Synthesis of heavy elements by the r-process

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R-process requirements

The r-process requires an environment with high neutron densities 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?
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 to 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

FRDM

$Z = 110$

ETFSI–2

Duflo–Zuker

HFB–17
Fission in the r-process

- Depends on 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

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

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

Barrier minus neutron separation energy (ETFSI barriers and masses).

Neutron-induced fission is the dominating process.
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)
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**
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.
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

- SkI3-DDDI
- SV-bas
- SLy6-DDDI
- SV-min
Spontaneous fission

- **SkI3-DDDI**
- **SV-bas**
- **SLy6-DDDI**
- **SV-min**

### Parameters
- Neutron number
- Proton number
- $\tau_{SF}$ (s)