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A numerical challenge on the core-collapse supernovae: physics of neutrino and matter at extreme conditions

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Abstract. Core-collapse supernovae are the explosive phenomena, which occur at the end of the life of massive stars. Despite the importance of these astrophysical events, the mechanism of supernova explosion has been a mystery even after the extensive studies for decades. The unsolved problem involves nuclear and neutrino physics at extreme conditions as well as the hydrodynamical aspects in astrophysics. The physics in femto-meter scale may change drastically the gigantic outcome of the core bounce after the gravitational collapse of the massive stars. In this contribution, I overview recent topics on the numerical challenges to clarify the supernova phenomena.

Recent advance of nuclear physics for unstable nuclei and exotic hadrons helps us to provide the nuclear data inside the supernova core. The influence of the dense matter on the explosion and supernova neutrinos has been clarified using the newly constructed data tables based on the theoretical and experimental developments. Recent studies demonstrated that the short neutrino bursts from the black hole formation in more massive stars can be a probe of exotic matter including hyperons and quarks by observations at the neutrino detector facilities. Despite the progress in nuclear and neutrino physics, no explosion is found in the numerical simulations under the spherical symmetry and hence novel effects in multi-dimensions are argued to be essential for the explosion mechanism. Toward the final goal to clarify the supernova mechanism, it is necessary to combine the best knowledge of nuclear, particle physics and astrophysics with computing science on supercomputing facilities.

1. Physics of core-collapse supernovae

Core-collapse supernova is a bright display frequently observed among astronomical events. A star becomes suddenly very bright, shines for months and fades away afterwards as in the case of a famous supernova observed in 1987 (SN1987A). These phenomena are actually the stellar explosions at the end of life of massive stars of $\sim$20M$_\odot$ [1, 2]. They are playing important roles in the Universe as the birth place of compact objects (neutron stars and black holes), the source of cosmic rays (including gravitational waves and neutrino bursts) and the driving force of the evolution of galaxies. Pulsars, which are rapidly rotating neutron stars, are found in the remnant of supernova explosion as in the case of the Crab nebula. Neutron stars have the typical mass of $\sim$1.4M$_\odot$ in the radius of $\sim$10 km, being the laboratory of extremely dense conditions. The burst of neutrinos on the occasion of SN1987A was observed at the neutrino detector facilities (ex. Kamiokande in Japan) and has led to the Nobel prize in Physics in 2002. Supernovae are also the production sites of heavy elements (for example, precious metals such as gold, platinum and uranium) through the explosive nucleosynthesis.

The explosion mechanism starts from the gravitational collapse of the Fe core of the massive star. Electron capture processes in the central core reduce the pressure support and trigger the collapse. Neutrinos are created and trapped inside the core due to high densities during the collapse. Further collapse leads to the core bounce due to the hard repulsive core of the nuclear force above the nuclear matter density, 3×10^{14} g/cm^3. The shockwave is launched and its successful propagation leads to the supernova explosion, leaving a neutron star, heavy elements and supernova neutrinos. During this episode, the gravitational energy of $\sim10^{53}$ erg is released by the contraction of the core radius down to $\sim$10 km. Most of this energy is carried away by neutrinos and accords with the total energy of the neutrino burst observed at the terrestrial detector in 1987 [2]. Note that the explosion energy of ejected material amounts to $\sim10^{51}$ erg, which is a tiny fraction ($\sim10^{-2}$) of the gravitational energy. Therefore, the energy transfer via neutrino-matter interactions is essential for the clarification of the explosion mechanism.

To attack this problem, one needs quantitative and careful studies by covering ingredients from nuclear physics in $\sim$fm scale to astrophysics in $\sim$1000 km scale. It is necessary to provide the equation of state, neutrino reactions and nuclear data from nuclear physics in order to solve hydrodynamics and neutrino transfer with stellar modeling of massive stars. One has to put all these ingredients to the numerical simulations of core-collapse supernovae on supercomputers. Therefore, this is a challenging problem of nuclear physics, particle physics, astrophysics and computational science. I focus here on the challenges on the properties of dense matter at high density and temperature. I explain that the role of neutrinos in the supernova core is important and the observation of neutrino bursts is helpful to get the information of dense core.

2. Nuclear physics at extreme conditions

The properties of dense matter at extreme conditions are necessary inputs to understand quantitatively the supernova mechanism. For example, pressure-density relation is essential to determine stellar structure and hydrodynamics. It crucially determines the maximum mass of neutron stars, which is the border to the black hole. Thermodynamical quantities such as entropy and composition (neutron, proton and nuclei) are important to determine neutrino reactions and neutrino distributions. Hence, one has to provide the data set of the equation of state (EOS) for numerical simulations of supernovae. The challenge here is to cover the wide range of conditions. Densities in the central core become higher than that inside nuclei, which is the nuclear matter density, 3×10^{14} g/cm^3. Dense matter becomes eventually very neutron rich as the neutron star contains a small fraction ($\sim$0.1) of free protons in contrast to the proton fraction of $0.46=\frac{26}{56}$ for ^{56}Fe. Temperature becomes high above 10 MeV ($\sim10^{11}$ K) during the evolution.

In order to cover consistently the wide range of environment, one has to work with the unified framework, which is checked by experimental data as much as possible. Such efforts have been made recently by the progress of nuclear physics. Together with the advance of relativistic nuclear many body theories [3] in 1990s, the experimental data of unstable nuclei provided by the radioactive nuclear beam facilities such as RIKEN are helpful for us. It is important to have new data on neutron rich nuclei in the nuclear chart in order to constrain the neutron-rich matter of neutron stars and supernovae. For example, the radii of Na isotopes have been measured systematically [4]. The radii of neutron distribution in very neutron-rich Na nuclei are found systematically larger than those of proton distribution (neutron skin). Such systematic studies are important to constrain the equation of state in astrophysics.

Based on the relativistic Brückner Hartree-Fock theory [5], the relativistic equation of state for supernovae has been obtained [6] by utilizing the experimental data of unstable nuclei to constrain the nuclear interaction [7]. The framework is based on the relativistic mean field theory with the local density approximation, which is necessary to describe the non-uniform matter distribution. The data table of the supernova EOS is constructed to cover the wide range of density, proton fraction and temperature [8]. This set of supernova EOS (Shen EOS) is available on the web and becomes very popular in the wide area of astrophysics. The Shen EOS table has been extended to the hyperon EOS with strange baryons [9] and to the quark EOS with the MIT bag model [10]. It is vital to have the experimental data of hyper-nuclei for this. Our reference is the conventional EOS by Lattimer and Swesty (LS EOS) based on the extension of the compressible liquid drop model [11]. I make comparisons by using the three EOS sets (Shen, Hyperon and LS) in the following discussion. They have different properties of dense matter such as stiffness and symmetry energy while they fulfill the basic requirement at the saturation point of nuclear matter. They give different values for the maximum mass of neutron stars due to different stiffness at high densities, for example. Having the sets of EOS newly developed, it is interesting to see the influence on the phenomena of core-collapse supernovae.

In addition to the properties of dense matter, it is mandatory to provide the rates of neutrino reactions with the dense matter in the supernova core [12]. The neutrino reactions change the number and energy of neutrinos, therefore, they contribute to the heating and cooling of matter as well as the change of composition. Numerical simulations need the implementation of neutrino reactions through the emission and absorption, the scattering with nucleons and nuclei as well as the thermal pair processes for three neutrino flavors [13]. Since the neutrino reactions proceed via the weak interaction, experiments to measure the reaction rates are difficult. In addition, the reaction rates depend on the energy and the structure of nuclei. Therefore, implementing the neutrino reaction rates is also a challenging task for the numerical simulation of supernovae.

3. Influence of equation of state of dense matter

Supernova neutrinos carry the information of dense matter in the supernova core [2]. Starting from the Fe core of a massive star of $\sim$20$M_\odot$, a proto-neutron star is born after the core bounce and the following explosion of outer layer. Since this hot object contains plenty of neutrinos, it cools down by emitting neutrinos. Due to the neutrino emission through the electron capture on protons, the object becomes neutron-rich, leading to a cold neutron star. During this cooling, a bunch of neutrinos ($\sim 10^{58}$) is emitted. They are the supernova neutrinos and were detected at the Kamiokande neutrino detector facility. In a case of the next galactic supernova, neutrino events of $\sim 10^4$ will be detected. By examining these neutrinos, one can extract the information of dense core since neutrinos are emitted from the hot and dense matter.

Numerical studies of the cooling of proto-neutron stars have been done extensively [2, 14, 15]. The neutrino burst lasts for the duration of $\sim$20 s, which is determined by the diffusion time scale of neutrinos inside the central core. The average energy and luminosity decrease gradually, reflecting the decrease of temperature of the proto-neutron star. These behaviors depend on the equation of state to determine the profile of density and temperature [16]. The time evolution of average energy is different in the comparison adopting two EOSs (Shen EOS and LS EOS, for example). Therefore, it should be possible to probe the EOS by examining the properties of the supernova neutrinos in detail (See also [15, 17] regarding exotic matter).

For more massive stars, the character of neutrino signal is different since they lead to the black hole formation promptly [18]. Starting from the Fe core of a $\sim$40$M_\odot$ star, there is no explosion intrinsically because of a large mass of Fe core [19, 20]. However, the proto-neutron star is born at center even in this case. Since the material from the outer layer accretes onto the proto-neutron star, its mass increases quite rapidly. When the mass reaches the critical mass, which is determined by the EOS, the central object dynamically collapses to the black hole. During this evolution in $\sim$1 s, neutrinos are emitted from the proto-neutron star until the black hole formation [21]. In this event, there is no optical display but the burst of neutrinos.

There will be 10^4 events of neutrinos, which are comparable to the case of ordinary supernova neutrinos, expected at the Super-Kamiokande for this kind of failed supernovae [22]. Hence, this is also a chance to probe the EOS at high density and temperature. Moreover, this is a new way to find the black hole formation. A black hole candidate corresponding to this scenario was discovered [23] and a systematic survey of failed supernovae is planned [24].

The properties of neutrino burst until the black hole formation are different from those of the ordinary supernovae. The duration of the burst is short within 1 s in contrast to 20 s for ordinary supernovae. The energy and luminosity increase rapidly due to fast increase of temperature of the intensively accreting proto-neutron star. For example, Figure 1 shows the time evolution of the average energies of neutrinos obtained from the numerical simulation of neutrino-radiation hydrodynamics [21, 25]. The average energy becomes very high after the core bounce for all cases. The neutrino bursts stop at 1.3 and 0.6 s for Shen EOS and LS EOS, respectively. The softer EOS leads to the smaller critical mass for the collapse, therefore, it leads to the earlier collapse and the shorter burst [18, 21]. Therefore, the neutrino burst from the failed supernovae can be used to probe the softness of EOS in a clear manner.

Since the proto-neutron star becomes massive, the temperature and density become high quickly. This leads to the appearance of exotic particles of hadrons and quarks. By performing the numerical simulation with the hyperon EOS, it is found that the hyperons appear abundantly at ∼0.5 s after the bounce [25]. The appearance of hyperons triggers the dynamical collapse to the black hole from the proto-neutron star because of additional softening of the EOS. The duration of the neutrino burst from the failed supernovae becomes shorter with the hyperon EOS (0.7 s) as compared to the case with the nucleonic Shen EOS (1.3 s) as in Fig. 1. Therefore, it should be possible to probe the emergence of hyperons by examining the duration of the neutrino burst and the rise of energies for different flavors by the detection of neutrinos at the Super-Kamiokande [26].

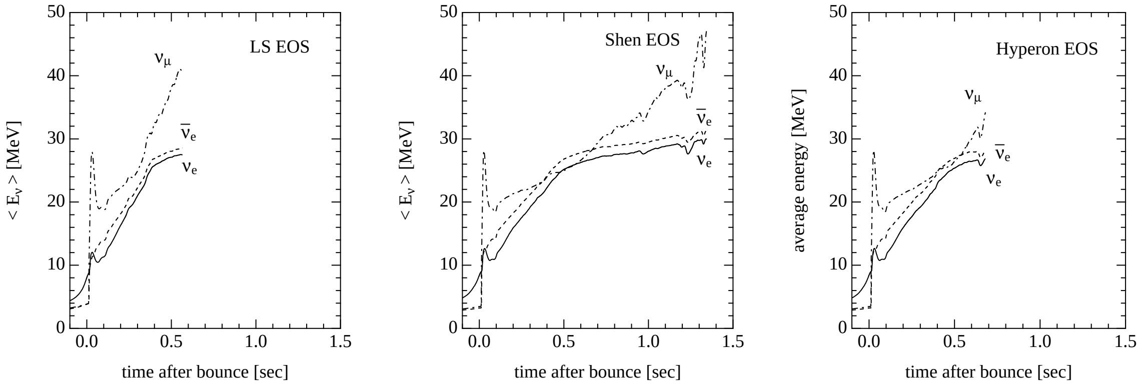

Figure 1. Time evolution of average energies of neutrinos (three species) emitted from the collapse of a $40M_\odot$ star with LS EOS (left), Shen EOS (middle) and Hyperon EOS (right).

4. Role of neutrinos in the explosion mechanism

Despite the extensive studies of the core-collapse supernovae, the explosion mechanism is still elusive. One has to examine carefully a delicate balance of counter-effects in a quantitative manner. As long as the numerical simulation of supernovae is performed in spherical (1D) geometry, no explosion is obtained in the neutrino-radiation hydrodynamics (for example, [27]). Note that the numerical simulations in 1D are the first principle calculations with the up-to-date EOS and neutrino physics. The shock wave is launched by the core bounce, however, it stalls on the way above 100 km for both LS EOS and Shen EOS [27]. This is mainly because the initial shock energy is used up by the dissociation of Fe during the propagation of the shock wave through the outer layer of Fe core. The initial shock energy by the release of gravitational energy amounts to several 10^{51} erg. However, the energy loss due to the Fe dissociation amounts to 1.6×10^{51} erg per $0.1M_{\odot}$, using up the initial energy.

Since the 1D calculations do not bring the explosion, one may need the multi-dimensional effects such as convection and rotation [28, 29]. The asymmetry away from the spherical geometry is also supported by the supernova observation and the analysis of spectra. The convection contributes to the effective heating of material and may help the revival of shock wave. It has been shown recently that the hydrodynamical instability of the standing accretion shock wave (SASI) may help further the launch of the shock wave to a larger radius and longer time scale for the neutrino heating. There are a handful cases of successful explosion in the state-of-the-art 2D simulations. However, there are several scenarios competing each other and the problem is not settled yet. This is partly because the numerical simulations by different groups adopt different models and methods with approximate treatment of neutrino transfer.

One of the important factors is the neutrino heating mechanism. When the shock wave stalls on the way above 100 km, the material is heated up by the absorption process of the neutrinos, which are emitted from the central core (proto-neutron star). This is the famous mechanism to have the delayed explosion [1]. Through the transfer of energy from neutrinos to matter, the size of heating amounts to typically $\sim2.2\times10^{51}$ erg, which is again comparable to the other effects. Apparently, the neutrino heating depends on the properties of supernova neutrinos (flux and energy), the available amount of targets and duration. Therefore, one has to evaluate this effect very carefully.

To examine this effect in a precise manner, one has to solve the neutrino transfer. Neutrinos diffuse outward in the central part and stream freely with few reactions through the outer layer. The neutrino heating takes place in the intermediate regime between them, therefore, one has to solve the equation of neutrino transfer together with all of neutrino reactions with the EOS data. The Boltzmann equation in 3 dimensional space and a phase space of 3D neutrino momentum is actually a 6 dimension problem, which is a challenging subject in astronomy, astrophysics and engineering. As for the supernova problem in 1D, the first principle calculations have been done to examine the microphysics and the systematics. In 2D, the approximate treatment has been adopted for the state-of-the-art simulations to explore the explosion mechanism. In 3D, simple prescriptions of neutrinos are adopted to explore the hydrodynamical instabilities. In order to establish the supernova mechanism, one has to perform the full 3D simulation of hydrodynamics and neutrino transfer with the EOS data and the neutrino reactions. Since the hydrodynamical instabilities can launch the position of shock wave to larger radii than that in the spherical calculations, the material is hovering around the heating region for longer time during the accretion, therefore, there would be more time for the neutrino heating.

In order to attack this problem, I am working on the project of the 3D neutrino-radiation hydrodynamics as a collaboration. I have developed a new numerical code of the Boltzmann equation in 3D to follow the time evolution of the neutrino distribution in 6D (3 space, 2 angles and 1 energy of neutrinos). The numerical code includes the progress of the physics of dense matter and neutrino reactions. This project is a computational challenge, which requires a large memory to store the neutrino distribution and a computational power to solve the large matrix for the implicit method for time steps. I have recently made the validation of the numerical code and started applications to the realistic supernova cores. Understanding the mechanism of supernova explosion is one of targets in the selected scientific areas for the K-computer, which is a 10 Pflops supercomputer being built at Kobe in Japan.

5. Summary

In summary, the physics of core-collapse supernovae is fascinating and puzzling. The supernovae from the gravitational collapse of massive stars lead to the explosion or collapse; the birth of neutron stars and black holes. The burst of neutrinos can be used to probe the state of matter deep inside the supernova core. The clarification of the supernova mechanism requires the wide knowledge of nuclear physics, particle physics and astrophysics. One needs the reliable information of matter and neutrino interaction at extreme conditions. The development of the EOS tables has made us possible to clarify its effect on the supernova neutrinos and the explosion mechanism. However, the full understanding of the explosion mechanism requires the large-scale numerical simulations in 3D on the next generation supercomputers with the collaboration of computational scientists.

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