Influence of astrophysical and \((\alpha, n)\) reaction rate uncertainties on the nucleosynthesis in neutrino-driven supernova ejecta

Julia Bliss (TU Darmstadt), Almudena Arcones (TU Darmstadt, GSI) Fernando Montes (NSCL, JINA), Jorge Pereira (NSCL, JINA)

Nuclear Physics in Stellar Explosions Workshop’18 Atomki, Debrecen (September 12th, 2018)
The origin of elements

**Slow neutron capture process**

- $n_n \approx 10^8 - 10^{12}$ cm$^{-3}$
- $\tau_\beta \ll \tau_{(n,\gamma)}$

**Rapid neutron capture process**

- $n_n \gg 10^{23}$ cm$^{-3}$
- $\tau_\beta \gg \tau_{(n,\gamma)}$

(courtesy of Y. Litvinov)
Observations of very old stars

- Clues about origin of heavy elements
- **Robustness** for elements **beyond Ba**
- **Scatter** in the abundances of lighter heavy elements (**Sr-Ag**)
  → more than one r-process
  
  (Qian & Wasserburg 2001, Hansen et al. 2014)

  → Lighter Element Primary Process?
  
  (Travaglio et al. 2004, Montes et al. 2007)

  → neutrino-driven winds produce Sr-Ag
  
  (Arcones & Montes 2011, Arcones & JB 2014)

\[
\log \varepsilon(X) = \log_{10} \left( \frac{N_X}{N_H} \right) + 12
\]

Sneden et al. 2008
Neutrino-driven winds

- **Hot neutron star** is born after core-collapse supernovae
- Mass outflow with supersonic velocity
- Nuclear statistical equilibrium (NSE) at the beginning of our calculations
- Alpha-rich freeze out
- Formation of $^{12}$C
- **Alpha-process** → seed nuclei

$2n + 2p \rightarrow ^{4}\text{He}$

$\bar{\nu}_e + p \leftrightarrow n + e^+$

$\nu_e + n \leftrightarrow p + e^-$

$Y_e < 0.5$: n + seed → heavy nuclei

$Y_e > 0.5$: $^{56}\text{Ni}$ & other Fe peak nuclei

$\rightarrow$ see e.g., Duncan et al. 1986, Meyer et al. 1992, Woosley et al. 1994, Witti et al. 1994
Nucleosynthesis parameters: entropy, expansion timescale, electron fraction

Necessary r-process conditions were identified by steady-state models
(e.g., Otsuki et al. 2000, Thompson et al. 2001)

- Neutron-rich ($Y_e < 0.5$):
  - $Y_n/Y_{\text{seed}} \approx 100 \rightarrow r$-process
    (Woosley et al. 1994)
  - But conditions are not found in hydrodynamical simulations
    (Fischer et al. 2010, Hüdepohl et al. 2010, Roberts et al. 2010, Arcones & Janka 2011)
  - $Y_n/Y_{\text{seed}} \lesssim 1 \rightarrow$ weak r-process
    (Witti et al. 1994)

- Proton-rich ($Y_e > 0.5$):
  - $Y_p > Y_n$, $Y_n/Y_{\text{seed}}$ very small
    $\rightarrow$ vp-process
Quantification of astrophysical uncertainties

- Uncertainties in supernova mechanism

- Calculation of **steady-state trajectories**: $0.8 \leq M_{\text{ns}}/M_\odot \leq 2$, $9 \leq R_{\text{ns}}/\text{km} \leq 30$, $0.40 \leq Y_e \leq 0.49$

- $S \propto L_\nu^{-1/6} \varepsilon_\nu^{-1/3} R_{\text{ns}}^{-2/3} M_{\text{ns}}$ and $\tau \propto L_\nu^{-1} \varepsilon_\nu^{-2} R_{\text{ns}} M_{\text{ns}}$ (Qian & Woosley 1996)

- Nucleosynthesis calculations: WinNet reaction network (Winteler et al. 2012), reaction rate library JINA Reacli V2.0 (Cyburt et al. 2010)
Different nucleosynthesis types

• Identification of four nucleosynthesis groups → $Y_\alpha/Y_{\text{seed}}$ and $Y_n/Y_{\text{seed}}$

• Not all combinations of $Y_\alpha/Y_{\text{seed}}$ and $Y_n/Y_{\text{seed}}$ are possible

• $Y_e$ has largest impact on nucleosynthesis

• NSE1 and NSE2 are mutually exclusive

Astrophysical uncertainties in neutron-rich conditions

- **NSE1 & NSE2:**
  
  * Matter cannot overcome neutron shell closure $N=50$
  
  * Binding energies and partition functions mainly determine abundances

Astrophysical uncertainties in neutron-rich conditions

- **NSE1 & NSE2:**
  - Matter cannot overcome neutron shell closure $N=50$
  - Binding energies and partition functions mainly determine abundances

Astrophysical uncertainties in neutron-rich conditions

- **NSE1 & NSE2:**
  - Matter cannot overcome neutron shell closure \(N=50\)
  - Binding energies and partition functions mainly determine abundances

Astrophysical uncertainties in neutron-rich conditions

- **CPR1:**
  - Matter does not proceed beyond $N=50$
  - $Q_{(\alpha,n)}$-values determine nucleosynthesis

- **CPR2:**
  - Path overcomes $N=50 \rightarrow$ charged particle reactions critically influence abundances
  - Small changes in $Y_n/Y_{seed}$ and $Y_\alpha/Y_{seed}$ lead to different evolutions
  - Large variations in Sr, Y, Zr, and Ag

Astrophysical uncertainties in neutron-rich conditions

- **CPR1:**
  * Matter does not proceed beyond \( N = 50 \)
  * \( Q_{(\alpha,n)} \)-values determine nucleosynthesis

- **CPR2:**
  * Path overcomes \( N = 50 \) \( \rightarrow \) **charged particle reactions critically influence abundances**
  * Small changes in \( Y_n/Y_{\text{seed}} \) and \( Y_{\alpha}/Y_{\text{seed}} \) lead to different evolutions
  * Large variations in \( \text{Sr, Y, Zr, and Ag} \)

Astrophysical uncertainties in neutron-rich conditions

- **CPR1:**
  - Matter does not proceed beyond $N=50$
  - $Q_{(\alpha,n)}$-values determine nucleosynthesis

- **CPR2:**
  - Path overcomes $N=50 \rightarrow$ **charged particle reactions critically influence abundances**
  - Small changes in $Y_n/Y_{\text{seed}}$ and $Y_\alpha/Y_{\text{seed}}$ lead to different evolutions
  - Large variations in Sr, Y, Zr, and Ag

Reactions in neutron-rich conditions

- Important reactions: $\alpha$, $n$, $p$-capture, $\beta$-decay
- $\tau_{\text{expansion}} \ll \tau_\beta \rightarrow (\alpha,n)$ are key reactions
- $\alpha$-process (Hoffman & Woosley 1992)
- Absence of relevant experiments $\rightarrow$ theoretical reaction rates
- Sensitivity studies for r-process (see e.g., Mumpower et al. 2016, 2017), Type I X-ray bursts (see e.g., Parikh et al. 2008), Nova (see e.g., Hix et al. 2003)

\[
\text{time : } 9.936\text{e-03 s, } T : 4.193\text{e+00 GK, } \rho : 2.481\text{e+05 g/cm}^3
\]
Estimation of \((\alpha,n)\) reaction rate uncertainties

- Reaction codes: TALYS 1.6 (Koning et al. 2017), NON-SMOKER (Rauscher & Thielemann 2000)
  - Based on Hauser-Feshbach model (Hauser & Feshbach 1952)
  - Different intrinsic technical aspects and nuclear physics inputs

- Nuclear physics inputs: \(\alpha\)-optical potentials, level densities, binning of excitation energy (Pereira & Montes 2016, Mohr 2016)

(α,n) reaction rate uncertainties

Reliability of uncertainties: comparison with experiments
→ for $A \approx 2–50$ good agreement (see Mohr 2015)

Reaction rate: $\langle \sigma \nu \rangle_{i,j} = \left( \frac{8}{\mu \pi} \right)^{1/2} (k_B T)^{-3/2} \int_0^\infty E \sigma(E) \exp(-E/k_B T) \, dE$

Problems:
• Few measurements on stable nuclei
• Gamow-window between 3–11 MeV
  (see e.g., Newton et al. 2007)
  → no measurements
• Measurements are not conform
• Disagreement up to a factor of 10
  at low energies

→ Reliability of theoretical (α,n) reaction rates is not better than a factor 10
Impact of $(\alpha,n)$ rate uncertainties on abundances

- Most abundant species: $26 \lesssim Z \lesssim 45$
- Factors of 5 and 10 have similar impact
- Abundances of heaviest elements vary
- Relatively small effect on Y and Zr

Sensitivity study of \((\alpha,n)\) reactions

- Independently vary each \((\alpha,n)\) reaction rate between Fe and Rh by a random factor
- 10,000 Monte Carlo runs
- Representative trajectories of group CPR2
- **MC one** & **MC two**: impact on \(Z=36–39\) → important for synthesis of lighter heavy elements
- **MC three**: effect on \(Z=28–35\) → relevant for explosive nucleosynthesis

JB, Arcones, Montes & Pereira (in preparation)
Identification of key (α,n) reactions

• Spearman rank order correlation (Spearman 1904)
  → Monotonic changes
• $^{82}\text{Ge(α,n)},\ ^{84}\text{Se(α,n)},\ ^{85}\text{Se(α,n)}$
  significantly influence the abundances for $Z=36–39$
• Measurement of $^{75}\text{Ga(α,n)}$ at ReA3 (NSCL/MSU) on July 5—15, 2016
• Accepted proposal for measurement of $^{85}\text{Br(α,n)}$ next year

JB, Arcones, Montes & Pereira (in preparation)
• Lighter heavy elements (Sr-Ag) are produced in neutrino-driven supernova ejecta

• **Astrophysical and nuclear physics uncertainties** critically influence synthesis

• Measurement of $^{82}\text{Ge}(α,n)$, $^{84,85}\text{Se}(α,n)$ will reduce nuclear physics uncertainties

• Comparison with **observations** will **constrain supernova conditions**
Summary and outlook

• Lighter heavy elements (Sr-Ag) are produced in neutrino-driven supernova ejecta

• Astrophysical and nuclear physics uncertainties critically influence synthesis

• Measurement of $^{82}\text{Ge}(\alpha,n)$, $^{84,85}\text{Se}(\alpha,n)$ will reduce nuclear physics uncertainties

• Comparison with observations will constrain supernova conditions

Thank you for your attention!