Supernovae and neutron stars: playgrounds of dense matter and neutrinos

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Abstract. Core-collapse supernovae are vital as the birthplace of compact objects, where one expects various phases of the dense matter. The current status of supernova studies with the nuclear data for dense matter and neutrino reactions is overviewed with a focus on recent progress of the neutrino-radiation hydrodynamics in two- and three-dimensions and remaining mysteries. In addition to its importance for the explosion mechanism, the equation of state is also essential to predict the neutrino bursts, which can be used to probe deep inside the compact objects. It is valuable to discuss variations of the extreme conditions for hyperons and quarks in central objects during explosive phenomena by looking into the pattern of neutrino signals in relation with dynamics and dense matter.

1. Introduction
Core-collapse supernovae occur through dynamical stages: collapse, bounce and explosion with the birth of compact objects. Despite extensive studies for decades, the explosion mechanism of core-collapse supernovae is still elusive [1, 2]. Starting with a central Fe-core of massive stars of about 20M$_\odot$, electron captures and photo dissociation trigger the gravitational collapse with production of neutrinos. Those neutrinos frequently scatter due to high density and are trapped inside the core during the collapse. Further collapse leads to the core bounce and a shock wave is launched. If the shock wave successfully propagates, it leads to the explosion with gigantic energy of $10^{51}$ erg. In the center, a hot proto-neutron star is born, which contains plenty of trapped neutrinos. The proto-neutron star emits a bunch of neutrinos, carrying away most of the gravitational energy of $10^{53}$ erg. A cold neutron star is born afterward and evolves through the long cooling phase.

One of the main questions in the conference is where the exotic phase may appear in these processes. To answer this important question, we need to solve a difficult problem from the launch of shock wave, the propagation in the Fe core for the explosion and the following history of compact star. It is rather difficult to get explosions in numerical simulations, though, because the shock wave stalls on the way during the propagation of shock wave. The shock wave must propagate through the outer part of Fe core, where the initial shock energy is used up by Fe dissociation. About 100 ms after the bounce, the shock wave stalls at around 100 km above the nascent proto-neutron star, which emits neutrinos from the reservoir of trapped neutrinos. A portion of the outgoing neutrinos are absorbed by the material just behind the shock wave through neutrino absorption on nucleons. The amount of energy transfer from neutrinos to matter is about $10^{51}$ erg, which is comparable to the explosion energy. This
idea of the neutrino heating mechanism [3, 4] is one of the main scenarios for the supernova explosion. However, this effect is sensitive to the neutrino energy and flux from the central object and depends on the dynamics such as the amount and duration of accretion for the heating [5]. After the longstanding development of first-principle-type simulations of neutrino-radiation hydrodynamics, recent simulations under the spherical symmetry (1D) show that no explosion is obtained for most of massive stars with detailed nuclear physics except for specific cases [6, 7].

The essential factor to tackle the obstacle to the explosion is the effect of hydrodynamical instabilities. The combination of neutrino heating and hydrodynamical instabilities assists to obtain successful explosions. For example, the shock wave is launched further away in some directions due to the deformation of shock wave and this results in a longer falling time of material for the heating. The convection makes the fluid flow stay long around the heating region in addition. These effects seen in two- and three-dimensional (2D and 3D) simulations contribute to turn the stalled shock wave into a successful explosion even when the 1D simulation fails [8, 9, 10, 11, 12].

There are remaining issues in supernova studies, though, having successful 2D and 3D simulations: the main trigger in the complicated dynamics with neutrinos, preference in 2D or 3D, reason for too small explosion energy (e.g. [11]). It is necessary to clarify the remaining mysteries by performing the full simulations by combining nuclear physics (equation of state and neutrino reactions) and astrophysics (hydrodynamics, neutrino transfer and general relativity) into the supercomputing technology. In this contribution, I focus on the two topics: neutrino transfer to evaluate the neutrino heating and equation of state to examine the influence of nuclear physics.

2. Neutrino Transfer

Neutrino transfer is important to determine the precise amount of neutrino heating in the 2D/3D hydrodynamics. It is necessary to evaluate the neutrino flux and heating through trapping, emission and absorption of neutrinos. This is a difficult task since one must describe the detailed transport and reactions of neutrinos in the intermediate region for the neutrino heating covering the two limiting regimes from diffusion to free-streaming. In the central part of supernova core, frequent reactions and scattering occur at high density and temperature so that the diffusion approximation can be applied. In outer layers of the core at low density, neutrinos propagate without any reaction so that the free-streaming limit can be applied. However, the important region for neutrino heating lies between the two regimes [13]. Therefore, it is mandatory to solve the Boltzmann equation (or its equivalent form), which has been a formidable task so far in 2D/3D.

Recently, we have developed the numerical code to solve the Boltzmann equation in six-dimensions (6D) [14]. 6D means 3D space and 3D neutrino momentum (energy and two angles to designate the propagating direction). We solve the Boltzmann equation directly to handle the time evolution of neutrino distribution in 6D with advection and reactions. Most important and difficult part is the collision term having energy- and angle-dependent reaction rates of neutrinos. The equation is stiff having largely different time scales for the reactions, non-linear with pair processes and frame dependent. It is necessary to handle conversion of the reaction rates between co-moving and laboratory frames. Therefore, it needs a huge computational load to handle the whole framework and various approximations have been adopted. For example, the diffusion approximation used inside the core is often extended to its outer region. Another popular approximation is the ray-by-ray method for 2D/3D. In this scheme, one solves the 1D spherical problem, which can be done in the basis of the first principle calculation, along the radial ray independently for various directions. However, the supercomputing power nowadays enables us to handle the 6D Boltzmann equation [14]. Using this new code, we have made...
comparison of the neutrino transfer in 3D supernova cores with that in the ray-by-ray method [15]. We found that there are underestimate and overestimate, depending on the radial direction, of about 20% in local neutrino heating rate due to the approximation.

Utilizing this Boltzmann solver, we have developed the numerical code for neutrino-radiation hydrodynamics in multi-dimensions [16]. The 6D Boltzmann equation is coupled with hydrodynamics and gravity in 2D with axial symmetry. The extension of the code to 3D supernovae is now under development. The Boltzmann part contains special relativistic effects such as the Dopper effect and angle aberration. The framework is partially general relativistic having the moving mesh method to handle wobbling motion of central compact object [17]. This code enables us to follow the evolution of neutrino transfer and fluid flow in the whole regime from diffusion to free-streaming. Recently we have successfully performed the long term evolution of two supernova models with the massive stars of 11M⊙ and 15M⊙ [18, 19]. These simulations are done with the Furusawa EoS table with the mixture of nuclei under the nuclear statistical equilibrium (NSE) [20] (extended version of Shen EoS [21, 22, 23]) and updated electron capture rates [24]. Although the neutrino heating works with hydrodynamical instability, the shock wave does not revive even after long evolution. We have found that no explosion occurs up to 400 ms and 600 ms for 11M⊙ and 15M⊙ models, respectively. Behavior of the shock propagation after the bounce is different in the two models depending on the progenitor profiles with different compactness (i.e. density profile). It is necessary to study further the dependence on nuclear physics under our framework. The results of additional simulations with the Lattimer-Swesty EoS [25] and other progenitors will be published elsewhere [19]. The full treatment of the neutrino-radiation hydrodynamics in 2D with the Boltzmann equation is a big step forward to the goal of the general relativistic neutrino-radiation hydrodynamics for 3D supernovae.

3. Equation of state

Data tables of equation of state (EoS) are necessary ingredient for supernova simulations. To cover the wide range of density, temperature and electron fraction, one needs to utilize a consistent framework for matter and nuclei with constraints from experimental data of nuclei and observational data of neutron stars. The number of available EoS tables for supernovae is increasing, but still limited as compared to that for neutron stars. The two major EoS tables: Lattimer-Swesty EoS (LS) [25] and Shen EoS (Shen) [21, 22, 23] have been used for many simulations. Recently, improvement of EoS tables is in progress with updates of nuclear interactions, treatment of multi-composition of nuclei under NSE and extensions to include hyperons and quarks [26].

I discuss the influence of EoS on the explosion with LS and Shen as examples of EoS tables [27]. LS and Shen have different symmetry energy and stiffness, being rather extreme cases in a modern sense, but using these two sets in simulations is a kind of benchmark test for the supernova problem. Maximum neutron star mass for cold neutron stars is 1.8M⊙ and 2.2M⊙ with LS and Shen, respectively. Here I choose the case of the incompressibility of 180 MeV for LS to illustrate the effects. When these sets have been applied to 1D supernova simulations, it turned out that both cases do not lead to the explosion with a small difference in the evolution of the shock wave [7]. The difference in the shock motion after the core bounce is not so large because the two cases have similar profiles at the core bounce.

In Fig. 1, the typical profiles of supernova core from the simulation of a 15M⊙ star with Shen are shown in the plane of temperature and electron fraction versus density. Due to the gravitational collapse, the central density increases up to the nuclear matter density and, consequently, the temperature increases along the adiabatic curve. The core bounce occurs just above the nuclear matter density and the temperature becomes high where the shock wave forms (0 ms of the left panel). At 150 ms after the bounce, the temperature increases high further due to the passage of shock wave through the outer layers at low densities, but the central
density does not change very much. Since the density at this stage is not yet extremely high, the difference of the EoSs turns out to be still small. Comparison using more recent EoS tables shows similar tendency [28, 29].

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**Figure 1.** Conditions of dense matter in a supernova core in the plane of temperature (left) and electron fraction (right) versus density. The snapshots are taken from the supernova core of 15\(M_\odot\) star with Shen EoS [7]. The conditions are shown for the fluid elements along the radial coordinate at 0 and 150 ms after the core bounce.

It is significant to see that neutron fraction is not yet large enough to have exotics around the core bounce as shown in the right panel of Fig. 1. During the collapse, the electron (proton) fraction decreases through the process of electron captures from the initial value (0.46 for \(^{56}\text{Fe}\)) up to the neutrino trapping. The proton fraction stays large around 0.3 at the center, because of the blocking due to neutrino degeneracy. The proton fraction gradually decreases in the limited region where neutrinos can escape through electron captures on protons. The proton fraction becomes \(\sim 0.1\) at low densities as seen in the curve of 150 ms, however, the proton fraction in the central region stays around 0.3. Therefore, the neutron fraction is not large enough, being different from the situation of neutron stars with the proton fraction less than 0.1.

Although it seems that the condition of dense matter in supernovae is not favorable, if exotic phases can appear, its effect may be drastic. For example, the appearance of quark degrees of freedom may bring successful explosions in 1D [30, 31, 32]. During the shock stall, there is a second collapse deep inside due to the phase transition and an additional shock wave is launched for the explosion. Although this scenario of the explosion by the second collapse is restricted to the soft EoS cases, which are not in accord with the 2\(M_\odot\) neutron stars, it attracts attention to quark physics as a possible way to get explosions.

In contrast to the detailed studies of EoS effects in 1D simulations, there are only a few studies by sophisticated 2D simulations to explore the influence on explosions [33, 34]. It seems that softer EoSs are favorable to have higher luminosity for neutrino heating. However, complicated system with hydrodynamical instabilities and neutrino transfer makes us still away from the clear understanding. One needs more systematic studies in 2D/3D by surveying the range...
of parameters in nuclear physics such as the symmetry energy and the incompressibility, for example.

4. Neutrino burst

The neutrino burst in proto-neutron stars and black hole formation is another subject to explore EoSs including exotic phases. In a successful explosion, a newly born proto-neutron star emits a plenty of neutrinos over $\sim 10$ seconds. About $10^4$ events of neutrinos will be detected at the terrestrial detectors such as Super-Kamiokande and LVD at Gran Sasso for a next Galactic supernova. Those neutrinos carry the information from hot and dense matter inside the compact object. Therefore, detailed studies on the signal of neutrino burst are invaluable as the probe of EoS.

The difference of EoS in stiffness and composition is reflected in the properties of the neutrino bursts. The neutrino signal evolves according to the shock passage, the thermal evolution and the accretion of material. The difference due to EoSs right after the bounce (for example, LS and Shen) is rather small due to the similar environment as discussed above [7]. If quarks appear as in [30, 31, 32], there is a clear feature in the signal of neutrino burst. In addition to the first peak from the usual shock wave, there is a second peak due to the second collapse and bounce shock. This can be a clear signal of the quark-hadron phase transition for the EoS, which has a low density threshold of the quark appearance.

Furthermore, the proto-neutron star leads to firm opportunities to probe EoS. The EoS differences become larger as the trapped neutrinos escape. Because of reduction of pressure, the proto-neutron star becomes more compact: density and temperature become higher. The difference in density profiles becomes large at late stages and central density can be different by a factor of 2–3. Temperature profiles become different accordingly. These differences are reflected to the properties of supernova neutrinos such as the average energies and luminosities [35, 36, 37]. They affect also the cooling speed and the corresponding decrease of luminosities for $\sim 20$ seconds. These differences of the neutrino signals are solid EoS probes by the terrestrial detection of neutrinos.

During the cooling evolution of proto-neutron stars, the matter becomes neutron rich due to deleptonization by emitting neutrinos. This opens up possibilities to have exotic phases such as hyperons and quarks. For example, hyperons appear at a late stage, $\sim 50$ seconds after the birth [36]. The average energy and luminosity are different from those in the nucleonic cases depending on the choice of hyperon interactions. Note that many of EoSs used so far in the previous simulations do not accord with the $2M_\odot$ neutron star mass constraint. Further careful studies are necessary to explore this delicate effect seen at the late stage where the luminosity becomes low.

Windows to see exotics may be open wider in case of more massive stars, which lead to failed-supernovae. When the Fe core mass is very large $\sim 2M_\odot$ for massive stars of $40M_\odot$, for example, there is no chance to have a successful explosion due to the total failure of the shock propagation through intense accretion [38, 39]. Matter from the outer layer of Fe core accretes onto a nascent proto-neutron star and its mass increases rapidly after the recession of shock wave. When the mass exceeds the critical mass of proto-neutron stars, which are hot and neutrino-rich, the dynamical collapse occurs and eventually the black hole is formed [40, 41]. During this evolution in $\sim 1$ second, neutrinos are emitted abundantly and will be detected by the terrestrial detectors. The event number of neutrinos from the black hole forming core-collapse is amount to $10^4$ and comparable to that of ordinary supernova neutrinos [42]. Although there is no bright optical display, there is a short neutrino burst, which informs us the black hole formation. Since the neutrinos are emitted from deep inside the collapsing central object toward the black hole, the neutrinos are probe of matter at very high density and temperature.
Figure 2. Conditions of dense matter in a failed-supernova core in the plane of temperature (left) and electron fraction (right) versus density. Trajectories of the dense matter are taken from the numerical simulation which follows the initial collapse to the black hole formation of 40M_⊙ star with Shen EoS [40]. The evolutions of conditions are shown for the fluid elements at the fixed baryon mass coordinate at the center and off-center (M_b = 0.6M_⊙).

Figure 2 shows conditions of dense matter taken from the numerical simulations of gravitational collapse of a massive star of 40M_⊙ [40]. After the core bounce, the density and temperature increase rapidly beyond the nuclear matter density, n_0 \sim 0.16 \text{ fm}^{-3}, due to the compression to support a massive proto-neutron star. The temperature at off-center location becomes high due to the shock passage with high entropy values. Because of the intense accretion of matter, the mass of proto-neutron star increases very fast and exceeds 2M_⊙. For example, it reaches the threshold for the black hole at 2.1M_⊙ for LS and 2.6M_⊙ for Shen [40]. The dynamical collapse to the black hole formation leads to extreme conditions beyond 10n_0 \sim 1.6 \text{ fm}^{-3} and 100 \text{ MeV}.

These are suitable places for exotic phase, where hyperons and quarks can appear. Note that the electron fraction stays \sim 0.3 due to the neutrino trapping and the matter is not very neutron rich in the black hole formation.

The neutrino emission till the black hole formation has a unique feature. Short duration of \sim 1 second and rapid increase of energy and luminosity are clearly different from the feature in ordinary supernova neutrinos. Average energy and luminosity increase rapidly due to the temperature increase and the persistent matter accretion. The duration is determined by the EoS stiffness, which controls the threshold mass of proto-neutron stars to the black hole formation. For example, the duration is 0.6 and 1.3 second for LS and Shen, respectively, leading to a factor of two difference between the two EoSs [40].

During the collapse toward the black hole, there is a chance to see hyperons or quarks [42, 43, 44]. When the density and temperature become high above the threshold for exotic particles, the new particles such as hyperons and quarks appear abundantly and the EoS becomes soft immediately due to the new degrees of freedom. The appearance of exotics shortens the duration of neutrino burst in general, therefore, this is a probe of exotic matter [42, 43]. Note again that the exotic EoS must be in accord with the 2M_⊙ constraint. When one adopts the EoS tables with the 2M_⊙ constraint satisfied, there may be difficulties to distinguish the exotics from
the soft nucleonic EoS cases [28]. In order to judge the appearance of exotic phases, it is necessary to examine the neutrino bursts toward the black hole formation using the new EoS tables with hyperons and quarks obtained with constraints from nuclear physics and astrophysics.

5. Extreme conditions

A wide variety of extreme conditions appear in supernovae, neutron stars and black hole formation as we have seen in the previous sections. I discuss further the characteristics of environment (density, temperature and electron fractions) in supernova explosions and black hole formations and extend discussion to the case of neutron star mergers.

The condition of hot and dense matter in supernova cores is extreme with respect to the one in our daily life, but is rather an extension from those of unstable nuclei. In fact, the density at the core bounce is just beyond the nuclear matter density and the proton fraction is around 0.3 as seen in Fig. 1. Therefore, the effort to obtain information extrapolated from experimental data of neutron rich nuclei is important. For example, there is a connection between the supernova conditions and the environment in heavy ion collisions [45, 46]. In the phase diagram of density-temperature plane, there is a region typically probed by heavy ion collisions near the boundary between nuclei and nucleonic gas or liquid. Supernova trajectories as in Fig. 1 go through near this boundary between nuclei and nucleonic gas [47], i.e. the region of cluster appearance.

When the temperature increases at a certain density, light clusters such as helium appear at the border before they are dissolved into nucleon gas from nuclei. This environment is similar to the one in heavy ion collisions. In supernova core, the light nuclei abundantly appear in such environment [48, 49]. By comparing the composition of dense matter from supernova EoS tables with the abundance of light clusters produced in heavy ion collisions, experimental data can be used to examine the composition of matter in supernovae [46]. Those light clusters including deuterons, tritons, $^3$He and $^4$He may also have impact on neutrino reactions in supernova cores. New channels of emission and absorption on light clusters may have influences on supernova explosions [50, 51, 52, 53].

In the case of black hole formation from very massive stars, conditions of dense matter attain very high density and temperature as seen in Fig. 2. Dynamical collapse to the black hole leads to extreme density beyond 10 times the nuclear matter density and temperature beyond 100 MeV. Therefore, exotic phase is expected at least just before the black hole formation. The trajectories of matter condition in collapsing dynamics move through interesting region of the QCD phase diagram. The thermal conditions may cross the phase boundary and/or the critical point depending on quark-hadron models [54].

In principle, any type of black hole forming phenomena such as collapsars for gamma ray bursts may have a chance to reach exotic phase. Density and temperature become extreme anyway just before the black hole formation because of dynamical collapse. One of such interesting scenarios is the black hole formation from a hypermassive object in merging binary neutron stars. The neutron star merger gets attention recently as a target of gravitational waves, which provides the patterns to probe the neutron star EoS, and a candidate of r-process nucleosynthesis. From inspiral motions of two neutron stars, the ensuing merging process may lead to the formation of a hypermassive neutron star, which is rapidly rotating, hot neutron star. This object eventually turns into the black hole formation. Therefore, the hypermassive neutron star is another interesting object to explore the exotic phase.

The environment inside the hypermassive object is fascinating for the exotic phase. Since the mass of the hypermassive neutron star is larger than the cold neutron star mass limit, the condition is more extreme than that of neutron stars. In the simulation of neutron star merger [55], for example, the hypermassive neutron star has the mass of $2.6M_\odot$, which is larger than the maximum mass of cold neutron stars, $2.4M_\odot$, using DD2 EoS table [28]. In Fig. 3, the condition of dense matter in the hypermassive neutron star [56] is shown in the plane of temperature and
electron fraction versus density. The density at center reaches three times the nuclear matter density to support the very massive object and the temperature becomes high beyond 20 MeV at the nuclear matter density. This situation is more extreme than the one in the supernova core seen in Fig. 1. It is remarkable that the matter is neutron rich for the wide range of densities including the high density at the center because of the neutron-richness originated from cold neutron stars. This is clearly different from the condition inside the proto-neutron star, which is less neutron rich with the trapped neutrinos as in Figs. 1 and 2. Therefore, the extreme condition in the hypermassive object is advantageous to have the mixture of exotic matter with high neutron chemical potentials.

Figure 3. Conditions of dense matter in a hypermassive neutron star in the plane of temperature (left) and electron fraction (right) versus density. The snapshots of hypermassive neutron star are taken from the neutron star merger simulation [55, 56]. The conditions are shown for the fluid elements along the polar direction (Z-axis) and on the equatorial plane (R-axis).

Through comparisons of the three cases of matter conditions in Figs. 1–3, one can see the dynamical situations of supernovae and neutron stars are playgrounds with a variety of the combination of density, temperature and electron fraction, being different from those in static and cold neutron stars. The extreme conditions in the dynamics toward black hole formation, which contain very massive objects, are fascinating for exotic phases among them. The neutron rich situation in neutron star mergers is very favorable having neutron-richness, which enhances the appearance of new degrees of freedom. Appearance of the exotic phases can be a trigger of dynamical collapse in the evolution of massive objects and may provide observational signatures of neutrinos bursts and gravitational waves. In order to pursue these possibilities, it is essential to combine the knowledge of extreme conditions with the astrophysical simulations by bridging various research fields.

6. Summary
The supernova mechanism relies on the nuclear physics such as the equation of state and the neutrino reactions. This fact becomes more apparent since it is now possible to perform neutrino-radiation hydrodynamics with the 6D Boltzmann equation. Detailed descriptions of the neutrino
transfer provide us with precise evaluation of the neutrino heating for the explosion mechanism. The equation of state is an important ingredient of physics to determine the outcome of the shock wave and the following evolution of compact objects. It also affects the neutrino bursts from the compact object born in the collapse of massive stars. The properties of neutrino signals are the valuable information to probe the EoS including possible appearance of exotic phases. The characteristics of neutrino burst in the supernova explosion and the black hole forming case are different each other in time duration and spectra, reflecting the dynamical evolution. Moreover, the neutrino signal at late stages may carry the information of appearance of exotics. Thermodynamic conditions of explosive phenomena may contain variety of extreme conditions and have a chance to access exotic phases especially at the moment toward the black hole formation. It is now important to merge efforts both from simulations and microphysics to explore interesting physics of quarks and hadrons in the QCD phase diagram.

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References
[1] Kotake K, Sumiyoshi K, Yamada S, Takiwaki T, Kuroda T, Suwa Y and Nagakura H 2012 Prog. Theor. Exp. Phys. 2012 01A301
[2] Janka H T, Melson T and Summa A 2016 Ann. Rev. Nucl. Part. Sci. 66 341–375
[3] Bethe H A and Wilson J R 1985 Astrophys. J. 295 14–23
[4] Bethe H A 1990 Rev. Mod. Phys. 62 801
[5] Janka H and M¨uller E 1996 Astron. Astrophys. 306 167
[6] Liebend¨orfer M, Mezzacappa A, Thielemann F, Messer O E, Hix W R and Bruenn S W 2001 Phys. Rev. D 63 103004
[7] Sumiyoshi K, Yamada S, Suzuki H, Shen H, Chiba S and Toki H 2005 Astrophys. J. 629 922
[8] Marek A and Janka H 2009 Astrophys. J. 694 664
[9] Suwa Y, Kotake K, Takiwaki T, Whitehouse S C, Liebendörfer M and Sato K 2010 Publ. Astron. Soc. Japan 62 L49
[10] Takiwaki T, Kotake K and Suwa Y 2012 Astrophys. J. 749 98
[11] Takiwaki T, Kotake K and Suwa Y 2014 Astrophys. J. 786 83
[12] Lentz E J, Bruenn S W, Hix W R, Mezzacappa A, Messer O E B, Endeve E, Blondin J M, Harris J A, Marronetti P and Yakunin K N 2015 Astrophys. J. 807 L31
[13] Yamada S, Janka H T and Suzuki H 1999 Astron. Astrophys. 344 533
[14] Sumiyoshi K and Yamada S 2012 Astrophys. J. Suppl. 199 17
[15] Sumiyoshi K, Takiwaki T, Matsufuru H and Yamada S 2015 Astrophys. J. Suppl. 216 5
[16] Nagakura H, Sumiyoshi K and Yamada S 2014 Astrophys. J. Suppl. 214 16
[17] Nagakura H, Iwakami W, Furusawa S, Sumiyoshi K, Yamada S, Matsufuru H and Imakura A 2017 Astrophys. J. Suppl. 229 42
[18] Sumiyoshi K, Nagakura H, Iwakami W, Furusawa S, Matsufuru H, Imakura A and Yamada S 2016 Proceedings of the 14th International Symposium on Nuclei in the Cosmos XIV ed Kubono S (Tokyo: JPS Conference Proceedings) in press
[19] Nagakura H, Iwakami W, Furusawa S, Okawa H, Harada A, Sumiyoshi K, Yamada S, Matsufuru H and Imakura A 2017 ArXiv e-prints (Preprint 1702.01752)
[20] Furusawa S, Sumiyoshi K, Yamada S and Suzuki H 2013 Astrophys. J. 772 95
[21] Shen H, Toki H, Oyamatsu K and Sumiyoshi K 1998 Nucl. Phys. A 637 435–450
[22] Shen H, Toki H, Oyamatsu K and Sumiyoshi K 1998 Prog. Theor. Phys. 100 1013–1031
[23] Shen H, Toki H, Oyamatsu K and Sumiyoshi K 2011 Astrophys. J. Suppl. 197 20
[24] Juodagalvis A, Langanke K, Hix W R, Martínez-Pinedo G and Sampaio J M 2010 Nucl. Phys. A 848 454–478
[25] Lattimer J M and Swesty F D 1991 Nucl. Phys. A535 331
[26] Oertel M, Hempel M, Klähn T and Typel S 2016 ArXiv e-prints (Preprint 1610.03361)
[27] Sumiyoshi K, Suzuki H, Yamada S and Toki H 2004 Nucl. Phys. A730 227
[28] Hempel M, Fischer T, Schaffner-Bielich J and Liebendörfer M 2012 Astrophys. J. 748 70
[29] Steiner A W, Hempel M and Fischer T 2013 Astrophys. J. 774 17
[30] Sagert I, Fischer T, Hempel M, Pagliara G, Schaffner-Bielich J, Mezzacappa A, Thielemann F K and Liebendörfer M 2009 Phys. Rev. Lett. 102 081101
[31] Fischer T, Sagert I, Pagliara G, Hempel M, Schaffner-Bielich J, Rauscher T, Thielemann F K, Käppeli R, Martínez-Pinedo G and Liebendörfer M 2011 Astrophys. J. Suppl. 194 39
[32] Nakazato K, Sumiyoshi K and Yamada S 2013 Astron. Astrophys. 558 A50
[33] Janka H T 2012 Annu. Rev. Nucl. Part. Sci. 62 407
[34] Suwa Y, Takiwaki T, Kotake K, Fischer T, Liebendörfer M and Sato K 2013 Astrophys. J. 764 99
[35] Sumiyoshi K, Suzuki H and Toki H 1995 Astron. Astrophys. 303 475
[36] Poins J A, Reddy S, Prakash M, Lattimer J M and Miralles J A 1999 Astrophys. J. 513 780
[37] Suzuki H, Kogure H, Tomioka F, Sumiyoshi K, Yamada S and Shen H 2003 Nucl. Phys. A 718 703
[38] Liebendörfer M, Messer O E B, Mezzacappa A, Bruenn S W, Cardall C Y and Thielemann F K 2004 Astrophys. J. Suppl. 150 263
[39] Sumiyoshi K, Yamada S, Suzuki H and Chiba S 2006 Phys. Rev. Lett. 97 091101
[40] Sumiyoshi K, Yamada S and Suzuki H 2007 Astrophys. J. 667 382
[41] Sumiyoshi K, Yamada S and Suzuki H 2008 Astrophys. J. 688 1176
[42] Nakazato K, Sumiyoshi K, Suzuki H and Yamada S 2010 Phys. Rev. D 81 083009
[43] Nakazato K, Sumiyoshi K and Yamada S 2008 Phys. Rev. D77 103006
[44] Sumiyoshi K, Ishizuka C, Ohnishi A, Yamada S and Suzuki H 2009 Astrophys. J. 690 L43
[45] Qin L, Hagel K, Wada R, Natowitz J B, Shlomo S, Bonasera A, Röpke G, Typel S, Chen Z, Huang M, Wang J, Zheng H, Kowalski S, Barbui M, Rodrigues M R D, Schmidt K, Fabris D, Lunardon M, Moretto S, Nebbia G, Pesente S, Rizzi V, Viesti G, Cinausero M, Prete G, Keutgen T, El Masry Y, Majka Z and Ma Y G 2012 Phys. Rev. Lett. 108 172701
[46] Hempel M, Hagel K, Natowitz J, Röpke G and Typel S 2015 Phys. Rev. C 91 045805
[47] Buyukcizmeci N, Botvina A S, Mishustin I N, Ogul R, Hempel M, Schaffner-Bielich J, Thielemann F K, Furusawa S, Sumiyoshi K, Yamada S and Suzuki H 2013 Nucl. Phys. A 907 13–54
[48] Sumiyoshi K and Röpke G 2008 Phys. Rev. C 77 055804
[49] Arcones A, Martínez-Pinedo G, O’Connor E, Schwenk A, Janka H T, Horowitz C J and Langanke K 2008 Phys. Rev. C 78 015806
[50] Nakamura S X, Sumiyoshi K and Sato T 2009 Phys. Rev. C 80 035802
[51] Furusawa S, Nagakura H, Sumiyoshi K and Yamada S 2013 Astrophys. J. 774 78
[52] Nasu S, Nakamura S X, Sumiyoshi K, Sato T, Myhrer F and Kubodera K 2015 Astrophys. J. 801 78
[53] Fischer T, Martínez-Pinedo G, Hempel M, Huther L, Röpke G, Typel S and Lohs A 2016 Euro. Phys. J. Web Conf. vol 109 p 00002 (Preprint arXiv:1512.00193)
[54] Ohnishi A, Ueda H, Nakano T Z, Ruggieri M and Sumiyoshi K 2011 Phys. Lett. B 704 284–290
[55] Sekiguchi Y, Kiuchi K, Kyutoku K and Shibata M 2015 Phys. Rev. D 91 064059
[56] Fujibayashi S, Sekiguchi Y and Sumiyoshi K 2017 in preparation