EFFECTS OF SHOCK PROPAGATION ON NEUTRINO OSCILLATION AND ν-INDUCED NUCLEOSYNTHESIS IN SUPERNOVA*

Heamin Ko[a], Myung-Ki Cheoun[a,b,c], Motohiko Kusakabe[b,c]
Toshitaka Kajino[b,c,d], Basak Ekinci[e], Yamac Pehlivan[e]

[a]Department of Physics and OMEG Institute, Soongsil University
Seoul 07040, Korea
[b]National Astronomical Observatory of Japan, Mitaka
Tokyo 181-8588, Japan
[c]School of Physics and Nuclear Energy Engineering
and International Research Center for Big-Bang Cosmology and Element Genesis
Beihang University, Beijing 100083, China
[d]University of Tokyo, Bunkyo-ku, Tokyo 113-0033, Japan
[e]Department of Physics, Mimar Sinan Fine Arts University
Istanbul 34380, Turkey

(Received December 19, 2018)

We discuss effects of shock propagation on neutrino (ν) oscillation in supernova environment, which affects directly ν-induced nucleosynthesis. Since electron number density varies rapidly behind and in front of the shock, multiple resonances of mixing angles by adiabatic and/or non-adiabatic electron density change can occur during the shock propagation. In this work, we report detailed analysis of the ν oscillation in matter and the ν-induced nucleosynthesis by the shock propagation. The shock effects increase abundances by about 16% of ^{138}La, 14% of ^{92}Nb and 7% of ^{98}Tc, whose main synthesized region is O–Ne–Mg layer in our supernova model. Here, we adopt a simple thermal bomb hydrodynamic model and the normal ν-mass hierarchy.

DOI:10.5506/APhysPolB.50.385

1. Introduction

Since the discovery of all neutrino (ν) mixing angles and their partial mass differences which properly elucidated the ν oscillation in free space, understanding of the ν oscillation in matter [1] has been extensively discussed in neutrino physics as well as astrophysics. In particular, supernova

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 26–September 2, 2018.

(SN) neutrinos are supposed to propagate in a dense matter shocked by the core collapsing SN explosion and change their flavors. Most of the calculations assumed that variations of matter density by the shock (SH) propagation do not affect so much the ν properties during the propagation if the SH propagation is adiabatic. However, some hydrodynamic (HD) models employed in the SN explosion calculation may have some non-adiabatic as well as adiabatic properties in the SH propagation. In this paper, we try to understand quantitatively the effect of the SH propagation in the ν process.

Already there appeared many analytical studies about the ν oscillation taking into account the adiabatic or non-adiabatic ν-matter eigenstates due to the shocked matter density [2–5]. These studies have been applied to the Sun in order to solve the solar neutrino problem more precisely because the solar electron density (n_e) is known to slowly vary. For non-adiabatic change of density, the Landau–Zener (LZ) crossing formula [4], $P = \exp(-\pi\gamma/2)$, is very useful for the ν-flavor transition in matter, which implies a kind of transition (or flavor-flip) probability among the ν-matter states by the non-adiabatic change of matter. The γ is an adiabatic parameter depending on the adiabaticity, *i.e.* whether they are adiabatic or non-adiabatic process. The ν-mixing stemming from the adiabatic parameter is calculated by the diagonalization of the total neutrino Hamiltonian including the varying matter density. Through the LZ formula, we can determine whether the ν-mass eigenstates are mixed and the flavor transition probability is flipped or not, *i.e.* undergoes non-adiabatic process for a given density profile [5]. This ν flip-probability has been analytically discussed in Refs. [3, 4].

Understanding of ν oscillation in matter is not just limited to the purpose of solving the solar-ν problem, but also unavoidable for explaining the ν-induced nucleosynthesis [6, 7] as well as the ν detection on Earth [8]. In this study, we focus on the ν oscillation in matter owing to the SH propagation during SN explosion. It turns out that the n_e profiles given by the HD models play a crucial role of inducing the ν-flavor flip due to the SH in the ν-oscillation resonance region and affect the subsequent ν process.

2. Neutrino oscillation by shock wave propagation

Here, we adopt the SN 1987A model, which has 6 $M_\odot$ He-core [9]. The reaction network for the explosive nucleosynthesis calculation is the same as that used in Ref. [7]. In this study, the most effective physical quantity is the density profile during the SN explosion given by adopted HD models, for which we use the public **blcode** with the initial density profile in Ref. [9]. This HD result [10] is derived assuming a simple thermal bomb based on a spherical symmetric Lagrangian HD, whose result is shown in Fig. 1 (a). For the ν-oscillation calculation, we adopt the standard ν-mixing and mass parameters in free space from Ref. [11] and perform calculations for 3-flavor neutrinos within the normal mass hierarchy (NH). With our model parameters, the level cross diagrams for adiabatic approximation are presented in Fig. 1 (b).

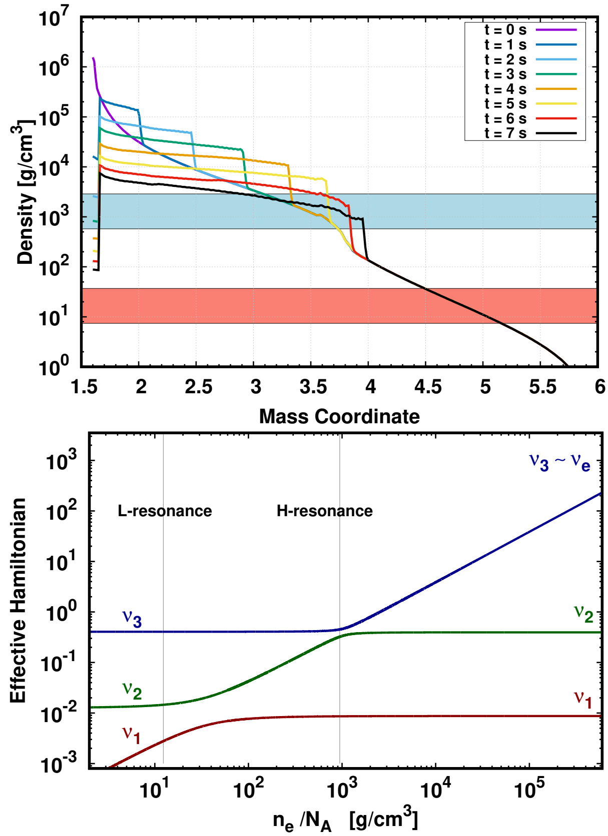

Fig. 1. (Color online) Baryon density during shock propagation for $t = 0, 1, \ldots, 7\,\mathrm{s}$ in the upper panel (a). Gray/blue and dark gray/red shaded regions mean high and low resonances for 10 MeV $< E_\nu <$ 50 MeV. The lower panel (b) shows the level crossing diagrams with the eigenvalues of diagonalized effective Hamiltonian via n_e per Avogadro number, where the NH is used for $E_\nu = 15$ MeV.

2.1. Non-adiabatic and adiabatic flavor conversion

When the Hamiltonian varies slowly, quantum states follow the adiabatic theorem. However, during SN explosion, because of the SH propagation, the n_e proportional to the baryon density can be changed rapidly, so that the neutrino (quantum) eingenstates can be mixed because of the rapid variation in n_e. A change of the mixing angle can be large enough to neglect the non-adiabatic property due to the small mixing angle (SMA) in Ref. [12]. The adiabatic condition is given as follows:

$$\Delta E \times \Delta t \gg \hbar\,, \tag{1}$$

where ΔE means an energy transition gap between matter states and $\Delta t = \Delta r/c = \frac{\delta n_e}{n_e}(n_e/\frac{\mathrm{d}n_e}{\mathrm{d}r})/c$ is transition time. During the ν oscillation in matter, the suddenly varied density profile does not cause a full flavor-conversion in the resonance region, which is called ν-flip probability [5]. In the resonance region, the adiabatic parameter γ is defined as [4]

$$\gamma = \frac{\Delta m_{ij}^2}{2E_\nu}\frac{\sin^2 2\theta_{ij}}{\cos 2\theta_{ij}}\frac{n_e}{\mathrm{d}n_e/\mathrm{d}r}\,, \tag{2}$$

where Δm_{ij}^2 and θ_{ij} are squared mass differences and vacuum mixing angles. The high (H) resonance is for the case of $i = 3$ and $j = 1$. For $\gamma \gg 1$, the resonance follows the adiabatic approximation (adiabatic theorem), by which a strong flavor transition occurs and the flavor-flip probability is nearly zero. However, in the case of $\gamma \approx 1$ or < 1, the states can be mixed so that the ν-flavor transition does not fully occur, *i.e.* non-adiabatic.

2.2. Flavor transition probability

Our results of the ν oscillation at $t = 0$ and $t = 3$ s are shown in Fig. 2. Panel (b) shows the multiple resonances for electron neutrino at $t = 3$ s after SH propagation.

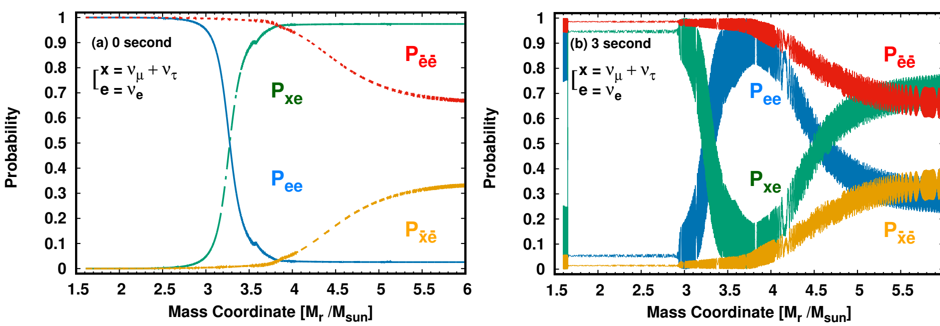

Fig. 2. Flavor transition probabilities at $t = 0$ s (a) and $t = 3$ s after the shock (b), respectively, for $E_\nu = 15$ MeV in the NH.

We obtain the flavor transition probabilities among electron, muon and tau ν flavors. The first resonance occurs in the inner region near 1.65 $M_\odot$ because the n_e in the present model decreased just after the SH and reached a resonance density. In the region near the resonance, the adiabatic parameters are $\gamma \approx 1.63$–4.8, so that the flavor transition is not totally operative. However, these values are large enough to neglect the non-adiabatic process because, if we take a linear density profile for n_e, the flip probability

$P_{\rm f} = \exp(-\frac{\pi}{2}\gamma)$ can be applicable and its value is $8\times10^{-2} \sim 5\times10^{-4}$. However, if we take other density profiles [5], the probability can be changed more or less.

Nevertheless, as a result of the first ν-flavor transition at $M_{\rm r} = 1.65\ M_\odot$, the electron neutrinos become more energetic due to the flavor change stemming from the mostly adiabatic SH before the next flavor transition (ν resonance). In the region around 3.3 $M_\odot$, the 2$^{\rm nd}$ ν-flavor oscillation occurs and the electron neutrino returns to its initial flux before the third resonance near to 4.7 $M_\odot$. The interesting point in this HD model is that the first resonance resembles the MSW region estimated by the other HD model used in our previous calculation [7]. These resonance effects are reflected in results of the ν process in Fig. 3.

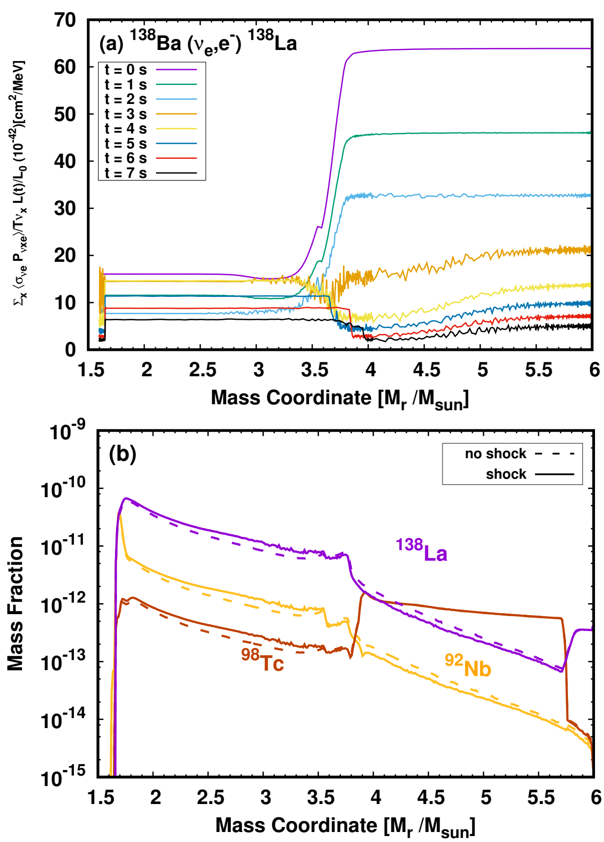

Fig. 3. Reaction rates of ^{138}Ba$(\nu_e, e^-)^{138}$La multiplied by $4\pi r^2$ and divided by initial ν luminosity at $t = 0, 1, \ldots, 7$ s (a) and abundances of ^{92}Nb, ^{98}Tc and ^{138}La in the case with and without shock propagation effect on ν oscillation (b).

2.3. Neutrino-induced reactions for nuclei

For charged- and neutral-current reactions induced by neutrinos for the nuclei, we used a QRPA model [13] for the cross sections and a Hauser–Feshbach calculation by the CCONE nuclear reaction calculation code for decay channels of the compound nuclei [14]. This QRPA method has been successfully applied to describe the relevant neutrino-induced reactions, not only for light nuclei [15], but also for heavy nuclei such as, ^{138}La and ^{180}Ta [16].

We generated ground and excited states of a target nucleus by applying a one-quasiparticle creation operator to an even–even core nucleus that was assumed to be in the Bardeen–Cooper–Schrieffer ground state. We include neutron–proton (np) pairing as well as neutron–neutron and proton–proton pairing correlations to treat odd-A and odd–odd nuclei in the same framework. In medium or medium-heavy nuclei, the np pairing is usually expected to contribute to some extent to the relevant transitions because of the small energy gaps between the proton and neutron energy spaces. For two-body interactions inside nuclei, the Brueckner G-matrix was employed by solving the Bethe–Salpeter equation based upon the Bonn CD potential for the nucleon–nucleon interactions in free space.

2.4. Neutrino–nucleus reaction rates and synthesized elements

The ν-flavor transition in Fig. 2 changes the ν-reaction rates in Fig. 3 (a), where y-axis means the reaction rate multiplied by $4\pi r^2$ to cancel a local dependence of the flux and divided by the luminosity at $t = 0$, L_0, in Ref. [17]. In the ν-reaction rate including the oscillation effects by the SH propagation, two physical quantities play vital roles. First is the luminosity which decreases exponentially along with the SH wave propagation time. For example, after $t = 7$ s, the ν luminosity decreases by a factor of about 10 from the initial luminosity. Second is the decreased n_e which induces the 1$^{\rm st}$ ν-oscillation resonance region and makes the higher energy ν_e flux after passing this region around $M_{\rm r} \sim 1.65\ M_\odot$ before reaching the next resonance. As shown in Fig. 3 (a), the reaction rate for ^{138}La decreased exponentially at $t = 1$ and 2 s since there are no flavor changes due to the SH propagation. However, at $t = 3$ s after SH propagation, when the ν luminosity is only 37% of the initial value, the n_e decreases to the resonance density, so that the oscillation effect increases the reaction rate. As a result, a reaction rate comparable to that at the initial SH wave is obtained in inner region. The increase in outer region above 3.6 $M_\odot$ comes from the MSW effects in the O–Ne–Mg layer.

Finally, we apply the reaction rate changed by the SH wave from $t=0$ to 7 s to the explosive nucleosynthesis calculation. Figure 3 (b) shows abundances of the synthesized elements with and without SH wave effect on ν oscillation. Inside $M_{\rm r} = 3.3\ M_\odot$, the reaction rates are increased compared to those without SH wave propagation, so that the abundances increase. However, in the region of $3.6\ M_\odot < M_{\rm r} < 4.7\ M_\odot$, where the $2^{\rm nd}$ resonance occurs, the ν spectra return to the original ν spectra and the abundances decrease, although the reaction rates decrease slightly by the SH.

3. Summary and conclusion

In this work, we argued that non-adiabatic change of matter (electron) density affects the ν oscillation in matter, which is called ν-flavor flip. The effect turns out to depend on the matter potential shape. A bomb type HD model employed in the present calculation has a steep decrease in n_e just behind the shock passage, which gives rise to a resonance at $M_{\rm r} = 1.6\ M_\odot$. Because of the suddenly decreasing electron density, the non-adiabatic process or the ν resonance occurs at the early SH propagation time. In fact, even in this region, adiabatic property dominated the SH property. This increased the electron ν density by about 10%, and affects the heavy ν-elements nucleosynthesis because the luminosity was not lost so much as that at $t = 3$ s. Finally, this effect has been applied to the neutrino-process, especially, for the elements related to ν-induced reactions. The abundances are increased by about 7% at least and 16% at most. However, this effect depends strongly on the HD model. The collective oscillations are not taken into account because in the NH scheme they do not play a role. Detailed results will be presented elsewhere.

This work was supported by the National Research Foundation of Korea (grant Nos. NRF-2015K2A9A1A06046598 and NRF-2017R1E1A1A01074023).

REFERENCES

[1] S.P. Mikheev, A.Y. Smirnov, *Nuovo Cim. C* **9**, 17 (1986).
[2] M.M. Guzzo, J. Bellandi, V.M. Aquino, *Phys. Rev. D* **49**, 1404 (1994).
[3] S.J. Parke, *Phys. Rev. Lett.* **57**, 1275 (1986).
[4] T.K. Kuo, J.T. Pantaleone, *Phys. Rev. D* **39**, 1930 (1989).
[5] A.S. Dighe, A.Y. Smirnov, *Phys. Rev. D* **62**, 033007 (2000).
[6] T. Yoshida *et al.*, *Astrophys. J.* **686**, 448 (2008).

[7] T. Hayakawa *et al.*, *Phys. Rev. Lett.* **121**, 102701 (2018).

[8] S. Kawagoe *et al.*, *Phys. Rev. D* **81**, 123014 (2010).

[9] T. Shigeyama, K. Nomoto, M. Hashimoto, *Astron. Astrophys.* **196**, 141 (1988).

[10] M. Kusakabe *et al.*, submitted to *Astrophys. J.*, 2018.

[11] K.A. Olive *et al.* [Particle Data Group], *Chin. Phys. C* **38**, 090001 (2014).

[12] A.Y. Smirnov, *Phys. Scr.* **T121**, 57 (2005).

[13] M.-K. Cheoun *et al.*, *Phys. Rev. C* **85**, 065807 (2012).

[14] O. Iwamoto *et al.*, *Nucl. Data Sheets* **131**, 259 (2016).

[15] M.-K. Cheoun *et al.*, *Phys. Rev. C* **81**, 028501 (2010).

[16] M.-K. Cheoun *et al.*, *Phys. Rev. C* **82**, 035504 (2010).

[17] T. Yoshida, M. Terasawa, T. Kajino, K. Sumiyoshi, *Astrophys. J.* **600**, 204 (2004).