1}$$

$$A = \langle E_{\nu_\beta}\rangle \tag{2.2}$$

$$\alpha = \frac{\langle E^2_{\nu_\beta}\rangle - 2\langle E_{\nu_\beta}\rangle^2}{\langle E_{\nu_\beta}\rangle^2 - \langle E^2_{\nu_\beta}\rangle} \tag{2.3}$$

where $\Gamma(x)$ is the gamma function. We executed the 3 flavor multi-angle calculation [12][23] in both normal ($\Delta m^2_{23} > 0$) and inverted ($\Delta m^2_{23} < 0$) mass hierarchies. Mixing parameters for neutrino oscillations are represented in Table 2.

	$L_{\nu_\beta}(\times 10^{51}$erg/s)	$\langle E_{\nu_\beta}\rangle$(MeV)	$\sqrt{\langle E^2_{\nu_\beta}\rangle}$(MeV)	α_{ν_β}
ν_e	2.69	10.1	10.8	5.80
$\bar{\nu}_e$	1.68	14.1	15.8	2.78
$\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$	9.09	20.7	25.3	1.04

Table 1: The parameter set of the neutrino initial conditions

$\theta_{23}(^\circ)$	$\theta_{13}(^\circ)$	$\theta_{12}(^\circ)$	$\Delta m^2_{21}(\mathrm{eV}^2)$	$\lvert\Delta m^2_{23}\rvert(\mathrm{eV}^2)$	δ(rad)
45.0	8.48	33.5	7.53×10^{-5}	2.42×10^{-3}	0

Table 2: The mixing parameters employed in the 3 flavor multi-angle calculation. Neutrino mass hierarchy (the sign of Δm^2_{23}) and the value of CP phase δ have not been determined by experiments. Here, we assume $\delta = 0$.

2.2 Time evolution of density matrices

Quantum states of neutrinos and anti-neutrinos are represented by density matrices ρ and $\bar{\rho}$ respectively [3]. We normalize the density matrices i.e., $\mathrm{Tr}\rho = \mathrm{Tr}\bar{\rho} = 1$. The diagonal components of these matrices include the information of probability. For example, $\rho_{\alpha\alpha}$ indicates the probability to find ν_α when one neutrino is observed. Neutrino oscillations are described by equation of motions (EOMs) of density matrices of neutrinos $\rho(r,E,\theta_p)$ and anti-neutrinos $\bar{\rho}(t,E,\theta_p)$[3][9]:

$$\cos\theta_p \frac{\partial}{\partial r}\rho(r,E,\theta_p) = -i\,[\rho(r,E,\theta_p), \Omega(E) + V_{\rm MSW}(r) + V_{\rm self}(r,\theta_p)] \tag{2.4}$$

$$\cos\theta_p \frac{\partial}{\partial r}\bar{\rho}(r,E,\theta_p) = -i\,[\bar{\rho}(r,E,\theta_p), -\Omega(E) + V_{\rm MSW}(r) + V_{\rm self}(r,\theta_p)] \tag{2.5}$$

where θ_p is a incidence angle between momentum $\mathbf{p}$ and radial direction. $\Omega(E)$ is a 3 flavor vacuum Hamiltonian. $V(r)_{\rm MSW}$ and $V(r,\theta_p)_{\rm self}$ are potentials derived by MSW effects [25] and neutrino self-interactions respectively.

2.3 Setup for nucleosynthesis

We employ neutrino absorption reactions on protons (Eq.(1.1)) and neutrons:

$$\nu_e + n \rightarrow e^- + p \tag{2.6}$$

We also take into account neutrino absorptions on α-particles (^{4}He) discussed in [26] and electron, positron capture reactions caused by free nucleons [27]. Neutrino oscillations have effects on the reaction rates of charged current reactions such as Eq.(1.1)(2.6). Except for these reactions, the data of other nuclear reactions and other nuclides are based on JINA Reaclib database [28]. We execute nucleosynthesis by using the *libnucnet* reaction network engine [29] and including the contributions from neutrino-induced reactions and electron, positron captures. The 3 flavor multi-angle calculation is carried out simultaneously and their effects are reflected in the nucleosynthesis consistently.

3. Results and discussions

3.1 The behaviors of collective neutrino oscillations

Fig.1 represents the evolution of angular averaged diagonal component $\langle\bar{\rho}_{ee}\rangle$ in 3 different typical energy 5.4, 15.6 and 30 MeV:

$$\langle\bar{\rho}_{ee}\rangle = \frac{2}{\pi}\int_0^{\frac{\pi}{2}} {\rm d}\theta_R\; \bar{\rho}_{ee}(r,E,\theta_R) \tag{3.1}$$

where θ_R is the emission angle on the surface of the neutrino sphere.

In normal hierarchy (the left panel in Fig.1), up to 125 km, flavor transitions are highly suppressed by the MSW effects and the synchronization of self-interacting neutrinos [9][10][11][12]. Around 125 km, collective neutrino oscillations are induced and the values of $\langle\bar{\rho}_{ee}\rangle$ are raised up irrespective of their energy. Therefore, more anti-electron neutrinos are produced by collective neutrino oscillations. As neutrinos propagate outwards, the angular dispersion of $V_{\rm self}(r,\theta_p)$ prevents the coherence in the neutrino many-body system and oscillation phenomena are smeared [10][12].

In inverted hierarchy (the right panel in Fig.1), collective neutrino oscillations occur in outer regions ($\sim$ 220 km) and their oscillation amplitudes are small. In multi-angle calculations, such delayed oscillations are observed in previous numerical studies [12][23] [30]. Nucleosynthesis in the multi-angle calculation causes crucial differences from the nucleosynthesis within the single-angle approximation [30]. Around 600 km, fluxes of neutrinos are weaken, so that collective neutrino oscillations are no longer effective. Instead, dramatic flavor transitions are induced by the coupling of the MSW resonance and solar vacuum frequency $\omega_{\rm solar} \equiv \Delta m^2_{21}/2E$.

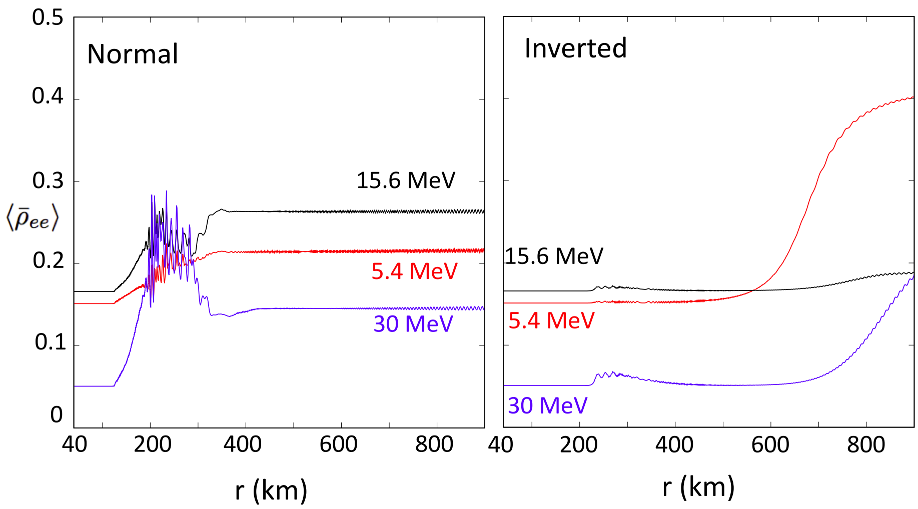

Figure 1: The left (right) panel shows the evolution of the angular averaged diagonal component $\langle \bar{\rho}_{ee} \rangle$ in normal (inverted) hierarchy.

3.2 The enhanced νp-process

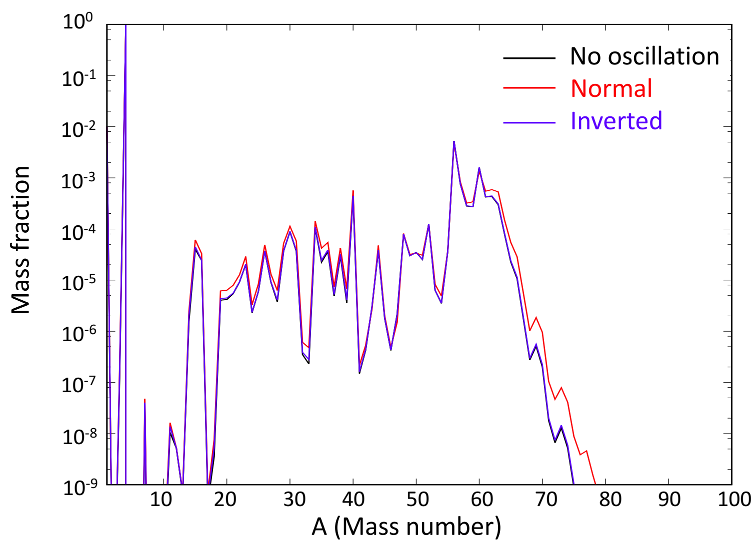

Figure 2: The mass fractions of nuclides with respect to the mass number A at 900 km. The inverted hierarchy case are corresponding to the no oscillation case completely. In normal hierarchy, mass fractions of heavier nucleus are raised up by 2-10 times because of the enhanced νp process.

Around the proto-neutron star ($\sim$20 km), the electron fraction Y_e is increasing significantly through Eq.(2.6). As a neutrino-driven wind is blown outwards, the gas velocity continues to increase. On the other hand, number fluxes of neutrinos keeps decreasing as neutrinos propagate far away.

Therefore, in outer regions, neutrinos can not heat materials enough to raise Y_e. Finally, around 50 km, Y_e has reached nearly a constant value. In our simulations, the neutrino-driven wind becomes a proton-rich gas flow ($Y_e \sim 0.505$). In high temperature regions ($T > 1$ MeV), only neutrons and protons exist. As the temperature of the gas flow decreases ($T < 1$ MeV), more α-particles are created consuming both neutrons and protons. Through $3\alpha \rightarrow ^{12}$C, $2\alpha + n \rightarrow ^{9}$Be and α-capture reactions, heavier elements are synthesized. After the α-particle creation, the absorption on protons Eq.(1.1) and on α-particles:

$$^{4}\mathrm{He} + \nu \rightarrow\ ^{3}\mathrm{He} + n + \nu' \tag{3.2}$$

are main sources of free neutrons which induce νp-process. Fig.2 describes the pattern of mass fractions of nuclides at 900 km where only β reactions and very weak neutron capture reactions are coupled with nucleosynthesis. In normal hierarchy, more heavier elements ($A > 64$) are produced by oscillation effects. On the other hand, in inverted hierarchy, oscillation effects are completely negligible. In our gas trajectory, νp process is dominant during $T = 2.0 \sim 3.3 \times 10^9$ K which is equivalent to $r = 180 \sim 400$ km. In normal hierarchy, collective neutrino oscillations occur before νp process proceeds actively, so that increasing $\bar{\nu}_e$ flux caused by collective neutrino oscillations is successful to enhance νp process. In inverted hierarchy, however, νp-process has already finished and oscillation effects are highly suppressed when the significant flavor transitions are induced by the MSW resonances and ω_{solar} effects.

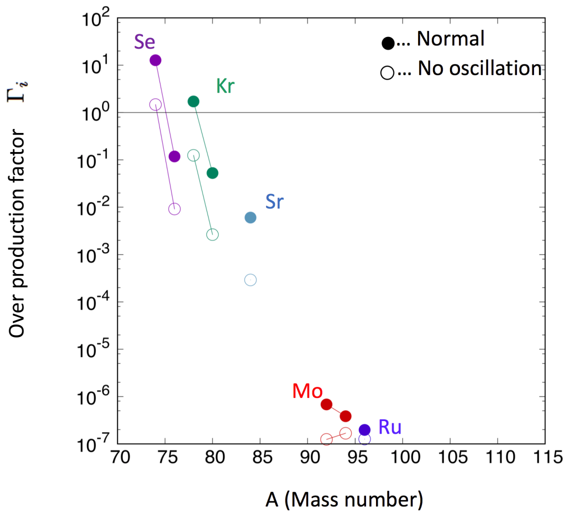

Figure 3: Over production factors of p-nucleus. Open circles show the no oscillation case. Filled circles shows the normal hierarchy case and they are raised up by collective neutrino oscillations especially in lighter nucleus Se, Kr and Sr.

The over production factor Γ_i for the nuclei i is useful quantity to compare obtained nuclear abundances with their solar abundances. Γ_i is defined by:

$$\Gamma_i = \frac{X_i}{X_{i,\mathrm{solar}}} \Big/ \frac{X_{^{56}\mathrm{Fe}}}{X_{^{56}\mathrm{Fe,solar}}} \tag{3.3}$$

where X_i is the final mass fraction of nuclei i after the all unstable particles settle down into stable nuclides. $X_{i,\mathrm{solar}}$ is the mass fraction of nuclei i in the solar system [31]. It is regarded that enough nuclei i are produced in the neutrino-driven wind to explain the solar abundance of nuclei i if Γ_i exceeds unity. Fig.3 shows the over production factors of p-nucleus. We find that lighter p-nucleus Se, Kr and Sr tend to be enhanced by collective neutrino oscillations greatly. However, heavier ^{92}Mo and ^{96}Ru are not so raised up ($\sim$several factors) and their over production factors are far from unity. In both no oscillation and normal hierarchy cases, the nuclear flows on the chart of nuclides have reached the stable $N = 50$ line, but they can not exceeds this stability line even though νp-process is enhenced by collective neutrino oscillations. Therefore, there is no crucial difference between both cases in heavier p-nucleus. Our gas trajectory is not so proton-rich gas flow ($Y_e \sim 0.505$), so that poorly target protons for Eq.(1.1) fail to enhance heavier nucleus prominently. It seems that in more proton-rich and slower gas flows, νp-process will proceed more actively and oscillation effects become more sensitive to nucleosynthesis [32].

4. Summary

We have studied the collective neutrino oscillations and their application to nucleosynthesis in a neutrino-driven wind. We find that in both hierarchies, anti-electron neutrinos are raised up by collective neutrino oscillations and other contributions from the MSW effects and the solar vacuum frequency ω_{solar}. In normal hierarchy, collective neutrino oscillations can enhance νp-process because significant flavor transitions occur before νp-process becomes dominant in nucleosynthesis. In inverted hierarchy, however, dramatic flavor transitions are induced after the νp-process, so that oscillation effects are nearly negligible towards the nucleosynthesis. In our mildly proton-rich gas flow ($Y_e \sim 0.505$), collective neutrino oscillations contribute to the enhancement of lighter p-nucleus such as Se, Kr and Sr.

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