Nuclei in Core-Collapse Supernovae

Shun Furusawa
Tokyo University of Science (TUS) & RIKEN, iTHEMS

Which nuclei appear in supernovae?
How they affect supernovae?

I. Mishustin (FIAS), J. Holt (TEXAS A&M),
H. Togashi (RIKEN), H. Nagakura (Princeton), K. Sumiyoshi (Numazu),
S. Yamada (Waseda), H. Suzuki, K. Saito (Tokyo U. of Sci.)

ICFNP2019 8/29
Evolutions of Stellar objects

Stellar formation ➔ White Dwarf ➔ Thermonuclear (Type Ia) Supernovae

Stellar formation ➔ Stars ➔ Core-Collapse Supernovae (CCSNe)

Core-Collapse Supernovae (CCSNe) ➔ Neutron Stars ➔ Black Holes

Compact Star mergers ➔ Neutron Stars

2019/8/29

Nuclei in Core-Collapse Supernovae (Shun Furusawa)
Gravitational Wave Signal (Hotokezaka ’11)

Soft EOS (APR4)

Stiff EOS (H4)

Mass-Radius relation of Neutron Star

Nuclear matter at high density ($\rho > \rho_0$) may be constrained in near feature. ⇒ low density and/or high temperature?
Core-Collapse Supernovae

- Energetic events $10^{51}$ erg (ejecta), $10^{53}$ erg (neutrino)
- Emissions of neutrinos and gravitational Waves
- Formations of a neutron star or a black hole
- Nucleosynthesis site of heavy elements
- Extreme test for nuclear physics

SN 1987A
Core-Collapse Supernovae

0, Stellar evolution (10 Myr)
1, Core collapse
   $\rho \sim 10^{10}$ [g/cm$^3$]
   $H(Z=1)$
   He (2)
   C, O (6, 8)
   O, Ne, Mg (8, 10, 12)
   Si (14)
   Fe+ (~26)

2, Neutrino trapping
   $\nu$: neutrinos
   $\rho \sim 10^{12}$ [g/cm$^3$]

3, Core bounce
   $\rho \sim 10^{14}$ [g/cm$^3$]

4, Shock Propagation in Core
   (1 sec after Core-Collapse)
   $E_\nu \sim 10^{53}$ [erg]

5, Supernova Explosion
   (1 day)
   $E_{kin} \sim 10^{51}$ [erg]
   (1% of $E_\nu$)

NS
Supernova matter in Core-Collapse Supernovae

① Collapsing Iron Core (heavy nuclei, n)
- ~2000 km

② Proto-Neutron Star (n, p, light nuclei)
- ~10 km
- ~140 km

③ Shocked Matter (n, p, light nuclei)
- ~10^8−9 km

- A, Z
- A', Z'
- α
- free p, n
- Electron photon (uniform)
- neutrinos (not always in equilibrium)

Fe (Si, C+O, He, H)
Supernova Simulations

1. Hydrodynamics of matter in 3D space
2. Neutrino transport in 3D space \times 3D momentum space

2D (axisymmetric) simulation (Nagakura+) at Supercomputer K based on Togashi-Furusawa EOS (SF+17d)
Inputs of Supernova Simulations

① Equation of State ⇒ Stiffness, Nuclear compositions (Which nuclei appear)
② Weak interaction rates ⇒ Neutrino emissions, absorptions, and scattering

Ex. \((N, Z) + e^- \leftrightarrow (N + 1, Z - 1) + \nu_e\)

Motions of neutrinos and matter around Proto-Neutron Star
（Nagakura+）Togashi-Furusawa EOS (SF+17d)
$(\rho, T, Y_e)$ in Core-Collapse Supernova Simulations

- Heavy nuclei ($A \approx 56 \rightarrow 1000$), Collapse
- Fe group ($A \approx 56$), Accretion
- n, p, light nuclei ($A \approx 2 \rightarrow 4$), Shocked matter
Central mass fraction of stellar core collapse

- Dense electrons reduce nuclear Coulomb energy.
  → large mass nuclei
- $\mu_n > \mu_p$
  → neutron-rich nuclei
- Nuclei are excited.
Abundant Nuclei for different nuclear excitation models at important densities $\rho \sim 10^{11-12}\text{g/cc}$

- Nuclei with $(N,Z)=(40-80,25-40)$
- Sensitive to choice of excitation models
- Nuclei with $(N,Z)\approx(50,30)$ are commonly abundant in all models

Mass Fraction $X_{AZ} = A n_{AZ} / n_B$

Mass fraction at $\rho = 2.0 \times 10^{12}\text{ g/cc}$, $T = 1.8\text{ MeV}$, $Y_e = 0.28$
Lack of Electron Capture Data \((N, Z) + e^- \rightarrow (N + 1, Z - 1) + \nu_e\)
(+ partition function level densities for Equation of State)

Theoretical EC data (Fuler '82~ Langanke 03)

Important Nuclei \(Z \approx 25-40, N \approx 40-80\)
Primary Targets \((Z, N) \approx (30, 50)\)
Electron captures on nuclei reduce neutrino bursts
(Sullivan et al. 16, see also Hix '03, Lentz '13)

More electron captures on nuclei

⇒ ① fewer leptons
⇒ smaller mass of proto NS
⇒ smaller shock radius $R_s$

⇒ ② more neutrino captures
⇒ larger neutrino spheres $R_v$

⇒ smaller neutrino emissions

Neutrino Luminosity

Higher electron capture rates
Light Clusters (d, t, α) after bounce.

Light clusters physics may affect shock dynamics and neutrino observations (SF+13 APJb, Nagakura, SF+ APJ)

Ex2) Mass fraction of shocked matter

<table>
<thead>
<tr>
<th>Radius[km]</th>
<th>Mass Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.00001</td>
</tr>
<tr>
<td>100</td>
<td>0.0001</td>
</tr>
<tr>
<td>150</td>
<td>0.001</td>
</tr>
<tr>
<td>200</td>
<td>0.01</td>
</tr>
<tr>
<td>250</td>
<td>0.1</td>
</tr>
<tr>
<td>300</td>
<td>1</td>
</tr>
</tbody>
</table>

A=1 (p+n)

A=2 (d)

A=3 (t+h)

He4 (α)

A>4
α particles do not condense in stellar matter but do in light cluster matter

SF & I. Mishustin submitted to PRC

stellar matter

light cluster matter (only Z,N ≤ 2)

\[ n_{\alpha c} \]

Heavy nuclei

\[ n + p \]

\[ \alpha \]

\[ d(A=2) \ t + h \ (A=3) \]

\[ T = 1.0 \text{ MeV}, \ Y_e = 0.5 \]
Supernova nuclei and multifragmentation
(in low E Heavy Ion Collision)

- common terms
  - $E/A \approx 3-10$ MeV
  - $\rho \approx 0.01-0.3 \rho_0$

- different terms
  - total baryon number
    Supernova: infinity
    HIC: $<500$ (ex Pb+Pb)
  - electron screening
    Supernova: strong
    HIC: weak

Buyukcizmeci et al. 2013
Core-Collapse Supernovae greatly depends on equation of state data (stiffness, nuclear composition) and weak interaction data.

The most ambiguous parts in model and data are nuclear excitation model for equation of state & electron capture rates for weak interaction data (see SF H. Nagakura et al. PRC ’17, PRC SF PRC ’18)

Nuclei with (N,Z)=(40-80,25-40) appear at $\rho \sim 10^{11-12}$ g/cc.

Primary targets are nuclei with (N,Z)≈(50,30)

Deuterons may affect dynamics and $\nu$ emissions after bounce. (SF, H. Ngakura et al. APJ ’13, H. Nagakura, S.F. et al. PRC ‘19)

$\alpha$-particles do not condense in stellar matter. (SF, I. Mishustin, submitted to PRC ’19)