核子の有効質量と multineutron 状態が超新星核物質に与える影響

Impact of the effective nucleon mass and multineutron states on supernova nuclear matter

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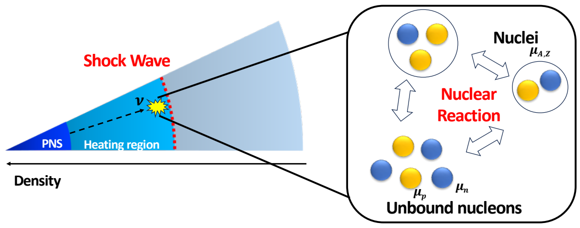
1. Introduction

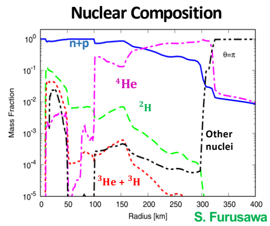
Neutrino reactions strongly depend on the nuclear composition

Nuclear Statistical Equilibrium



$$\mu_{A,Z} = (A-Z)\mu_n + Z\mu_p$$

Nuclear Composition



S. Furusawa et al (2023)

At the center, the abundance of light nuclei becomes significant

⇩

Neutrino reactions involving light nuclei are not negligible

N. Ohnishi et al. (2007) S. Furusawa et al. (2013)

However, uncertainties in nuclear matter remain

(1) Multineutron states are not yet included in SN simulations

A weakly bound state or resonant state consisting only of neutrons

dineutron (^{2}n) — $B_{^2n} = -0.066$ MeV (resonant) — Panov et al. (2019)

tetraneutron (^{4}n) — $B_{^4n} = -2.37$ MeV (resonant) — Deur et al. (2022)

(2) The effective nucleon mass M^* alters SN dynamics

A larger M^* leads to lower pressure ⇨ Rapid contraction, Faster explosion

Schneider et al. (2019), Yasin et al. (2020)

We investigate the impact of these factors on the composition

2. Model

To minimize the free energy, we impose the following conditions

$$n_n + n_p + \sum_{A,Z} n_{A,Z} A = n_B \qquad n_p + \sum_{A,Z} n_{A,Z} Z = Y_p n_B$$

Local baryon number conservation — Local charge conservation

Nuclei

$$n_{A,Z} = \kappa g_{A,Z}(T)\left(\frac{M_{A,Z}k_BT}{2\pi}\right)^{\frac{3}{2}} \exp\left(\frac{(A-Z)\mu_n + Z\mu_p - M_{A,Z} - E_{Coul} - p_{nuc}A/n_0}{k_BT}\right)$$

Hempel et al. (2010)

- $\kappa \left(= 1 - \frac{n_B}{n_0}\right)$: Excluded volume effect
- $g_{A,Z}(T)$: Internal degrees of freedom (incl. excited states) — Rauscher (2003)
- E_{Coul} : Coulomb energy between nuclei and electrons
- $p_{nuc}A/n_0$: Contribution from surrounding nucleon gases

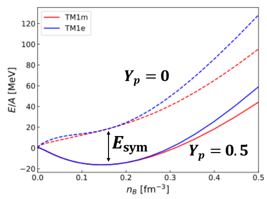
Unbound Nucleon

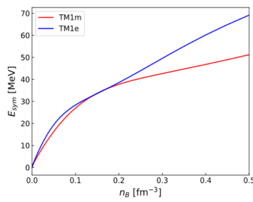
Relativistic Mean-Field Theory (TM1m ・ TM1e) — Li et al. (2025), H. Shen et al. (2020)

- Constrained by NS observations and nuclear experiments
- TM1m model has a larger effective mass $M^* = M + g_\sigma \sigma$

$$\mathcal{L} = \sum_{i=p,n} \bar\psi_i\left[\gamma_\mu\left(i\partial^\mu - g_\omega\omega^\mu - \frac{g_\rho}{2}\tau_a\rho^{a\mu}\right) - (M + g_\sigma\sigma)\right]\psi_i + \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 - \frac{1}{4}W_{\mu\nu}W^{\mu\nu} - \frac{1}{4}R^a_{\mu\nu}R^{a\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu + \frac{1}{2}m_\rho^2\rho^a_\mu\rho^{a\mu} + \frac{1}{4}c_3(\omega_\mu\omega^\mu)^2 + \Lambda_v(g_\omega^2\omega_\mu\omega^\mu)(g_\rho^2\rho^a_\mu\rho^{a\mu})$$

Energy per nucleon E/A — Symmetry energy E_{sym}



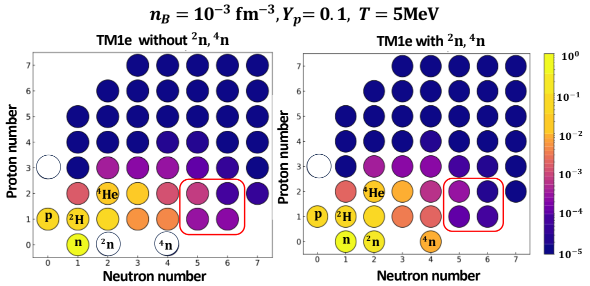


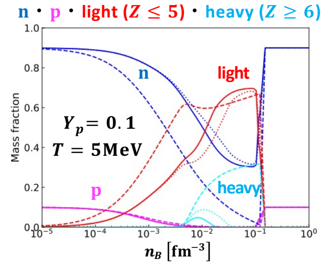
The density dependence of E_{sym} in TM1m is weaker

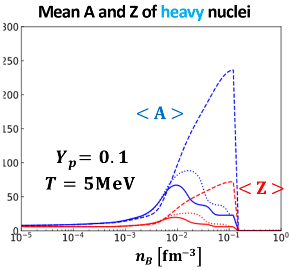
3. Mass fractions ($X_{A,Z} = n_{A,Z}A/n_B$)

Nuclear chart

$n_B = 10^{-3}$ fm^{-3}, $Y_p = 0.1$, $T = 5$MeV







- $X_{^2n}$ and $X_{^4n}$ are large under typical SN conditions
- The abundance of neutron-rich nuclei becomes smaller

$X_p = 3.63 \times 10^{-2}$ ⇨ $X_p = 4.38 \times 10^{-2}$

ν_e emission may increase

$X_n = 0.811$ ⇨ $X_n = 0.623$

ν_e emission may decrease

- ^{2}n and ^{4}n decrease X_n and increase X_p
- The TM1m shows smaller E_{sym} at low densities

⇨ $\mu_n \downarrow$, $\mu_p \uparrow$ ⇨ X_{heavy} < A > < Z > increase

Neutrino-nucleus coherent scattering may increase

⇨ Neutrino emission duration may increase

Summary

- ✓ Multineutron states appear significantly, leading to a decrease in X_n and an increase in X_p and X_{heavy}.
- ✓ The model with a large effective nucleon mass increases X_{heavy}.

Outlook

- ➢ A larger M^* and the existence of ^{2}n and ^{4}n may significantly affect neutrino emission and scattering processes.
- ➢ We are constructing EOS data for SN simulations based on TM1m/TM1e, with and without ^{2}n and ^{4}n.