Impacts of multineutrons on the nuclear compositions and neutrino reaction rates in the core-collapse supernova

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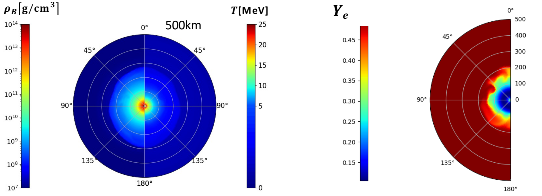
1. Introduction

In the core-collapse supernova, the central region exhibits higher density and temperature, and becomes neutron-rich

Baryon mass density ρ_B, temperature T and charge fraction Y_e of the 2D supernova simulation at 100ms after core bounce

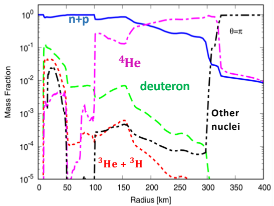
H. Nagakura et al (2019)



Neutrino reactions are important for determining supernovae dynamics Contraction of PNS・Shock wave revival

Most simulations have not considered the neutrino reactions with light elements in detail!

Nuclear composition calculated with the supernova simulation



S. Furusawa et al (2023)

Light elements are abundant in the central region

⬇

Neutrino reactions with light elements are not negligible

N. Ohnishi et al (2007), S. Furusawa et al(2013), Fischer et al(2020)

In the central region, multineutrons might appear

Panov et al (2019)

Multineutron : Quasibound state consisting only of neutrons

Purpose

To investigate the impacts of assuming the existence of ^2n and ^4n on the nuclear compositions and neutrino reactions at 100ms after core bounce

2. Model

Assumptions

- Nucleons and nuclei behave as Boltzmann gases

κ: excluded volume effect

$$n_{N,Z} = \kappa g_{N,Z}\left(\frac{M_{N,Z}k_BT}{2\pi}\right)^{\frac{3}{2}} \exp\left(\frac{N\mu_n + Z\mu_p - M_{N,Z}}{k_BT}\right)$$

$$M_{N,Z} = Nm_n + Zm_p - B_{N,Z} \qquad B_{^2n} = -0.066\ \mathrm{MeV} \qquad B_{^4n} = 0.42\ \mathrm{MeV}$$

Panov et al (2019) T. Faestermann et al (2021)

- Nuclear statistical equilibrium(NSE)

$$\begin{gathered}(N,Z) \leftrightarrow (N,Z-1) + p \\ (N,Z) \leftrightarrow (N-1,Z) + n\end{gathered} \quad \Rightarrow \quad \mu_{N,Z} = N\mu_n + Z\mu_p$$

Solve two conditions for determining nuclear compositions

$$\sum_{N,Z} n_{N,Z}(N+Z) = n_B \qquad \sum_{N,Z} n_{N,Z}Z = Y_e n_B$$

Local baryon number conservation Local charge conservation

Charged current neutrino reaction rates with n, p, ^{2}H, and ^2n

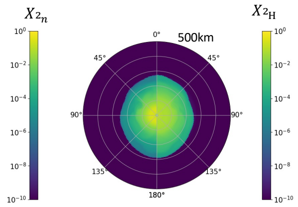
$$Q = \mathrm{G_F^2}(1+3a^2)\, n_i^b \int \frac{d^3p_f^l}{(2\pi)^3} \int \frac{d^3p_i^l}{(2\pi)^3}\, \varepsilon_\nu f_i^l(1-f_f^l)$$

$$\times 2\pi\delta\left(E_f^l + \sum_f \mu_f^b - (\mu_i^b - B_{N,Z}) - E_i^l\right)$$

$\mathrm{G_F}$: the weak coupling constant $a(=1.26)$:the nucleon axial-vector coupling constant

- Nucleons and nuclei are static and their energies are replaced by μ^b or $\mu^b - B_{N,Z}$, respectively.
- The degeneracy of leptons and Pauli block are taken into account with Fermi-Dirac distribution f_i, $1-f_f$.
- Chemical potential of leptons is taken from the 2D supernova simulation

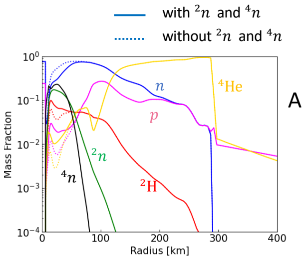
3. Nuclear Compositions



Mass fraction $X_{N,Z} = \frac{n_{N,Z}(N+Z)}{n_B}$

^2n is abundant inside the shock radius

Within 100km, ^2n is more abundant than ^{2}H



With ^2n and $^4n \cdots$

n	decrease
p ^{2}H ^{4}He	increase

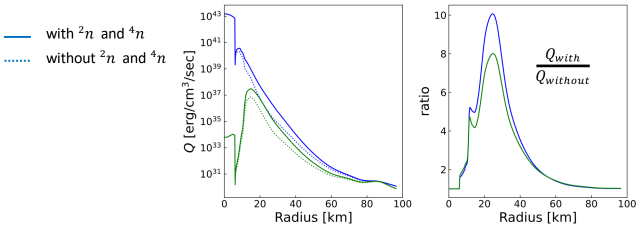
Assuming the existence of ^2n and ^4n

➡ The decrease in n leads to smaller μ_n

➡ Neutron-rich nuclei such as ^{5}H decrease

➡ p ^{2}H ^{4}He increase

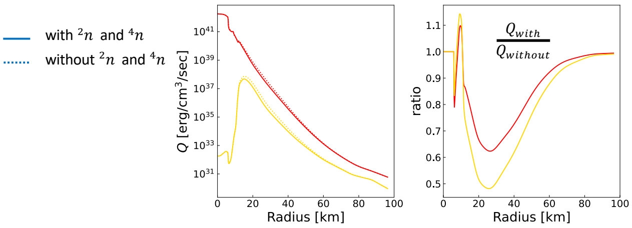
4. Neutrino Reaction Rates



Neutrino emission rates	Antineutrino absorption rates
$e^- + p \rightarrow n + \nu_e$	$\nu_e + p \rightarrow n + e^+$
$e^- + {}^2\mathrm{H} \rightarrow n + n + \nu_e$	$\nu_e + {}^2\mathrm{H} \rightarrow n + n + e^+$

These rates increase by eight times due to the increase in p, ^{2}H

➡ ^2n and ^4n promote the reactions p ⇨ n



Neutrino absorption rates	Antineutrino emission rates
$\nu_e + n \rightarrow p + e^-$	$e^+ + n \rightarrow p + \nu_e$
$\nu_e + {}^2\mathrm{H} \rightarrow p + p + e^-$	$e^+ + {}^2\mathrm{H} \rightarrow p + p + \nu_e$
$\nu_e + {}^2n \rightarrow p + n + e^-$	$e^+ + {}^2n \rightarrow p + n + \nu_e$

These rates decrease by 40%–50% due to the decrease in n

➡ ^2n and ^4n suppress the reactions n ⇨ p

5. Summery and Outlook

- ✓ Within 100km, ^2n is more abundant than ^{2}H, leading to the dcrease in n and the increase in p, ^{2}H, ^{4}He.
- ✓ The existence of ^2n and ^4n promotes the neutrino reactions where protons convert into neutrons, and suppresses those where neutrons convert into protons.
- ✓ ^2n and ^4n may accelerate the neutronization of PNS and shorten its neutrino cooling time.