Nucleosynthesis and characteristics in liquid-gas coexistence phase of supernova matter

Chikako Ishizuka[1*)], Akira Ohnishi[1] and Kohsuke Sumiyoshi[2]

[1] *Division of Physics, Graduate School of Science Hokkaido University, Sapporo 060-0810, Japan*
[2] *Numazu College of Technology, Numazu 410-8501, Japan*

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For the study of supernova explosion and neutron star strucure, it is important to know the equation of state (EoS) as well as the nuclear composition of matter. At present, one of the standard approaches is based on the mean field treatment, in which the matter is assumed to be composed of one kind of large nucleus surrounded by nucleon and alpha gas.[1)] On the other hand, recent heavy-ion collision studies have shown that nuclear matter should be regarded as a statistical ensemble of various fragment configurations at around the critical temperature of the liquid-gas phase transition at sub-saturation densities. Based on this understanding, we have proposed a nucleosynthesis process in which various nuclei are formed through the liquid-gas phase transition (LG process) as a preprocess of the standard r-process.[2)] We have also demonstrated that it would be possible for a part of ejected paths in the actual supernova explosion to experience the liquid-gas coexisting region before freeze-out. In addition, if the freeze-out temperature is around the critical temperature, many fragments are formed even at very low densities, and then we can describe bulk structure of the solar abundance. With this nuclear distribution as the initial condition, it may be easier to proceed the r-process up to the third peak.

In this paper, we turn our attention to one of the characteristic features of the liquid-gas coexistence phase in supernova matter, which allows many fragments to be formed even at very low densities. First we define a new quantity, gas baryon ratio Y_g, Y_g = (baryons in gas phase)/(baryons in whole system), as a measure of bulk fragment yield. For example, all baryons are bound in nuclei at $Y_g = 0$. In Fig.1, we show this gas baryon ratio of asymmetric nuclear matter as a function of the baryon density and the asymmetry, $A = 1 - 2Y_p$, calculated in RMF. The behavior of Y_g in asymmetric nuclear matter is smooth. In symmetric matter, both of the liquid and gas phase are symmetric, and the density in each phase is constant during the coexistence. Then the gas baryon ratio can be expressed by these liquid, gas, and the given average densities (ρ_0, ρ_g, ρ_B) as, $Y_g = \rho_g(\rho_0 - \rho_B)/\rho_B(\rho_0 - \rho_g)$. This is a monotonically decreasing function of the baryon density, and very small in the density range under consideration. When the asymmetry increases, the liquid phase loses the symmetric energy and nucleons are emitted to gas phase, while Y_g is still a decreasing function of ρ_B.

The behavior of Y_g in supernova matter is very different from that in asym-

*) E-mail:chikako@nucl.sci.hokudai.ac.jp

metric nuclear matter. As shown in the thick line in Fig.1, as the baryon density decreases, Y_g first decreases, then grows again. Since Y_L is kept constant but Y_p is free from constraint, the supernova matter searches its free energy minimum by changing Y_p. At high baryon densities, lepton Fermi energy and nuclear symmetry energy competes. The former favors $Y_e = Y_p = 2/3Y_L$ to share the lepton density by electrons and neutrinos according to their spin degeneracy (2:1), and the latter favors symmetric nuclear matter, $Y_p = 1/2$. At low densities but temperatures $T > m_e$, anti-leptons are easily created then the equilibrium Y_p is mainly determined by the symmetry energy, i.e., the proton ratio goes towards $Y_p = 0.5$. Nuclei can be more stable in symmetric matter than in asymmetric matter. Therefore, baryons favor nuclear state than nucleon gas in the coexistence region of thin supernova matter, though baryons in asymmetric nuclear matter are almost in gas state at low baryon densities.

This characteristic behavior of Y_g in supernova matter is also seen in a Nuclear Statistical Equilibrium (NSE) calculation. From the calculated proton ratio in the gas phase (free proton to free nucleon ratio in NSE) and that in the liquid phase (mean Y_p of nuclei in NSE), we find the following qualitative evolution of supernova matter composition in the coexistence phase:
(1) symmetric nucleon gas and symmetric nuclei at very low baryon densities,
(2) neutron gas and neutron rich nuclei at low baryon densities.
Therefore these bulk properties of supernova matter may play an essential role in determining the types and quantities of nuclei formed in the coexistence region, and it is important to discuss fragment formation in supernova matter.

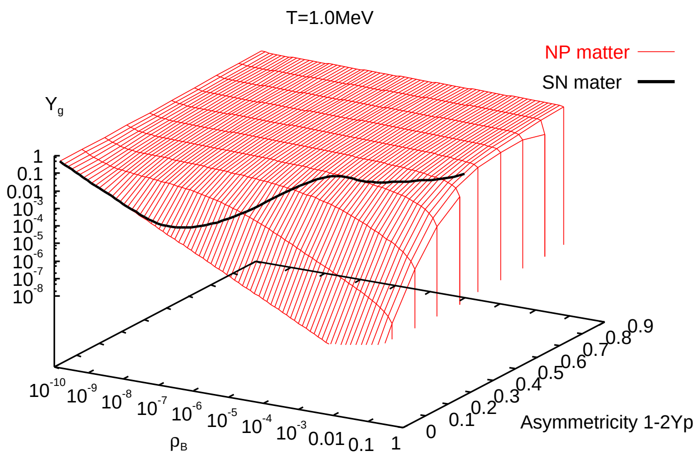

Fig. 1. Gas baryon ratio Y_g in asymmetric nuclear matter (thin line surface) and in supernova matter (thik line) as a function of the baryon density and the asymmetry, $A = 1-2Y_p$ calculated at $T = 1$ MeV and $Y_L = 0.35$ in RMF.

References

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