Nuclear Matter in Core-Collapse Supernovae: Insights from Simulations

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Core-collapse supernova explosions are among the most important phenomena in the universe, playing a central role in cosmic evolution and the origin of elements, and ultimately leading to the formation of neutron stars [1, 2]. In the central region of these explosions, all four fundamental forces of nature become relevant under extreme conditions. In particular, the strong interaction, which governs nuclear matter, still involves significant theoretical uncertainties, and several models of the equation of state (EOS) have been proposed to cover a wide range of densities, temperatures, and proton fractions. At the same time, neutrinos play a crucial role in transporting energy from the dense interior and in depositing part of it behind the shock, thereby contributing to the explosion mechanism. For these reasons, large-scale numerical simulations are indispensable for understanding both the explosion mechanism of supernovae and the formation of neutron stars.

There have been extensive studies by numerical simulations of core-collapse supernovae by having the rapid progress of supercomputers to solve the equations of neutrino-radiation hydrodynamics in multi-dimensions [3]. There is an emerging picture of the neutrino-driven explosion mechanism through the combination of neutrino heating and hydrodynamical instabilities [4]. During the gravitational collapse of the massive star, neutrinos are produced and trapped inside the central core due to high densities. The shock wave launched by the core bounce first propagates outward, but stalls along the way. The revival of the shock propagation toward the outside requires enough assistance of heating through neutrino absorptions on matter behind the shock wave together with the asymmetric hydrodynamical motion. This combination of neutrino heating with shock dynamics necessitates rigorous treatments of neutrino and nuclear physics in numerical simulations. Although numerical methods for astrophysical simulations are approaching the first-principles calculation by solving the Boltzmann equation and hydrodynamics under general relativity [5], investigation of uncertainties in neutrino and nuclear physics is becoming important in finding the impact of physical processes in the determination of the fate: explosion or failure.

Among various factors in the physics ingredients, the EOS of hot-dense matter is essential to determine the fate of massive stars through the computation of hydrodynamics and neutrino processes via weak interactions [6, 7]. The increasing feature of pressure (stiffness/softness) at high densities, for example, is important for the dynamics of the central core, the formation of compact objects, and the associated neutrino burst. The softness means that the matter can easily be compressed to high densities. The composition of matter, i.e. nucleons and nuclei, at low densities is also essential to evaluate the reaction rates of neutrinos, which affect their trapping and transport, and, therefore, is influential in determining the neutrino heating rates for the explosion and the emission rates of supernova neutrinos [8]. It is considered as a general tendency that the soft EOS leads to high densities and temperatures in central hot neutron stars and, therefore, to more intense emission of higher energy neutrinos, which can contribute to the increased heating of material for the shock revival [4, 2]. There are also arguments that differences other than the stiffness, such as those in composition, are influential for the explosion mechanism [9, 10, 11].

There has been progress in providing data sets of the EOS for numerical simulations of supernovae [6]. One of the recent developments is the supernova EOS data table based on the microscopic nuclear many body theories in addition to the mean field frameworks such as the relativistic mean field theory [12, 13]. The EOS data tables are constructed by utilizing the nuclear many body framework of the variational method (VM) [14, 15] and the Dirac-Brueckner Hartree-Fock (DBHF) theory [16]. They are the two representative EOSs based on the non-relativistic and relativistic frameworks, which show different properties of stiffness. The other developments are the evaluation of the composition of nuclei, based on the single nucleus approximation (Single) [14] and the nuclear statistical equilibrium (NSE) [15]. The former assumes a representative nuclide and the latter considers a mixture of various nuclides in the evaluation of matter. They provide two limiting cases of description for the mixture of nuclei, which can alter the neutrino transport. These sets of the EOS have been applied to the numerical simulations of core-collapse supernovae and cooling of proto-neutron stars [17, 18].

We focus on the effects of composition on the collapse and bounce of the supernova core [18]. We demonstrate an example of the influence of the EOS in core collapse supernovae through comparisons of VM vs DBHF and Single vs NSE. We show here the snapshots from the numerical simulations of core-collapse and bounce of the central core of a massive star of $11.2\mathrm{M}_\odot$ using the three EOS tables using DBHF and VM with NSE (DBHF, VM) and VM with Single (VM-S). In the left panel of Fig. 1, we show the proton and neutron numbers of the nuclei in the collapsing core. The main composition is the nucleus during the collapse, and neutrinos frequently scatter with the nuclei, leading to the neutrino trapping at high densities beyond $10^{11}\,\mathrm{g\,cm^{-3}}$. The amount of trapped neutrinos affects the size of the bounce core, which is the starting point of the shock wave for explosions.

The proton and neutron numbers for VM-S are larger than those for DBHF and VM and, therefore, the neutrino trapping is stronger for VM-S having larger mass number. The corresponding difference in the mass number for DBHF and VM is rather small.

In the right panel of Fig. 1, we show the initial position of the shock wave at the core bounce. The position for VM-S is at $\sim 0.6 M_\odot$ and is located at the largest mass coordinate (most outside) among three cases. The outer initial position is preferable for the success of explosion because there are energy losses due to the dissociation of the nuclei when the shock wave propagates toward the surface of the Fe core. The energy loss for $\sim 0.1 M_\odot$ of the Fe nuclei is comparable to the explosion energy of 10^{51} erg. We note that the two sets of VM-S and VM adopt the same EOS of uniform matter at high densities, and the different models (NSE and Single) for the mixture of nuclei at low densities. It is interesting to see that the difference in the initial positions between VM-S and VM is larger than that between DBHF and VM, which adopt the same model of NSE. We note also that there are effects from different rates of the electron capture on free protons and nuclei having different compositions. This is one of the examples which suggest that the composition of matter at low densities is important on the same footing as the stiffness of matter at high densities.

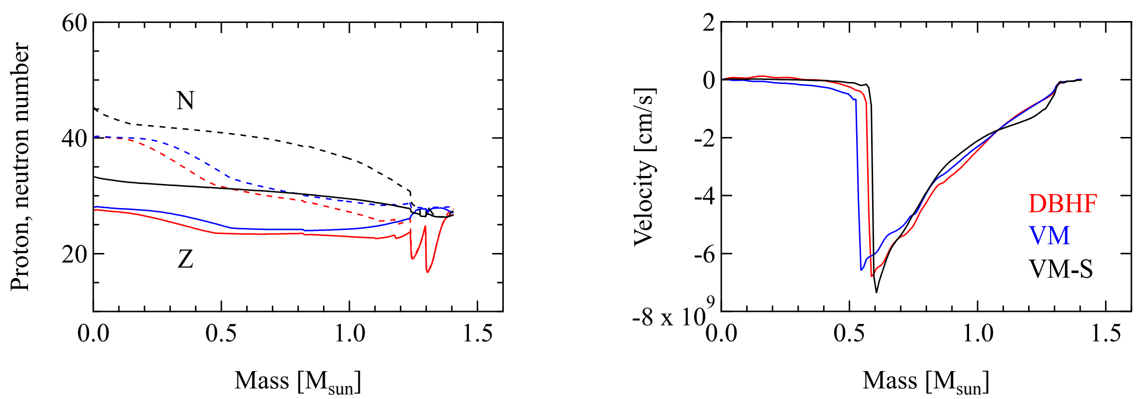

Figure 1: Snapshots from the numerical simulations of core-collapse and bounce using the three EOS tables using DBHF with NSE (DBHF, red) and VM with NSE (VM, blue) and VM with Single (VM-S, black). Left panel shows the proton and neutron numbers of nuclei as a function of the mass coordinate in the collapsing core at the central density of $10^{11}\,\mathrm{g\,cm^{-3}}$. Right panel shows the velocity as a function of the mass coordinate at the core bounce. This is the starting point of the shock wave, moving outwardly for an explosion [18].

Large numbers of neutrinos continue to be emitted even from the cooling process of a proto neutron star, which is a hot compact remnant formed after the supernova explosion [19]. This neutrino emission is largely insensitive to the detailed dynamics of the explosion itself, making it a particularly useful probe of the nuclear EOS. Since this emission persists over a much longer timescale, on the order of 10–100 seconds, directly solving neutrino-radiation hydrodynamics described above is not generally practical, due to its high computational cost. Instead, the quasi-static evolution of the proto neutron star structure is followed, with neutrino transport treated using the multigroup flux-limited diffusion scheme. This approach is computationally less demanding and is well suited for studying many different EOS models in a systematic way.

For the purpose of a systematic study, we introduce a parametric model of the nuclear EOS at supra-nuclear densities [20], characterized by different symmetry energies and incompressibilities, into proto neutron star cooling simulations. Based on 90 models with different EOS, we find that the time evolution of the neutrino luminosity (so called neutrino light curve) is mainly determined by the mass m and radius r of the neutron star and its decay timescale is expressed as [21]

$$\tau_{\rm cool} = \tau^* \left(\frac{m}{1.4 M_\odot}\right)^2 \left(\frac{r}{10\,\mathrm{km}}\right)^{-3} \frac{1}{(1-0.5\beta)\sqrt{1-2\beta}}, \tag{1}$$

with $\beta = Gm/c^2 r$, where G is the gravitational constant, c is the velocity of light, and $\tau^* \sim 35\,\mathrm{s}$ is a coefficient determined from numerical simulations. This relation is an extension of the Kelvin–Helmholtz timescale and indicates that the influence of the EOS at supra-nuclear densities is encoded in m and r, which represent global properties of the star.

In contrast, the EOS at sub-nuclear densities affects the average energy of emitted neutrinos and the decay behavior of the neutrino light curve at very late times. In this density regime, matter is no longer composed of uniformly distributed free nucleons, but instead forms heavy nuclei embedded in a dilute nucleon gas. These nuclei interact with neutrinos via coherent scattering, whose cross section scales approximately with the square of the mass number, A^2. In general, EOS models with smaller symmetry energy slope parameter L predict nuclei with larger A, leading to stronger neutrino–matter coupling. Consequently, the outer layers of the proto neutron star undergo a slower temperature decline, resulting in higher average neutrino energies and more prolonged emission at late times.

The nuclei in the outer layers of the proto neutron star are also closely related to the formation of the crust. The crust is formed as the temperature of matter decreases, and heavy nuclei crystallize into a Coulomb lattice. The temperature at which crystallization begins is determined by the strength of the Coulomb interaction and therefore becomes higher for nuclei with larger proton numbers Z. The nuclei predicted by EOS models with smaller L tend to have larger Z as well as larger A. As a result, the EOS dependence of the crust formation time is nontrivial: while enhanced neutrino–matter coupling tends to delay cooling, the larger Z raises the crystallization temperature. In such a situation, numerical simulations play an essential role in quantitatively determining which effect dominates.

To address the question outlined above, we perform proto neutron star cooling simulations employing a set of EOS models with different symmetry energies [22]. These EOS models are constructed in a unified manner in which both the uniform nuclear matter phase and the non-uniform phase are treated consistently. While the former is based on a macroscopic nuclear model [23, 24] and a parametric model [20], the latter is described within the Thomas–Fermi method under the single nucleus approximation [25, 14]. The simulation results are summarized in Fig. 2, which compares the matter temperature and the crystallization temperature. The crust is formed where the matter temperature is lower than the crystallization temperature. We find that EOS models with smaller values of L lead to earlier onset of crust formation despite the slower cooling (see the right panel of Fig. 2).

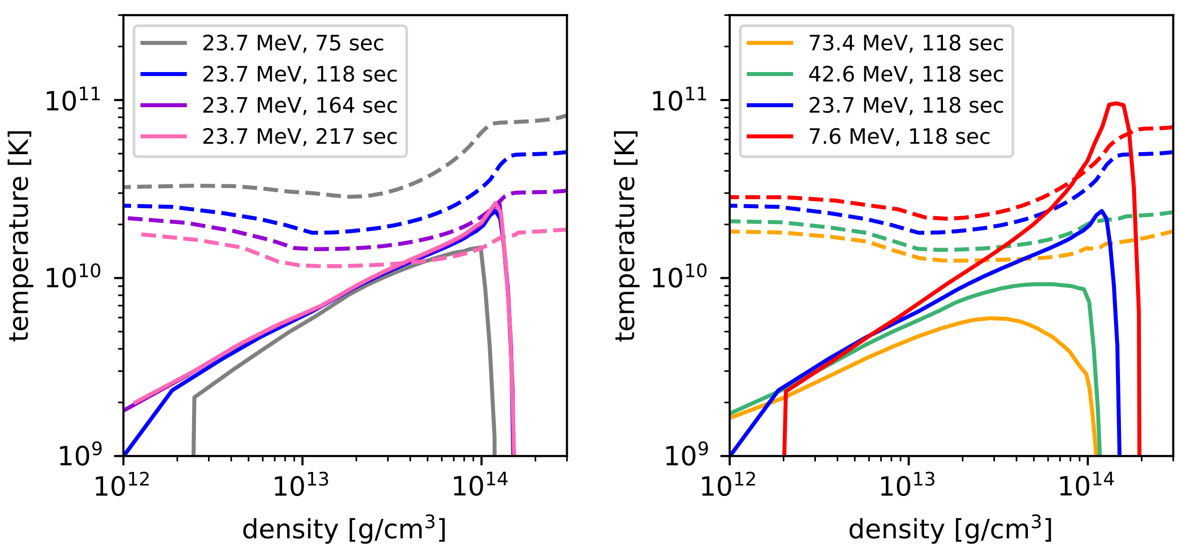

Figure 2: Snapshots of profiles of the matter temperature (dashed lines) and the crystallization temperature (solid lines) from the numerical simulations of proto neutron star cooling [22]. Left panel shows the time evolution for the EOS model with the symmetry energy slope parameter of $L = 23.7\,\mathrm{MeV}$. Right panel shows the comparison among EOS models with different L, where orange, green, blue, and red lines corresponds to the models with $L = 73.4\,\mathrm{MeV}$, $42.6\,\mathrm{MeV}$, $23.7\,\mathrm{MeV}$, and $7.6\,\mathrm{MeV}$, respectively.

Future progress in this field will rely on advances in theoretical modeling of nuclear EOS as well as large-scale simulations of general-relativistic neutrino-radiation hydrodynamics in multiple dimensions. In particular, as seen in this report, the non-uniform phase in EOS models is typically described by two main approaches: the NSE and the Thomas–Fermi method under the single nucleus approximation. The former provides a description in terms of a finite-temperature gas of nuclei, whereas the latter corresponds to a Coulomb solid relevant for the cold neutron star crust. A physically consistent picture of the time evolution would involve a smooth transition from the former to the latter. An intermediate state may appear, in which a multi-component ensemble of nuclei forms a structure analogous to a highly impure crystal. Understanding such a transition would require investigation not only from the perspective of nuclear physics but also from that of condensed matter physics.

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