R-process Nucleosynthesis during the Magnetohydrodynamics Explosions of a Massive Star

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Abstract. We investigate the possibility of the r-process during the magnetohydrodynamic explosion of supernova in a massive star of 13 solar mass with the effects of neutrinos induced. We adopt five kinds of initial models which include properties of rotation and the toroidal component of the magnetic field. The simulations which succeed the explosions are limited to a concentrated magnetic field and strong differential rotation. Low $Y_e$ ejecta produce heavy elements and the third peak can be reproduced. However, the second peak is low because $Y_e$ distribution as a function of radius is steep and ejecta corresponding to middle $Y_e$ is very few.

Keywords: supernovae, r-process, magneto-hydorodynamics, neutrino

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INTRODUCTION

It has been considered that the origin of heavy neutron-rich elements like uranium is mainly due to the r-process nucleosynthesis that occurs during the supernova explosions and/or neutron star mergers [1, 2, 3, 4]. The main issue concerning the r-process research is to reproduce the three peaks ($A \approx 80, 130, \text{ and } 195$) in the abundance pattern for the r-elements in the solar system. Among models of the r-process, it has been believed that supernovae are the most plausible astrophysical site [5].

In the present paper, we will carry out the calculations of the MHD explosion of the He-core of $3.3 \, M_\odot$ during $t_f \sim 500 \, \text{ms}$ whose mass in the main sequence stage is about $13 \, M_\odot$ star. For the MHD calculations, five distributions of initial rotation and magnetic

| TABLE 1. Initial parameters of precollapse models. |
|----------------------------------|
| $T/\left| W \right|$ (%) | $E_m/\left| W \right|$ (%) | $X_0(10^8\, \text{cm})$ | $Z_0(10^8\, \text{cm})$ | $\Omega_0 \left( s^{-1} \right)$ | $B_0 \left( G \right)$ |
|----------------------------------|
| model 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| model 2 | 0.5 | 0.1 | 1 | 1 | 5.2 | $5.4 \times 10^{12}$ |
| model 3 | 0.5 | 0.1 | 0.5 | 1 | 7.9 | $1.0 \times 10^{13}$ |
| model 4 | 0.5 | 0.1 | 0.1 | 1 | 42.9 | $5.2 \times 10^{13}$ |
| model 5 | 1.5 | 0.1 | 0.1 | 1 | 72.9 | $5.2 \times 10^{13}$ |
fields are assumed with parametric forms. We include the effects of neutrinos by using Leakage scheme [6]. Thereafter, we investigate the r-process nucleosynthesis using the results of MHD calculations.

**INITIAL MODELS**

The presupernova model has been calculated from the evolution of He-core of $3.3 \, M_\odot$ that corresponds to $13 \, M_\odot$ in the main sequence stage [7]. We adopt cylindrical properties of the angular velocity $\Omega$ and the toroidal component of the magnetic field $B_\phi$ as follows [10]:

\[
\Omega(X, Z) = \Omega_0 \times \frac{X_0^2}{X^2 + X_0^2} \cdot \frac{Z_0^4}{Z^4 + Z_0^4}, \quad B_\phi(X, Z) = B_0 \times \frac{X_0^2}{X^2 + X_0^2} \cdot \frac{Z_0^4}{Z^4 + Z_0^4}
\]

where $X$ and $Z$ are the distances from the rotational axis and the equatorial plane with $X_0$ and $Z_0$ being model parameters.

Both $\Omega_0$ and $B_0$ are the initial values at $X = 0$ and $Z = 0$. Initial parameters of five precollapse models are given in Table 1. The spherically symmetric case is denoted by model 1. In model 2, the profiles of rotation and magnetic field in the Fe-core are taken to be nearly uniform. We present model 4 and 5 as the case having a differentially rapid rotating core and strong magnetic fields. An intermediate example, model 3 between model 2 and model 4 is prepared for reference.

**EXPLOSION MODELS AND r—PROCESS NUCLEOSYNTHESIS**

We perform the calculations of the collapse, bounce, and the propagation of the shock wave with use of ZEUS-2D [8] in which the realistic equation of state [9] has been implemented by Kotake et al[10]. It is noted that the contribution of the nuclear energy generation is usually negligible compared to the shock energy. In Table 2, our results of MHD calculations are summarized.

The simulations which succeed the explosions are model 4 and model 5. Explosion fails for spherical (model 1) and/or large $X_0$ models, which indicate that explosions need concentrated magnetic field and strong differential rotation. Model 4 eject large area around rotation axis, but this area has high $Y_e$. Therefore elements responsible for the third peak do not appear. On the other hand, Model 5 ejects collimated jet and this ejecta from deep area has very low $Y_e$. Therefore we investigate the possibility of the r-process for model 5. Low $Y_e$ ejecta produces heavy elements and the third peak can be reproduced(Fig. 2). However, the second peak is low because $Y_e$ distribution as a function of radius is steep and ejecta corresponding to middle $Y_e$ is very few(Fig. 1).

**SUMMARY**

We calculated magneto-hydrodynamical simulations with neutrino effects included and investigated the $r$-process nucleosynthesis during the purely magneto hydrodynamic ex-
TABLE 2. Hydrodynamics simulation results.

|       | $t_b$ | $T/|W|_f$ | $E_m/|W|_f$ | $E_{exp}^*$ | $M_{ej}/M_\odot$ | $M_{rej}/M_\odot$ |
|-------|-------|-----------|-------------|-------------|-------------------|------------------|
| model 1 | 111   | 283       | 0           | 0           | 0.023             | -                |
| model 2 | 125   | 311       | 6.91        | 0.053       | 0.127             | -                |
| model 3 | 129   | 329       | 8.74        | 0.116       | 0.164             | -                |
| model 4 | 133   | 433       | 8.80        | 0.142       | 1.13              | 0.111            |
| model 5 | 180   | 548       | 15.3        | 0.339       | 0.484             | 0.022            |

$t_b$ indicates the time (ms) at the bounce. The calculations are stopped at the time $t_f$ (ms). The ratios $T/|W|_f$ and $E_m/|W|_f$ are expressed in %. $E_{exp}^* = E_{exp}/10^{51}$ ergs.

FIGURE 1. Ejected mass as a function of $Y_e$ (model4 and model5).

FIGURE 2. Abundances obtained from model5.

Explosion in a massive star of $13\ M_\odot$ progenitor model by [7]. Weak differential rotation model does not succeed in explosion. So, explosion need very strong and concentrated rotation, and magnetic field. Low $Y_e$ ejecta from which the third peak elements appear needs strong differential rotation and concentrated magnetic field. Explosion depend on the parameter of magnetic field and rotation profile and $Y_e$ distribution of ejecta is very different, which depend on each parameter. For model 5, third peak can be reproduced but the second peak is low because $Y_e$ distribution as a function of radius is steep.

REFERENCES

1. Seeger, P. A., Fowler, W. A., & Clayton, D. D. Astropysical Journal Supplement Series, 11, 121, (1965).
2. Sato, K. Prog. Theor. Phys. 51, 726, (1974).
3. Thielemann, F.-K., et al. Proceedings of 1CRC 2001: 1©Copernicus Gesellschaft 2001.
4. Qian Y.-Z. Prog. Part. Nucl. Phys. 50, 153, (2003).
5. Qian, Y-Z. 2005, First Argonne/MSU/JINA/INT RIA Wokshop
6. van Riper, K. A., & Lattimer, J. M. Astropys. J, 249, 270, (1981).
7. Hashimoto, M. Prog. Theor. Phys. 94, 663, (1995).
8. Stone, J. M., & Norman, M. L. Astropysical Journal Supplement Series, 80, 791, (1992).
9. Shen, H., Toki, H., Oyamatsu, K., & Sumiyoshi, K. Nucl. Phys. A. 637, 435, (1998).
10. Kotake, K., Sawai, H., Yamada, S., & Sato, K. 2004, Astrophys. J, 608, 391, (2004).