Nucleosynthesis in neutrino-heated matter

Gabriel Martínez Pinedo

GSI

June 30, 2006

Outline

1. Proton-rich ejecta
   - Are light p-nuclei synthesized in neutrino heated ejecta?
2. Neutron-rich ejecta: The role of fission
   - Nuclear physics input and models
   - Results
3. Conclusions

Outline

1. Proton-rich ejecta
   - Are light p-nuclei synthesized in neutrino heated ejecta?
2. Neutron-rich ejecta: The role of fission
   - Nuclear physics input and models
   - Results
3. Conclusions

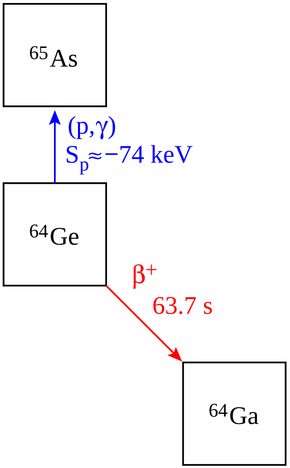
Outline

1. Proton-rich ejecta
   - Are light p-nuclei synthesized in neutrino heated ejecta?
2. Neutron-rich ejecta: The role of fission
   - Nuclear physics input and models
   - Results
3. Conclusions

Proton-rich ejecta: The νp-process

- Proton-rich ejecta could be the major contributor of ^{45}Sc, ^{49}Ti and ^{64}Zn (Pruet *et al.* 2005, Fröhlich *et al.* 2006)
- Can proton-rich ejecta be the site of a kind of rp-process in supernovae?
- Problem with the short time scales for explosive nucleosynthesis in supernovae ($\sim$ seconds).
- Antineutrino absorption can speed up matter flow.

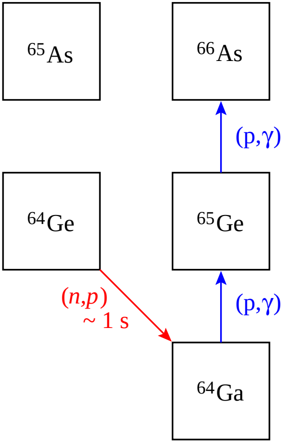
$$\bar{\nu}_e + p \rightarrow e^+ + n \ (\text{time} \sim \text{seconds})$$



Proton-rich ejecta: The νp-process

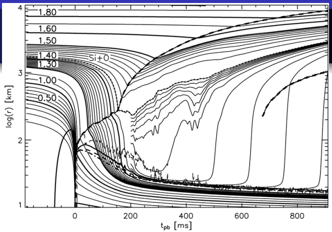
- Proton-rich ejecta could be the major contributor of ^{45}Sc, ^{49}Ti and ^{64}Zn (Pruet *et al.* 2005, Fröhlich *et al.* 2006)
- Can proton-rich ejecta be the site of a kind of rp-process in supernovae?
- Problem with the short time scales for explosive nucleosynthesis in supernovae (~ seconds).
- Antineutrino absorption can speed up matter flow.

$$\bar{\nu}_e + p \rightarrow e^+ + n \,(\text{time} \sim \text{seconds})$$

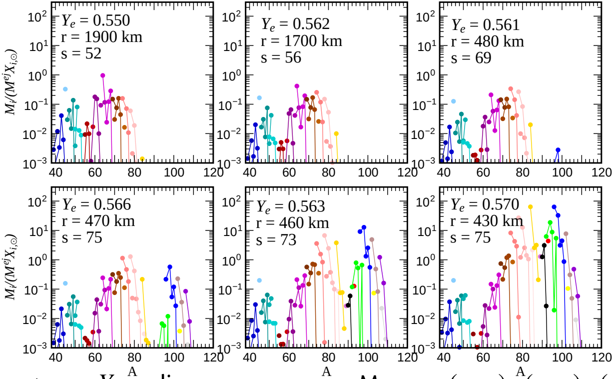


The νp-process
C. Fröhlich, *et al.*, PRL **96**, 142502 (2006)
Physical Review Focus (April 21).

Nucleosynthesis variability



Trajectories from Garching group [Pruet *et al.*, ApJ **644**, 1028 (2006), Poster ID: 180]

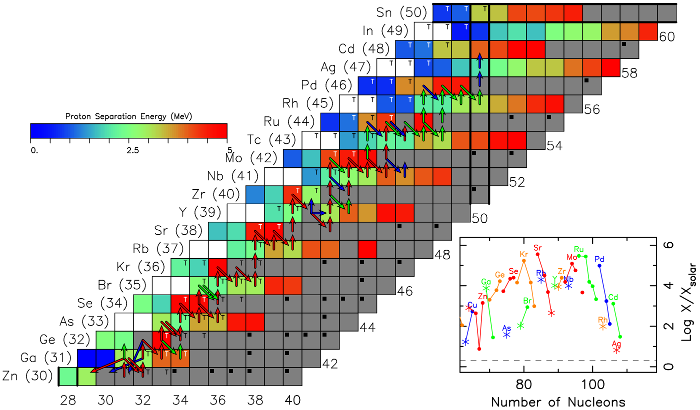


Sensitivity entropy, Y_e, radius.

Masses, (p,γ), (n,p), (n,γ),

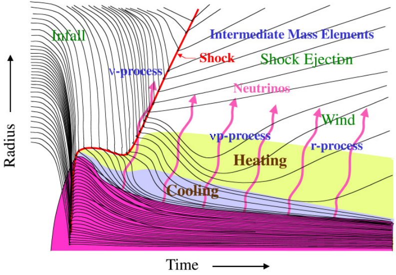
Nucleosynthesis fluxes

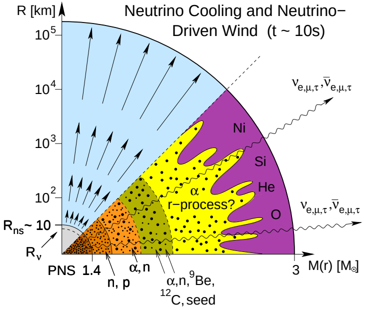
Figure from Pruet *et al*, ApJ **644**, 1028 (2006) [Poster ID: 180]



Production of ^{92}Mo is sensitive to the masses (and proton capture rates) in the region of ^{92}Pd.

Composition in neutrino heated ejecta

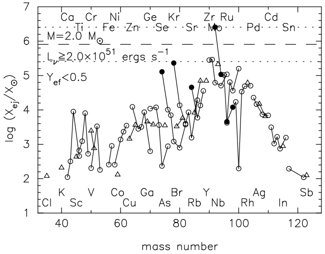


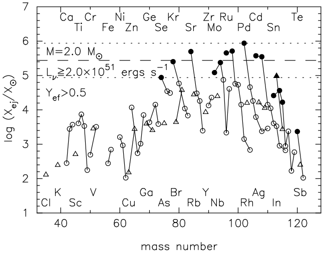


- Early ejecta proton-rich: νp-process
- Later ejecta neutron rich: r-process.
- Nucleosynthesis sentsitive to proton to seed ratio (νp-process) and neutron to seed ratio (r-process).

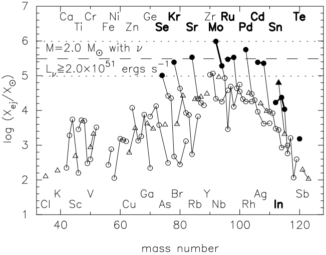
Production of light p nuclei

S. Wanajo, astro-ph/0602488 (Poster ID: 105)

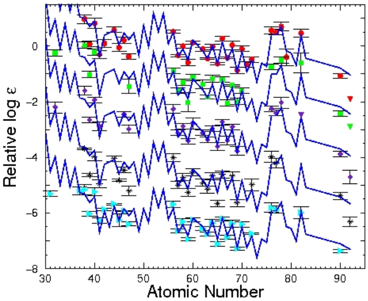




- ^{92}Mo is produced in slightly neutron rich ejecta, $Y_e \approx 0.47$–0.49 (Fuller & Meyer 1995, Hoffman *et al.* 1996).
- The rest is produced in proton-rich ejecta.



r-process and metal poor stars



J. Cowan, NIC-IX talk
Cowan & Sneden, Nature **440**, 1151 (2006)

r-process sites:

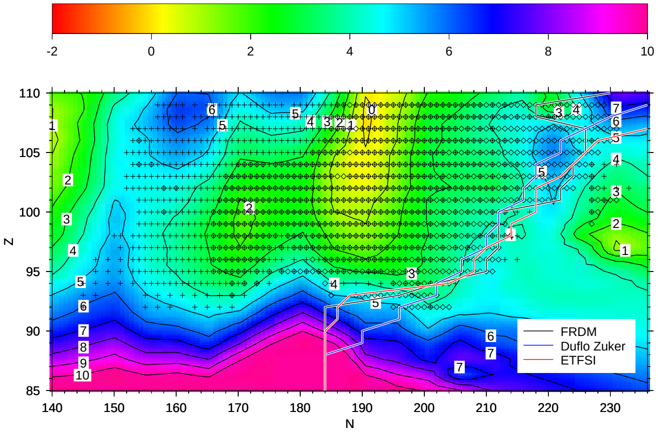
- High entropy neutrino-driven wind (Woosley *et al.* 1994, Takahashi *et al.* 1994).
- Low entropy, low Y_e ejecta:
  - Prompt explosion of ONeMg white dwarfs. Seems to be rule out by recent calculations (Kitaura, Janka and W. Hillebrandt 2006, Adam Burrows talk).
  - Neutron stars mergers (Freiburghaus, Rosswog, and Thielemann 1999).

Our calculations

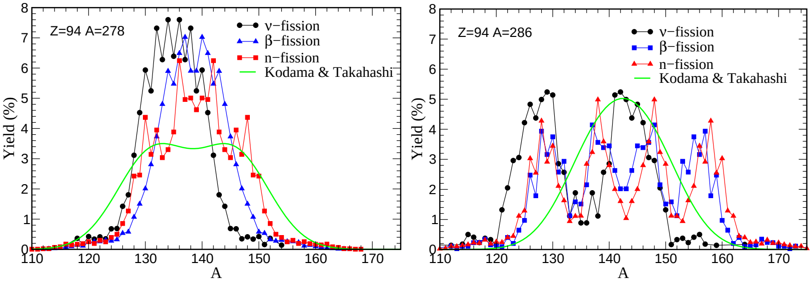
- Adiabatic expansions (Freiburghaus *et al.* 1999). Expansion velocity 4500 km/s ($\tau = 50$ ms), $Y_e = 0.45$. We want to achieve large enough neutron to seed ratio to study the effect of fission in the r-process.
- Full nuclear network (p,n…Eu) before alpha-rich freeze-out.
- R-process code (D. Mocelj), $Z \leq 110, A \leq 340$.
- neutron-capture and neutron fission cross sections (I. Panov, T. Rauscher, F.-K. Thielemann)
- Beta-decay rates and beta-delayed fission (P. Möller, B. Pfeiffer, and K.-L. Kratz).
- neutrino absorption and neutrino induced fission (N. Zinner & K. Langanke)
- Fission yields for all processes (ABLA code, N. Zinner, A. Kelić, K.-H. Schmidt)

Where does fission occur?

Myers & Swiatecki Barriers

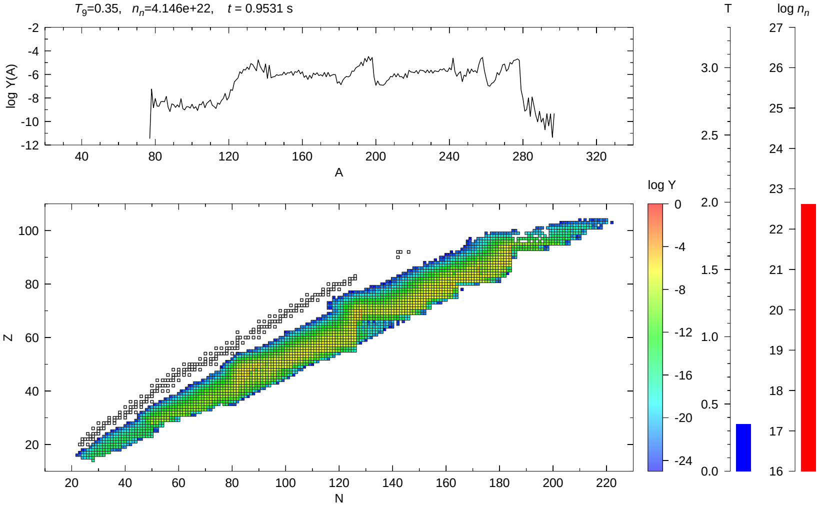


Fission yields

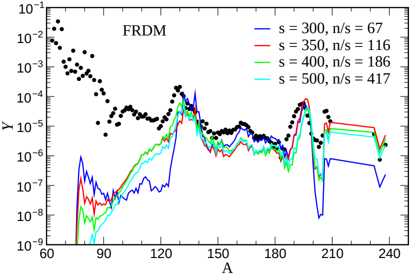


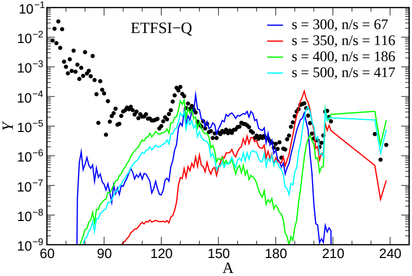
Heavier nuclei tend to produce lighter fragments.

Snapshot

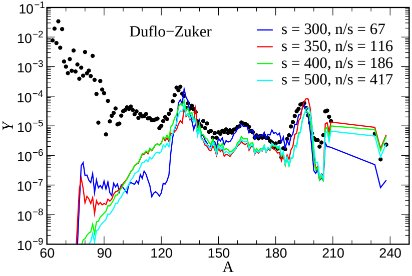


Comparison of abundances





Differences are due to different shell structure at $N = 82$



Some quantitative results

Percent of final abundance that has undergone fission.

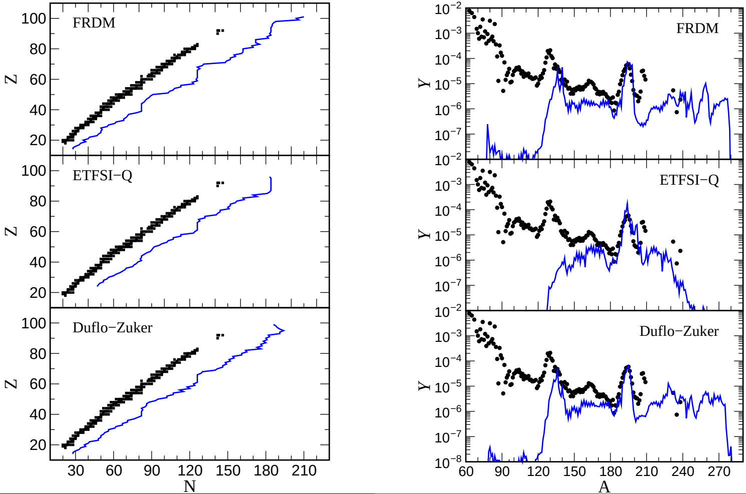
$n/s = 116$	$(n,\text{fission})$	β-fission	ν-fission	Total
ETFSI-Q	0	0	0	0
FRDM	10	1	0	11
Duflo-Zuker	10	1	0	11

$n/s = 186$	$(n,\text{fission})$	β-fission	ν-fission	Total
ETFSI-Q	33	5	0	38
FRDM	36	3	0	39
Duflo-Zuker	36	3	0	39

$n/s = 417$	$(n,\text{fission})$	β-fission	ν-fission	Total
ETFSI-Q	56	4	0	60
FRDM	58	5	0	63
Duflo-Zuker	58	5	0	63

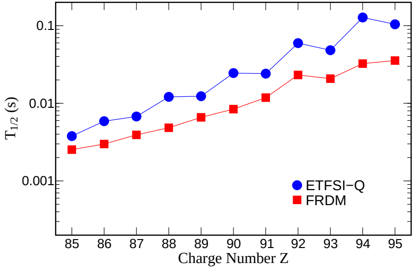
Abundances at freeze-out

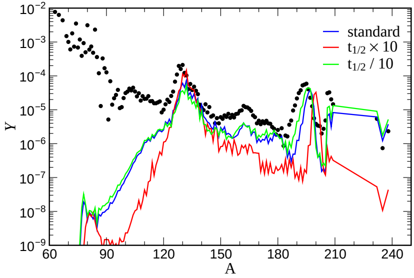
R-process path and abundances at freeze out for $n/s = 116$.
$T_9 = 0.6, N_n = 6.4 \times 10^{23}\ \text{cm}^{-3}$



Role of half-lives at N=184

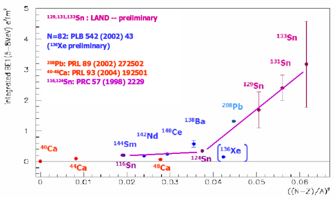
- Matter accumulated at $N = 184$ ($A \sim 270$) will fission in the decay to "stability".
- During the decay will reach a region with large fission probabilities and fission will take place. Mainly neutron induced (chain reaction in atomic bomb).
- The released neutrons can produce mayor shifts in the $A \sim 195$ peak if the beta decay half-lives are too long. They are responsible for a kind of weak r (strong s) process with $N_n \sim 10^{16}$ cm^{-3}. Sensitive to (n, γ) cross sections.

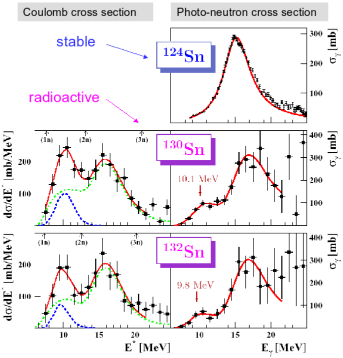




Soft dipole strength in neutron-rich nuclei

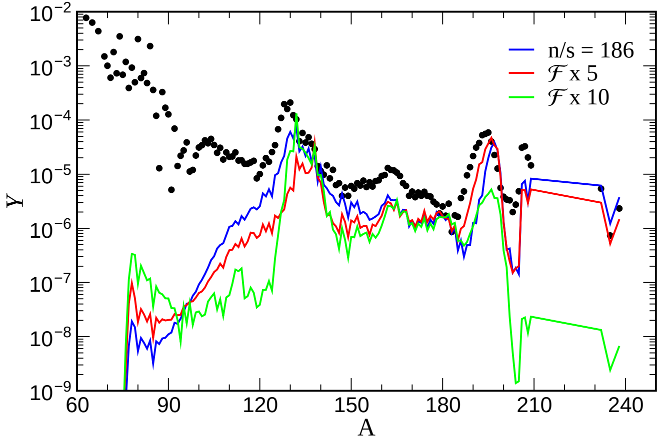
Coulomb dissociation measurements by the LAND Collaboration (GSI) show an increase in $E1$ strength at low energies in neutron rich Sn isotopes. [P. Adrich *et al.*, PRL **95**, 132501 (2005)]



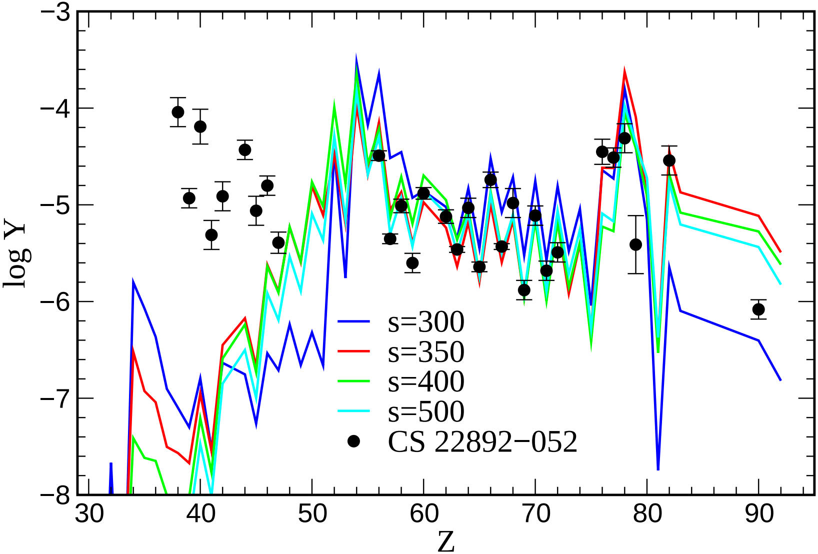


Role of neutrinos

If we increase neutrino fluence there is no production of heavy r-process nuclei (α-effect, Fuller & Meyer 1995).

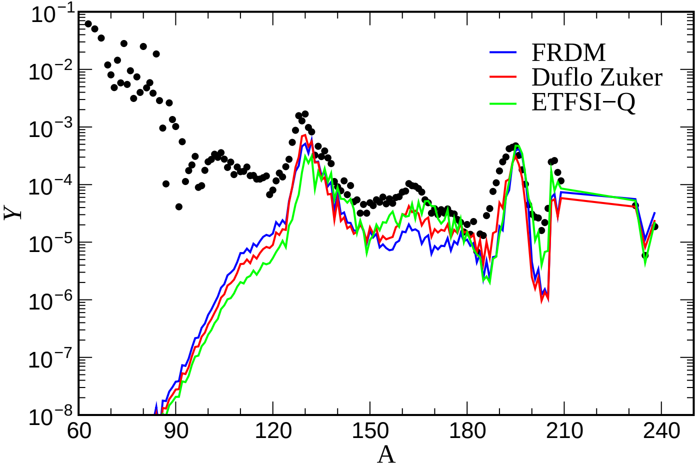


Elemental abundances



Neutron stars mergers

Trajectory from Freiburghaus, Rosswog, and Thielemann 1999 ($Y_e = 0.1, n/s = 238$).



Conclusions

- A combination of proton-rich material (νp-process) and slightly neutron-rich material ($Y_e \sim 0.48$) could explain the solar abundances of light p-nuclei (^{92,94}Mo, ^{96,98}Ru).
- Fission plays a very important role in determining the final abundances and dynamics of the r-process.
- The strength of the $N = 82$ plays a very important role in determining the role of fission.
- Mass models with strong shell effects are able to produce a consistent and robust r-process patters as soon as the neutron to seed ratio is large enough to induce fissions.
- Neutrino-induced fission is irrelevant for the determination of the r-process abundances. Neutron-induced fission is the dominating channel.

Collaborators

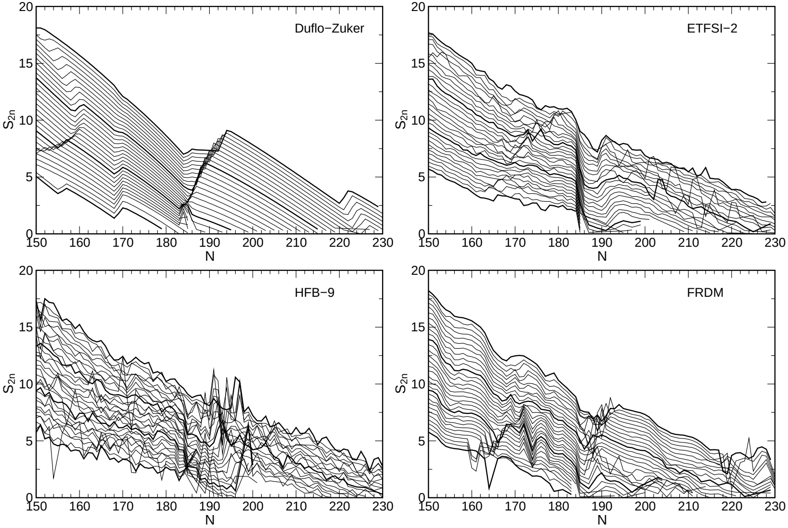
- Proton-rich ejecta.

C. Fröhlich (Basel)	F.-K. Thielemann (Basel)	M. Liebendörfer (Basel)
K. Langanke (GSI)	N. T. Zinner (Århus)	R. Hix (Oak Ridge)
E. Bravo (Barcelona)		

- r-process nucleosynthesis.

D. Mocelj (Basel)	F.-K. Thielemann (Basel)	T. Rauscher (Basel)
K. Langanke (GSI)	A. Kelić (GSI)	K.-H. Schmidt (GSI)
N. T. Zinner (Århus)	I. Panov (Moscow)	P. Möller (Los Alamos)
B. Pfeiffer (Mainz)	K.-L. Kratz (Mainz)	

N=184 Two-Neutron separation energies



N=82 and N=126 Two-Neutron separation energies