EOS of hyperonic matter for core-collapse supernovae

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Abstract

We discuss the properties of supernova matter equation of state (EOS) including hyperons, and the emergence of hyperons in dynamical core-collapse processes. The recently tabulated EOS including hyperons is based on an $\mathrm{SU}_f(3)$ extended relativistic mean field (RMF) model, in which the coupling constants of hyperons with scalar mesons are determined to fit the hyperon potential depths in nuclear matter, $(U_\Sigma, U_\Xi) = (+30\mathrm{MeV}, -15\ \mathrm{MeV})$, which are suggested from recent analyses of hyperon production reactions. Hyperon effects are found to be small in the core-collapse and bounce stages, but abundant hyperons appear when the temperature becomes high during the black hole formation and promote earlier collapse of the accreting proto-neutron star. The maximum mass of hot proto-neutron star is discussed, and it gives a rough estimate of the critical mass of the accreting proto-neutron star, at which the proto-neutron star re-collapses to a black hole.

Key words: EOS, hyperon, supernova, black hole, neutrino
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1. Introduction

Hyperons are generally believed to emerge in compact astrophysical objects such as neutron stars at around $(2-3)\rho_0$. Because of the large neutron Fermi energy and less repulsive interaction with nucleons, hyperon single particle energies can be lower than the chemical potential. Among exotic constituents (hyperons, kaons, pions, quarks, and color superconductors), the interactions with nucleons are relatively well known for hyperons, and the mass difference is not large, $M_\Lambda - M_N \simeq 180$ MeV. These two features have motivated many researchers to investigate the equation of state (EOS) of hyperon mixed neutron star matter.

In dynamical processes such as supernovae and black hole formations, temperature and density are very different. In the collapse and bounce stage of supernovae, warm ($T \sim 20$ MeV) and mildly dense ($\rho_B \sim 1.6\rho_0$) nuclear matter is probed. In black hole formation processes, temperature can be as large as $T \sim 70$ MeV, and the density at the horizon formation can reach $\rho_B \sim 4\rho_0$. In this proceedings, we discuss the properties of supernova matter EOS with hyperons, and the role of hyperons in neutron stars, supernovae and black hole formation.

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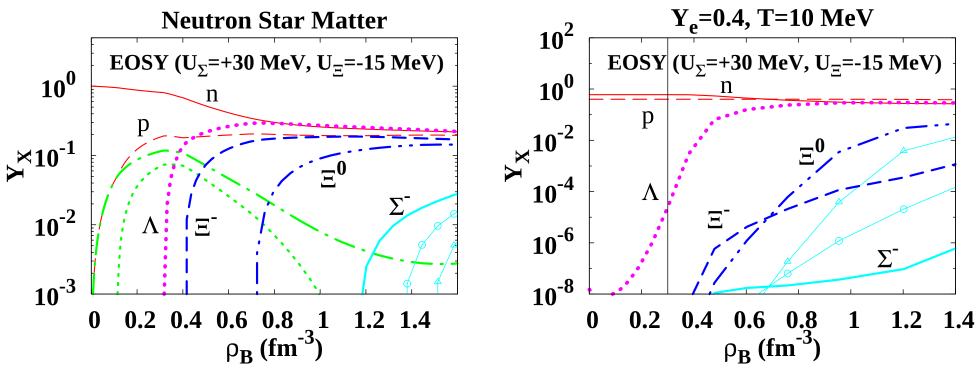

Figure 1: Particle fraction in neutron star matter (left panel, $T = 0$ under β equilibrium) and in supernova matter (right panel, $Y_e = 0.4, T = 10$ MeV).

2. EOS table of hyperonic matter

We have recently presented several sets of EOS table of nuclear matter including hyperons using an $SU_f(3)$ extended relativistic mean field (RMF) model with a wide coverage of density, temperature, and charge fraction for numerical simulations of core-collapse processes (EOSY)[1]. In modern studies, core-collapse processes are simulated by the neutrino radiation general relativistic hydrodynamics. The time scale ($\sim$ a few 100 ms) is long enough for particles other than neutrinos to equilibrate, then the main input would be the EOS of nuclear matter in addition to the ν-related reaction rate on baryons and nuclei. One of the most widely used EOS table is based on a Skyrme type (non-relativistic) mean field and the liquid-drop model of nuclei (LS EOS) [2]. Another EOS table is based on an RMF model [4], and nuclear formation is described in the Thomas-Fermi approximation (Shen EOS) [3]. Hyperons are not included in these EOS tables, then their applicable range may be limited to relatively low T and ρ_B region, where hyperons do not abundantly emerge.

EOSY is constructed as an extension of the Shen EOS. In including hyperons, we have adopted the potential depths of $(U_\Lambda, U_\Sigma, U_\Xi) = (-30\text{ MeV}, +30\text{ MeV}, -15\text{ MeV})$ in symmetric nuclear matter at ρ_0, which are suggested in recent hypernuclear experiments. The potential depth of Λ is well known from single-particle energies of many Λ hypernuclei. From the recently observed quasi-free Σ production spectra [5] and theoretical analyses [6, 7], it is considered that Σ baryons would feel repulsive potential in nuclear matter, $U_\Sigma(\rho_0) \simeq +30$MeV. Also for Ξ baryons, the analyses of the twin hypernuclear formation [8] and the Ξ production spectra [9, 7], suggest the potential depth of around $U_\Xi^{(N)}(\rho_0) \simeq -15$MeV. We have modified the coupling of scalar-mesons with hyperons to reproduce these potential depth as the Schrödinger equivalent potential in symmetric nuclear matter. Hyperon-vector meson couplings are fixed based on the flavor-spin SU(6) symmetry. At low densities, the EOS in RMF is smoothly connected with the Shen EOS.

These Σ and Ξ hyperons are particularly important in neutron stars [10], since nuclear matter can take a large energy gain from neutron Fermi energy and symmetry energy by replacing, for example, two neutrons with a proton and a negatively charged hyperon (Σ^- or Ξ^-). When we adopt more attractive potentials, Σ^- would be the next hyperon to Λ which appears in neutron stars [10, 11]. With the present choice, Σ baryons feel repulsive interaction at high densities, and

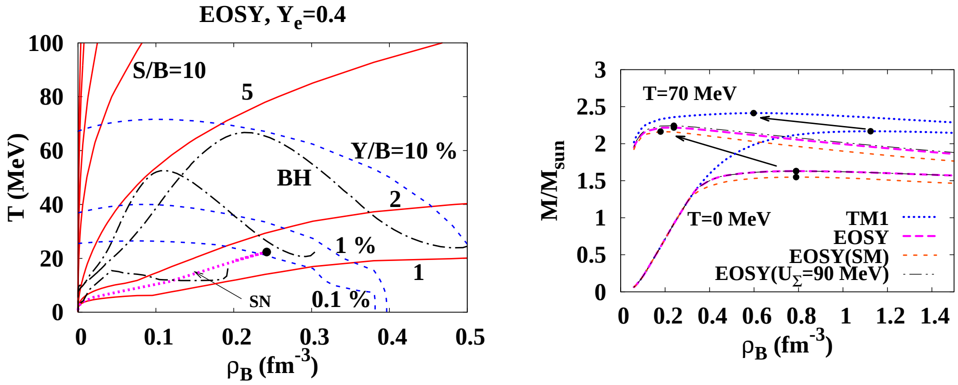

Figure 2: Left: (ρ_B, T) profile (dot-dashed curve) during black hole formation from the gravitational collapse of a 40 $M_\odot$ star at $t = 0$ (at bounce), 500 msec and 680 msec (just before the horizon formation), adiabatic paths (solid), hyperon fraction contours (dashed) and (ρ_B, T) profile (dotted) of the central grid in the core-collapse and bounce stages of a 15 $M_\odot$ star. Adiabatic paths and hyperon fraction contours are calculated with the electron fraction $Y_e = 0.4$. Right: Mass of a hot neutron star ($T = 70$ MeV) as a function of the central density in comparison with that at $T = 0$.

cannot appear until $\rho_B \sim 1.2$ fm^{-3}. Instead of Σ^-, Ξ^- is found to appear at around 0.4 fm^{-3} [10]. Thus the potential depth of Ξ^-, which will be measured in J-PARC, has an impact on the contents in dense matter.

3. Emergence of hyperons in dynamical processes

Compared to neutron stars, warm and mildly dense ($\rho_B \sim 1.6\rho_0$) matter is probed at smaller proton-neutron asymmetry ($Y_e \sim 0.4$) in the core-collapse and bounce stage of supernovae. In order to examine the property of the EOS table, we perform the hydrodynamical calculations of the adiabatic collapse of iron core of massive stars of $15M_\odot$ [12] under the spherical symmetry without neutrino-transfer by assuming that the electron fraction is fixed to the initial value in the stellar model. We have found that the adiabatic collapse of $15M_\odot$ star with EOSY leads to a prompt explosion. We plot the trajectory of density and temperature of the central grid in the left panel of Fig. 2. Since the density and temperature are not enough for hyperons to appear, the hyperon fraction is very small within 10^{-3} [1]. This small mixture does not affect largely the dynamics in the *model* explosion.

Next we investigate the emergence of hyperons in the dynamical collapse of a non-rotating massive star to a black hole by the neutrino-radiation hydrodynamical simulations in general relativity [13]. During the dynamical collapse of accreting proto-neutron star formed from the gravitational collapse of a 40M$_\odot$ star, we find that the hyperons populate quickly at ~(0.5–0.7) s after the bounce. When hyperons appear, they soften the EOS and promote the re-collapse to a black hole. The duration time of the neutrino emission with hyperons is much shorter than that with Shen EOS (without hyperons). The results with the LS EOS, which is soft at around the saturation density, show a similar duration time, but the average neutrino energies are higher than those with EOSY. These two features may be used as a signal of the emergence hyperons or other new degrees of freedom during the black hole formation.

In the black hole formation, the temperature can be as high as $T \sim 70$ MeV. We plot the (ρ_B, T) profile in the proto-neutron star at $t = 0, 500$ and 680 ms after the bounce. It is interesting to find that higher temperatures are realized off center, where the accretion heats up the materials. The temperatures and densities are high enough for hyperons to emerge, and around 10 % of nucleons are replaced with hyperons just before the horizon formation in the inner region [13].

The black hole is formed at $t = 0.7(1.3)$ s with (without) hyperons, and the mass of the accreting proto-neutron star is 2.1 (2.4) $M_\odot$. These masses are larger than the neutron star maximum masses in EOSY and Shen EOS. Namely, the critical mass at which the black hole is formed is larger than the static cold maximum mass. In the right panel of Fig. 2, we show the mass of hot ($T = 70$ MeV) proto-neutron star as a function of the central density. At finite temperature, the pressure is increased and the EOS can support more massive proto-neutron stars, $2.22(2.41)M_\odot$ with(without) hyperons at $T = 70$ MeV compared with $1.63(2.17)M_\odot$ at $T = 0$. This maximum mass of a hot proto-neutron star is comparable with that at black hole formation, but the central density at black hole formation is larger than the central density which support the maximum mass. This suggest that the accreting proto-neutron stars may be already in a transient state before the black hole formation. This causes the difference from the slow black hole formation through the cooling and deleptonization of a quasi-static proto-neutron star [14].

4. Summary

In this proceedings, we have discussed the properties of the relativistic EOS including hyperons, and the emergence of hyperons in dynamical core-collapse processes. Coupling constants between scalar mesons and hyperons are determined to fit the hyperon potentials at ρ_0, $(U_\Sigma, U_\Xi) = (+30\text{MeV}, -15\text{ MeV})$, which are suggested from recent analyses of hyperon production reactions. We demonstrated that the hyperons emerge in the collapse processes of a massive star. The shorter and less energetic neutrino burst may signal the formation of hyperonic matter.

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