Synthesis of heavy elements by the r-process

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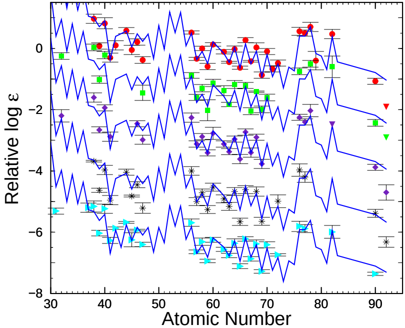
R-process requirements

The r-process requires an environment with high neutron densitities relative to the amount of seed nuclei available to capture them. We need to address the following questions:

- What are the seed nuclei and how are they produced?
- How do temperature and density evolve with time during the r-process?
- What are the properties of nuclei participating in the r-process and the relevant rates?
- What and how many are the astrophysical sources?

r-process and metal-poor stars

Cowan & Sneden, Nature **440**, 1151 (2006)



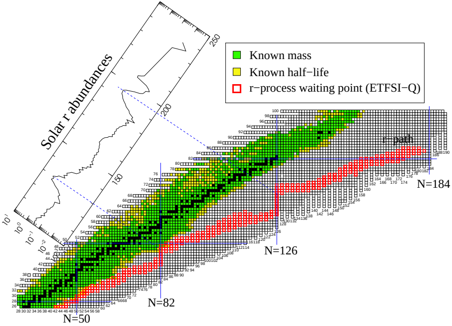
Several stars show robust r-process for $Z > 56$.

- Nucleosynthesis Signatures of few (single?) events.
- Abundances $Z > 56$ consistent with solar r-process abundance. $Z < 56$ are underproduced with respect solar abundances.
- At least two different astrophysical sites are necessary to explain solar r-process abundances.

What is the origin of the robust r-process?

The decay of U and Th can be used to determine the age of the star

The r-process



The r-process is responsible for the synthesis of half the nuclei with $A > 60$ including U, Th and maybe the super-heavies.

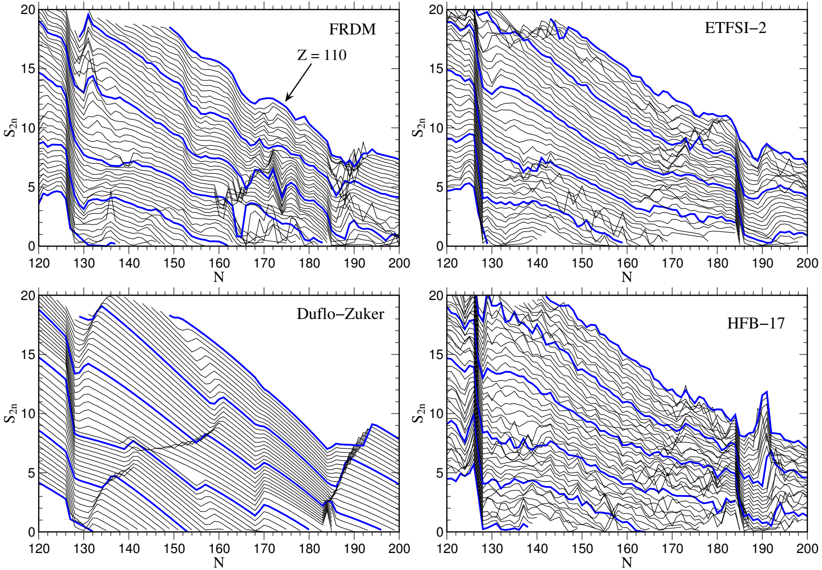
The r-process requires the knowledge and the evolution with neutron excess of:

- Nuclear masses.
- Beta-decay half-lives.
- Neutron capture rates.
- Fission rates.
- Reactions with neutrinos.

Main parameter determining the nucleosynthesis is the neutron-to-seed ratio n_s.

$$A_f = A_i + n_s$$

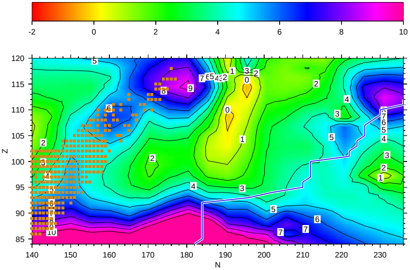
N=126 – N=184 Two-Neutron separation energies



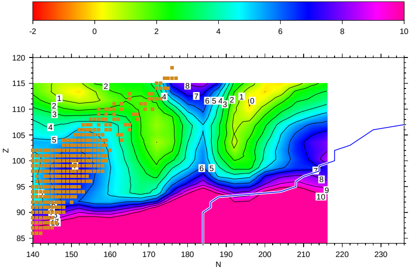
Fission in the r-process

- Depends of the fission barriers.
- It is necessary to consider all fission inducing processes (neutron induced, beta delayed, spontaneous fission, …) and the corresponding yields.

Thomas-Fermi
[Myers & Świątecki, PRC **60**, 014606 (1999)]



Extended Thomas-Fermi
[Mamdouh *et al*, NPA **679**, 337 (2001)]



Neutron-induced fission is the dominating process.

Fission in the r-process

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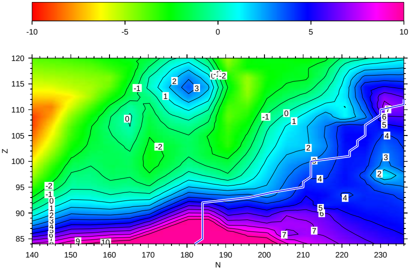
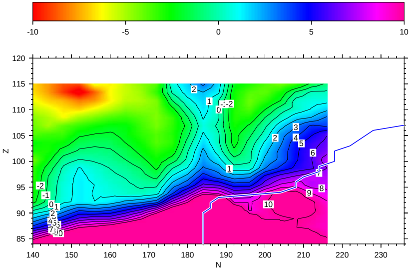
Barrier minus neutron separation energy (TF barriers, FRDM masses).



Barrier minus neutron separation energy (ETFSI barriers and masses)



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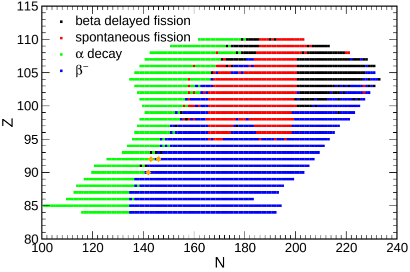
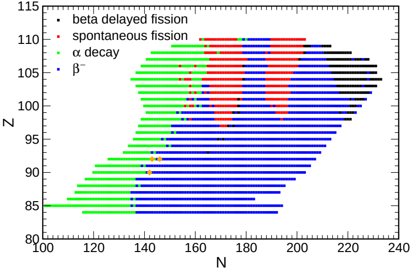
Fission in the r-process

Other fission channels become relevant after neutron exhaustion.

TF barriers



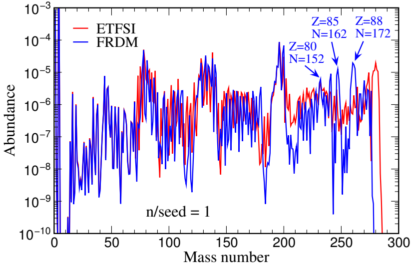
ETFSI barriers



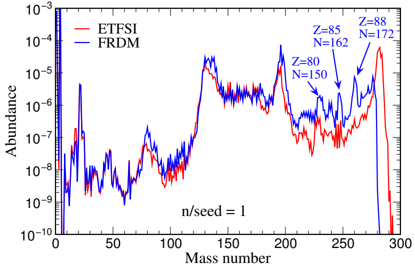
Influence in r-process abundances

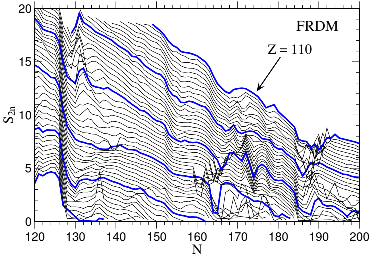
Depends on both the nuclear physics input and the temperature evolution.

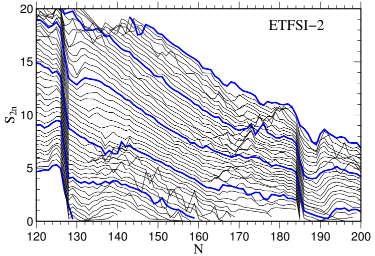
Hot r-process



Cold r-process





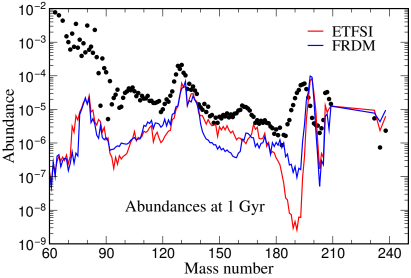


(I. Petermann PhD Thesis)

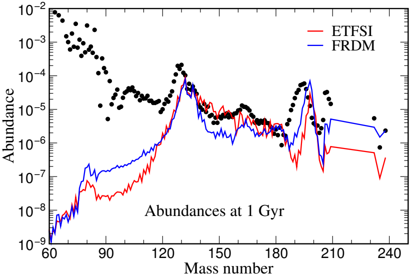
Influence in r-process abundances

- Strong $N = 184$ shell results in larger production of superheavy nuclei.
- Late time fission produces large changes in the r-process distribution.

Hot r-process



Cold r-process

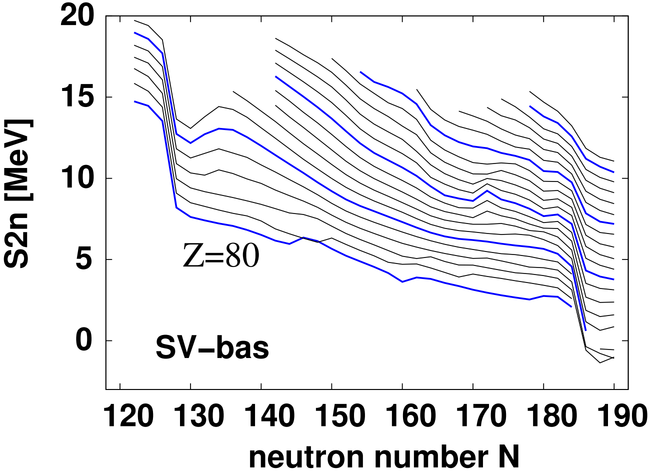


Summary

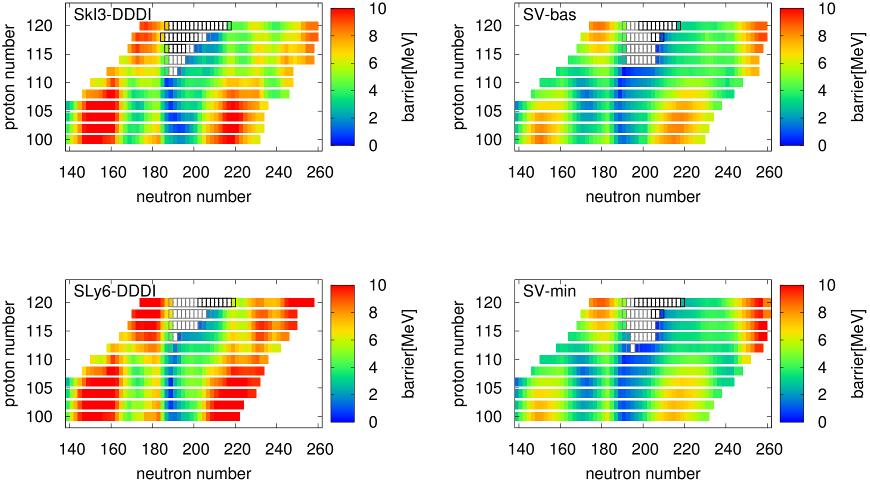
- r-process nucleosynthesis is rather sensitive to the nuclear physics input and to the long term evolution of the ejected matter.
- A better understanding of the decay modes and structure of heavy nuclei is necessary to obtain reliable estimates of the abundances of U and Th.

Outlook

We are currently exploring the sensitivity of neutron separation energies, barriers and fission half-lives to different Skyrme forces (J. Erler, H. P. Loens, P.-G. Reinhard, GMP)



Systematic of barriers



Spontaneous fission