NUCLEAR MASS MODIFICATION IN SUPERNOVA MATTER

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In the statistical model calculation, we find that fragmentation in the liquid-gas coexistence region may help the later r-process to proceed and the nuclear mass medium modification of supernova matter plays an essential role for r-process peak nuclei synthesis.

1 Introduction

One of the most exciting current problems in nuclear physics is to elucidate the mechanism of heavy element synthesis in the universe and its relation to the properties of nuclei and nuclear matter,[2] which can be probed experimentally in the laboratory.[1] In this context, we have proposed a new process, supernova matter fragmentation at around the liquid-gas phase transition, which may contribute to synthesize heavy nuclei.[3,4] When supernova matter cools down and experiences the liquid-gas phase transition in the neutrino sphere ($\rho_B \geq 10^{-5}\mathrm{fm}^{-3}$) where equilibrium is expected to be achieved, this matter will fragment and form various nuclei in a critical manner. Then the statistical distribution of fragments at freeze out will give the initial condition of the later processes such as the r-process.

Our qualitative study of the realization possibility of this process shows that leptons in supernova matter play an important role in keeping the critical temperature and entropy high enough to eject the matter to the outer space, and in synthesizing nuclei even at very low densities. These characteristic behaviors are brought by the change of proton to baryon ratio, Y_p. In supernova matter, proton number is not conserved, but lepton number and charge are conserved. Then supernova matter searches its optimal value of Y_p to reduce the free energy. As a result, at some densities such as $\rho_B \sim 10^{-7}\mathrm{fm}^{-3}$ and $10^{-3}\mathrm{fm}^{-3}$, nuclear fragment formation becomes much more favorable than isolated nucleons as shown in Fig. 1.[4] We refer to these density regions as the first ($\rho_B \sim 10^{-7}\mathrm{fm}^{-3}$) and the second ($\rho_B \sim 10^{-3}\mathrm{fm}^{-3}$) *fragment windows.*

In this paper, we investigate nuclear distributions and supernova matter medium effects on this distribution in fragment windows and at densities

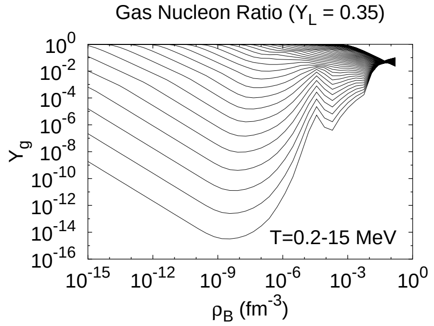

Figure 1. Isolated (gas) nucleon to total nucleon ratio calculated in the statistical model as a function of density and temperature in the case $Y_L = 0.35$.

between these two fragment windows.

2 Fragment Distribution and Coulomb Correction Effects

In order to deal with the distributions of nuclei having finite size, we apply a statistical model used in heavy-ion collision study, which is similar to the Nuclear Statistical Equilibrium (NSE) used in the field of astrophysics. In the calculation, we solve the statistical equilibrium among nucleons, fragments, and leptons with fragment-based grandcanonical ensemble. In heavy-ion collision studies, the experimental values are used for the binding energies and only observed nuclei are considered as fragment species. In supernova matter, however, several modifications are required. First, since the electron density is much higher in supernova matter, the Coulomb energy is reduced due to the screening effect. We here assume that electrons are uniformly distributed in a sphere whose radius is chosen to cancel the charge of the nucleus at a given electron density. Then the Coulomb energy correction is analytically obtained.[2,3] In addition, because of the finite gas nucleon density, nuclei outside of the dripline might be stabilized. Then we have adopted the mass table of Myers and Swiatecki [5] which contains 9000 kinds of nuclei.

By using the modified statistical model described above for supernova matter, we solve the thermal and chemical (β) equilibrium condition for a given (ρ_B, T, Y_L) and total charge neutrality condition

In the first fragment window ($\rho_B = 10^{-7}\mathrm{fm}^{-3}$) corresponding to outside of the neutrino sphere, the main products in the liquid-gas coexistence region are nucleon, α and iron peak nuclei, and the Coulomb correction effect is negligible. Although we cannot expect β-equilibrium at these low densities, neutrinos supplied from the inner core frequently hit nucleons and fragments then thermal equilibrium may be achieved. In addition, since the fragment distribution is determined by Y_p, the results would be similar without assuming β-equilibrium once Y_p value is given appropriately. Although the above distribution seems to be similar to the initial seed nuclear distribution in a standard treatment of r-process, we would like to point out that when the temperature rise to around the critical value ($T_c \sim 0.8$ MeV at this density), the distribution broaden out by thermal fluctuation.

Next, we consider the density $\rho_B = 10^{-5}\mathrm{fm}^{-3}$ which corresponds to the middle of two fragment windows and the surface region of the neutrino sphere. At around this density, fragment distribution is localized at around the r-process 1st peak at low temperature, and they are broaden out as the temperature rises. The Coulomb correction effect is not large, but at around the critical temperature ($T_c \sim 1.44$ MeV) where small change of binding energies causes large difference in distribution, fragments with larger masses over the first peak are strongly enhanced by the Coulomb correction.

Finally, we show the fragment mass distribution in the second fragment window ($\rho_B = 10^{-3}\mathrm{fm}^{-3}$) in Fig. 2. As in the case of lower densities, the distribution is localized at lower temperatures than $T_c \sim 3.8$ MeV, and broaden out to be power-law like behavior at $T \sim T_c$. We find that the mass distribution inside the coexistence region at this density is shifted to heavier mass side due to the supernova matter medium effect, i.e. Coulomb correction. As a result, the center of the distribution changes from the r-process first peak with bear mass to the r-process second peak with Coulomb correction.

3 Summary

In this work, we have investigated the fragment distribution in the liquid-gas coexisting region of supernova matter at densities of fragment windows. As the freeze-out density rises from 10^{-7} to $10^{-5}, 10^{-3}\mathrm{fm}^{-7}$, the main products evolve Fe peak nuclei to r-process first and second peak nuclei. At higher densities $\rho_B \sim 10^{-2}\mathrm{fm}^{-3}$, the main product reaches the third peak of the r-process. The peak positions of the distributions are considered to be determined by both of the shell effect which stabilizes nuclei with $N = 50, 82$, and 126 and Coulomb correction which makes the binding energy larger. Therefore we can conclude that the medium effect in supernova matter would play an essential role for production of heavy elements inside the liquid-gas coexistence region.

Although we have limited our interest to the Coulomb correction, it would be very interesting to consider *nuclear interaction* correction in the medium.

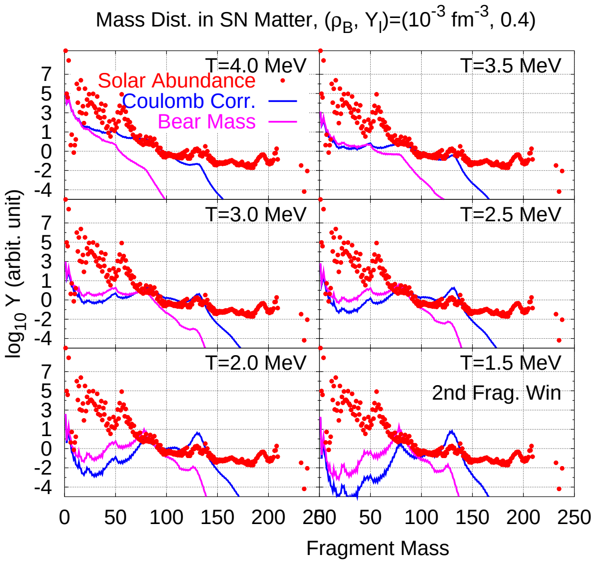

Figure 2. The fragment mass distribution near the critical temperature of liquid-gas phase transition at lepton to baryon ratio $Y_L = 0.4$ and baryon number density $\rho_B = 10^{-3}\mathrm{fm}^{-3}$,which values are reasonable inside the neutrino sphere. The dark solid line corresponds to the distribution without medium effect and the black line corresponds to that with the medium effect of supernova matter.

References

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