The ν process

in supernova explosions of massive stars

A. Sieverding[1], G. Martínez-Pinedo[1],
K. Langanke[1,2], A. Heger[3], J.A. Harris[4,5], W.R. Hix [5,6]
[1]Technische Universität Darmstadt
[2]GSI Helmholtzzentrum, Darmstadt
[3]Monash Centre for Astrophysics, Melbourne
[4]Lawrence Berkeley National Laboratory, Berkeley CA
[5]University of Tennessee, Knoxville TN
[6]Oak Ridge National Laboratory, Oak Ridge TN

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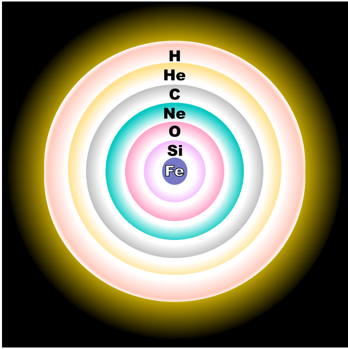
Outline

1. Introduction
   - Neutrino nucleosynthesis
2. Results
   - Experimental constraints on neutrino-nucleus cross-sections
   - The ν process with updated physics in spherical symmetry
   - Multi-D effects on the ν process
3. Conclusions

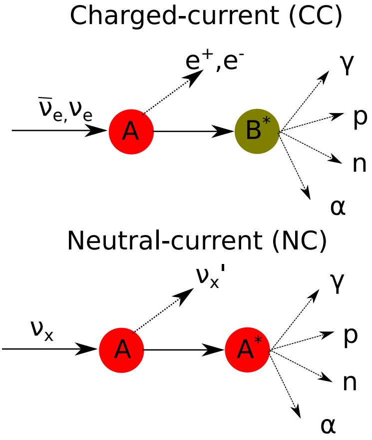
Neutrinos and Supernovae

- The core of a massive star collapses after the nuclear burning phases that leads to an explosion
- Supernova shock triggers explosive nucleosynthesis
- Core emits neutrinos
- Neutrinos can influence the nucleosynthesis in outer layers of SNe
- **Looking for the fingerprint of neutrinos in the chemical composition of the universe**



Schematic structure of a massive star

- Emission of 10^{58} neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 8 - 20$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$



Neutrino nucleosynthesis

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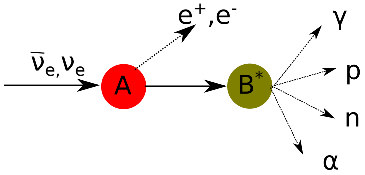
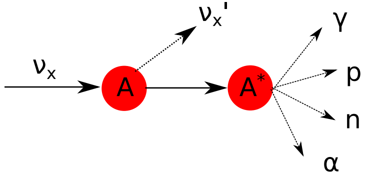
- $\langle E_\nu \rangle \approx 8 - 20$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$
- Inverse β-decay
- Particle evaporation
- Capture of spallation products

Charged-current (CC)



Neutral-current (NC)



First detailed calculations

THE ν-PROCESS[1]

S. E. Woosley,[2,3] D. H. Hartmann,[2,3] R. D. Hoffman,[4] and W. C. Haxton[5]

Received 1989 August 17; accepted 1989 December 11

- Nucleosynthesis including neutrino nucleus reactions
- $\langle E_{\nu_e}\rangle$=13 MeV, $\langle E_{\nu_x}\rangle$=25-30 MeV
- based on detailed stellar models
- parametrized thermodynamic trajectories

^{7}Li and ^{11}B via ^{4}He(ν_x,ν_x' p/n) and ^{12}C(ν_x,ν_x' p)

^{19}F via ^{20}Ne(ν_x,ν_x' p/n)

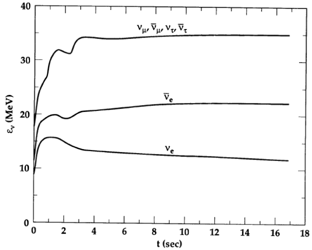
^{138}La and ^{180}Ta via ^{138}Ba(ν_e,e$^-$) and ^{180}Hf(ν_e,e$^-$)

Summary Table: Species Due to Neutrino Nucleosynthesis[a]

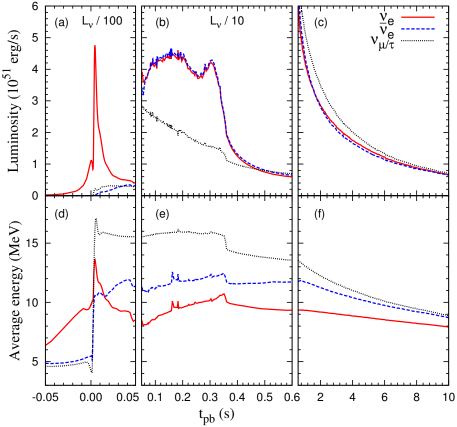
Species	H	He	C	Ne	O	NSE
^{7}Li	B	A	C	...	...	A
^{10}B	...	C	B	...	...	...
^{11}B	...	B	A	...	...	A
^{15}N	...	...	C	C	C	...
^{19}F	...	...	...	A	...	...
^{22}Na	...	...	...	E	...	...
^{26}Al	...	...	...	E	...	...
^{27}Al	...	...	...	...	C	...
^{31}P	...	...	...	...	E	...
^{35}Cl	...	...	...	E	E	...
^{39}K	...	...	...	...	E	...
^{40}K	...	...	...	E	B	...
^{41}K	...	...	...	...	E	...
^{43}Ca	...	...	...	C	C	...
^{45}Sc	...	...	...	...	C	B
^{47}Ti	...	...	...	C	C	C
^{49}Ti	...	...	...	...	...	B
^{50}V	...	...	...	E	B	B
^{51}V	...	...	...	C	E	E
^{55}Mn	...	...	...	...	...	E
^{59}Co	...	...	...	...	...	E
^{63}Cu	...	...	...	...	...	B
^{138}La	...	...	...	A	...	...
^{180}Ta	...	...	...	A	...	...

[a] A = species produced in full abundance; B = important production; C = minor production; E = enhanced significant production.

Progress since the first studies



Woosley et al. (1994), based on models by Wilson et al. (1988)



Wu et al. (2015)

- Structure of the neutrino signal
- Detailed neutrino transport has reduced expected energies
- $\langle E_{\nu_e} \rangle = 9$ MeV, $\langle E_{\bar{\nu}_e} \rangle = \langle E_{\nu, \bar{\nu}_{\mu,\tau}} \rangle = 12$ MeV

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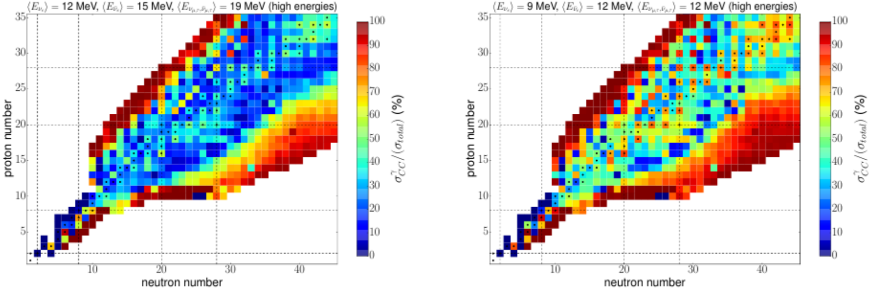
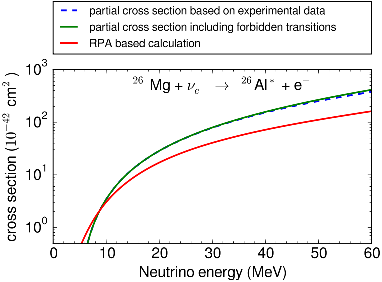
Increased relevance of charged current reactions

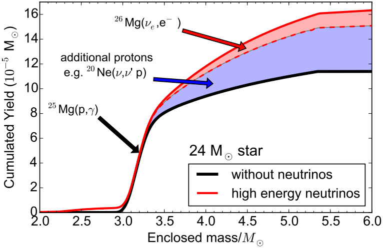
relative importance of inverse β-decay: $\sigma_{CC}^{\gamma}/(\sigma_{CC}^{\text{total}} + \sigma_{NC}^{\text{total}})$ (in %)



- For high ν energies, neutral current spallation clearly dominates for the most abundant nuclei
- reducing the energy shifts the balance more towards charged current reactions
- Increased sensitivity to individual low energy transitions

Cross-sections based on experimental data





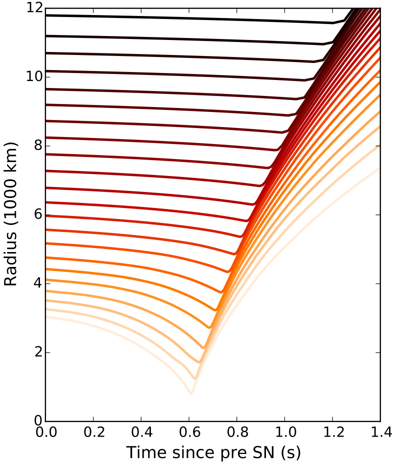
- ~10 % constribution to the ^{26}Al production

- $B(GT)$ from ^{26}Mg(^{3}He,t) measurements
- Forbidden transitions are added from the theoretical calculations
- Branchings are calculated based on a statistical model

Outline

Supernova model

- 1D piston driven explosions with the KEPLER code *(Woosley et al. 2007)*
- kinetic explosion energy $E_{\mathrm{expl}} = 1.2 \times 10^{51}\mathrm{erg}$



Neutrino flux

- Exponentially decreasing neutrino luminosity
- Fermi-Dirac spectrum
- Constant neutrino energies

Updated Physics

- Reduced neutrino energies
- $\langle E_\nu \rangle$=8-13 MeV
- Improved and extended set of neutrino-nucleus cross-sections

← Explosion trajectories for a 25 $M_\odot$ model

Production factors and IMF average

- The solar abundances provide observational information for nucleosynthesis results to compare with

Production factor

- $P_{A,\text{normalized}} = \left(\frac{X_A}{X_A^{\odot}}\right) / \left(\frac{X_{^{16}\text{O}}}{X_{^{16}\text{O}}^{\odot}}\right)$

Assuming that CCSNe are the main source of solar ^{16}O

- $P_{A,\text{normalized}} \sim 1$ indicates CCSNe as possible production site
- $P_{A,\text{normalized}} \ll 1$ hints another production site or mechanism

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Initial Mass Function (IMF)

Distribution of progenitor masses: $dN_*/dm_* \propto m_*^{-1.35}$

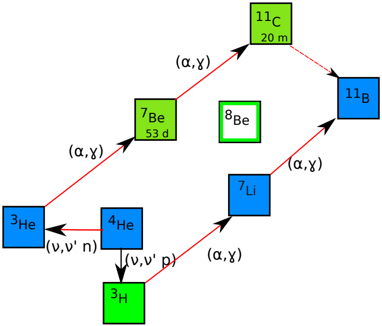
Production factors normalized to ^{16}O

- IMF averaged production factor for 13-30 $M_\odot$ stars (solar metallicity)

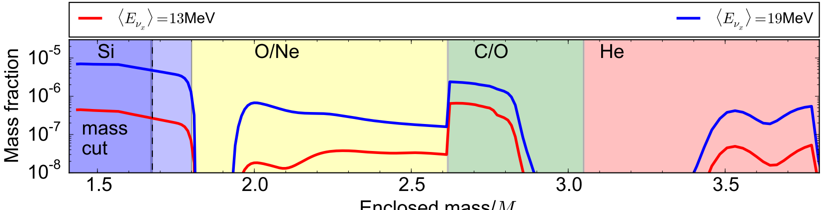
Nucleus	no ν	Low energies[1]	High energies[2]
^{7}Li	0.001	0.07	0.91
^{11}B	0.005	0.45	1.81
^{15}N	0.06	0.09	0.15
^{19}F	0.12	0.25	0.40
^{138}La	0.12	0.86	1.70
^{180}Ta*	0.24	0.49	0.88

- 1) $\langle E_{\nu_e} \rangle = 9$ MeV, $\langle E_{\bar{\nu}_e,\nu_x} \rangle = 13$ MeV
- 2) $\langle E_{\nu_e} \rangle = 13$MeV ,$\langle E_{\bar{\nu}_e} \rangle = 16$ MeV, $\langle E_{\nu_x} \rangle = 19$ MeV
- *) Only about 40% of ^{180}Ta survive in the long-lived isomeric state

Production of ^{11}B



1. Si shell (NSE)
   - α-rich freeze-out
   - Spallation of ^{4}He
2. O/Ne shell
   - Production from ^{12}C and ^{16}O
3. C/O shell
   - Production from ^{12}C
4. He shell
   - Spallation of ^{4}He



15 $M_\odot$ progenitor model, parametrized trajectories

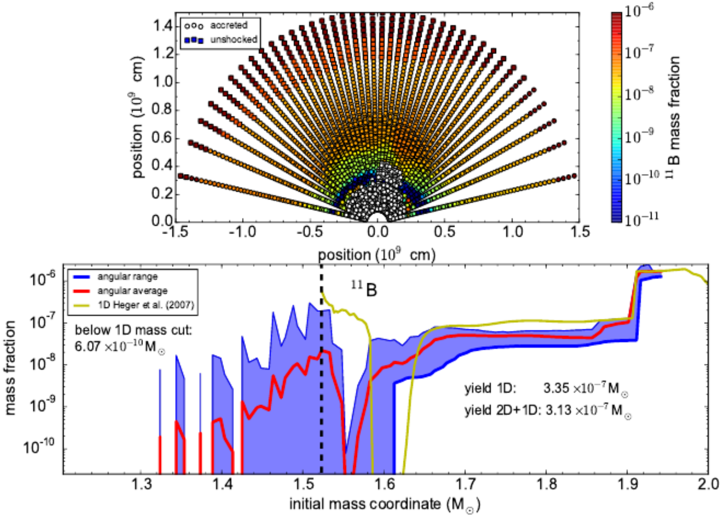
Outline

The ν process in 2D

- Possibly stronger exposure due to convective motion

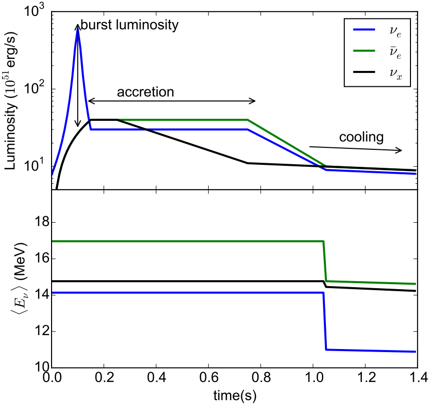
- 2D axisymmetric simulation with CHIMERA (ORNL group, Bruenn et al. 2016, Harris et al. 2017)
- Nucleosynthesis calculations with lagrangian tracer particles
- based on a non-rotating 12 $M_{\odot}$ progenitor of solar metallicity (Woosley et al. 2007)
- Neutrino fluxes and energies from the simulation calculated with a multi-group flux-limited diffusion method

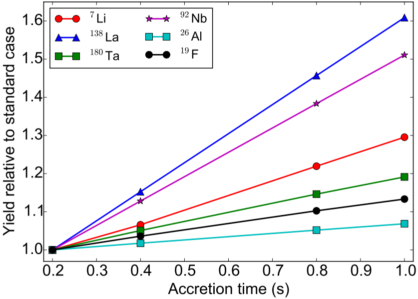
2D effects on ^{11}B production (preliminary)



Detailed neutrino signal

- Neutrino luminosity including burst and accretion, time-dependent energies
- Explosion delayed accordingly





- Correlation between ^{138}La and accretion time

Conclusions

- Study of neutrino induced nucleosynthesis for piston driven explosions in 1D with improved neutrino-nucleus cross-sections and modern estimates for neutrino energies
- Multi-D effects do not change the light element production in the ν process significantly
- Correlations between the yields ^{138}La and ^{92}Nb and the strength of the neutrino bursts and accretion time

Conclusions

- Study of neutrino induced nucleosynthesis for piston driven explosions in 1D with improved neutrino-nucleus cross-sections and modern estimates for neutrino energies
- Multi-D effects do not change the light element production in the ν process significantly
- Correlations between the yields ^{138}La and ^{92}Nb and the strength of the neutrino bursts and accretion time
- Outlook
  - Quantify uncertainties accociated with the ν process and nuclear reaction rates for nucleosynthesis sensitivity