Modelling Nucleosynthesis in Massive Stars

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Outline

- Evolution of Massive Stars (General)
- How to Model Nucleosynthesis
- Sample Results
- Isotopic Yields and Their Dependence On...
  - Stellar Evolution (+ Nuclear Physics)
  - Stellar Evolution and Explosion Energy
  - Explosion Mechanism
- (r-Process)
Stellar Evolution

Life Cycle of a Massive Star

Supernova
Black Hole
Neutron Star
Recycling
Nebula

Red Supergiant
Life of a Massive Star

- Stars with $M > 8M_\odot$ experience all burning stages: H, He, C, Ne, O, Si core- and shell-burning $\Rightarrow$ type II supernova (explosive burning)
  - $8M_\odot \leq M \leq 10M_\odot$: degenerate late burning
  - $M > 10M_\odot$: normal burning

- Details of stellar evolution and nucleosynthesis depend on stellar mass
  (and on $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$)

- Final state: Neutron star
  (black hole?)
net nuclear energy generation (burning plus neutrino losses) in erg g$^{-1}$ s$^{-1}$

<10$^{-12}$ <10$^{-11}$ <10$^{-10}$ <10$^{-9}$ <10$^{-8}$ <10$^{-7}$ <10$^{-6}$ <10$^{-5}$ <10$^{-4}$ <10$^{-3}$ <10$^{-2}$ <10$^{-1}$ 0

net nuclear energy loss (burning plus neutrino losses) in erg g$^{-1}$ s$^{-1}$

total mass of the star (reduced by mass loss due to stellar winds)

convective envelope (red supergiant)

H shell burning

He shell burning

C shell burning

O shell burning

convection

semi-convection
Dependence on $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$
How to Model Nucleosynthesis

- In principle, 3D hydro necessary to follow convection, mixing and explosion
- Problems:
  - Coupling to reaction networks (energy generation, nucleosynthesis)
  - Explosion
- Compromise:
  - 1D hydro + reduced energy generation network
  - mixing length theory, convection criteria (Ledoux, Schwarzschild, semi-convection)
  - Parameterized explosion
- Nevertheless, mostly reliable nucleosynthesis expected (for nuclides independent of expl. mech.)
Parameterized Explosion

- **Thermal Bomb**
  - Thermal energy deposited in Fe core ($T^\uparrow$)
  - Mass cut chosen to reproduce $^{56}$Ni
  - Nomoto et al. 1997, Thielemann et al. 1996,...

- **Piston**
  - Kinetic energy induced by inward-outward motion of „piston“
  - Mass cut implicit, energy chosen to reproduce either explosion energy or $^{56}$Ni

- **Radiation Domained Shock approximation (RDA)**

- **Innermost high entropy layers (r-process)** cannot be described by these procedures
Nucleosynthesis in Massive Stars
($M > 10M_\odot$)

- First Calculation with large network
- Pop I, all burning phases + explosive nucleosyn.
- No r-process zones!
- Param. explosion
- >1000 hydrodyn. zones
- 5 stellar masses
- Tests of different rate sets
- Basis for studies of galactic chemical evolution

Rauscher et al. 2002 (with UCSC and LLNL)
The Full Network

Rauscher et al. 2002 (with UCSC and LLNL)
Nucleosynthesis Results (15 M☉)

- $^{16}$O is indicator
- Mostly hydrostatic burning
- $^{62}$Ni overproduction?!
- „weak“ s-process component

Rauscher et al. 2002 (with UCSC and LLNL)
Overproduced:

$^{23}\text{Na}$, $^{40}\text{K}$,

$^{46}\text{Ca}$, $^{62}\text{Ni}$
Nucleosynthesis Results (15 M☉)

Rauscher et al. 2002 (with UCSC and LLNL)
Explosive Nucleosynthesis

- Li, Be, F from $\nu$-burst
- Ti-Fe by high n-flux
- $\gamma$-Process (depending on mass/stellar structure)

Rauscher et al. 2002 (with UCSC and LLNL)
Dependence On Explosion Energy (25 $M_{\odot}$)

Ratio: $H/L$

- $L$: $0.1\, M_{\odot}\, ^{56}\text{Ni} (1.735\times10^{51}\, \text{ergs})$
- $H$: $0.2\, M_{\odot}\, ^{56}\text{Ni} (2.293\times10^{51}\, \text{ergs})$
Nuclide Classes

Yields determined by:

- **Stellar evolution only (hydrostatic + explosive burning)**
  - Depending on progenitor mass
  - Sensitive to structure, mixing, rotation, rates
  - He, C, O, Ne, Mg; $^{26}\text{Al}$, $^{59}\text{Co}$, $^{56}\text{Fe}$

- **Stellar evolution + explosion energy**
  - Weakly progenitor mass dependent
  - Si, S, Ar, Ca

- **Explosion mechanism**
  - Depending on mass cut, size of Fe core
  - Also depending on explosion energy, $Y_e$
  - Fe-group, also including Ti ($^{44}\text{Ti}$, $^{56,57}\text{Ni}$); r-process!?
Some Key Reactions

- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$: very important, determines C/O, stellar evolution, collapse and explosion; required accuracy < 10%
The Reaction $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$

Boyes, Heger & Woosley 2002
Some Key Reactions

$^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$: very important, determines C/O, required

$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$, $^{22}\text{Ne}(\alpha')^{26}\text{Mg}$, $^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$: 2nd largest

Stellar evolution, collapse and explosion; required

Current uncertainty, neutron source for weak s-process

Current uncertainty; current uncertainty is a factor of 2

Accuracy $> 10\%$
(\(\alpha, n\))/(\(\alpha, \gamma\)) Branching at \(^{22}\text{Ne}\)

Ratio of results with \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\) and \(^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}\) rates varied within experimental uncertainties. The branching ratio determines the production of the weak s-process component, because the neutron source is \(^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}\).

Rauscher et al. 2002 (with UCSC and LLNL)
Some Key Reactions

- $^{12}\text{C}(\alpha,\gamma)^{16}\text{O}$: very important, determines C/O, stellar evolution, collapse and explosion; required accuracy < 10%
- $^{22}\text{Ne}(\alpha,\gamma)^{26}\text{Mg}, ~^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$: 2\textsuperscript{nd} largest uncertainty, neutron source for weak s-process component; current uncertainty is a factor of 2
  - $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$: 60Fe decay can be observed with INTEGRAL, no experimental value!
  - $^{62}\text{Ni}(n,\gamma)^{63}\text{Ni}$: (+other Ni) Overproduction, no data in relevant energy range!
Multi-D Nucleosynthesis

(Have to assume explosion)

1. Nuclear burning zones are non-spherical
   - Different explosive nucleosynthesis?

2. Ashes of burning are mixed BEHIND the front
   - Different observational signature
Further Contributions On Modelling

Details

- Rotation and $^{26}\text{Al}$ synthesis in metallicity-poor stars: Meynet, this afternoon
- Explosion mechanism: Fryer, this afternoon
- Multi-D nucleosynthesis: Travaglio, this afternoon
- R-process: Pfeiffer, Kratz, Tuesday afternoon
- P-process: Kajino, Tuesday afternoon
- S-process: Gallino, Wednesday morning

+ many observations and data!

Thanks to the organizers and have a good conference!