The role of fission in r-process nucleosynthesis

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GSI

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NAVI Nuclear Astrophysics Virtual Institute

HELMHOLTZ GEMEINSCHAFT

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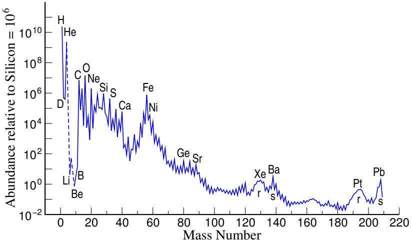
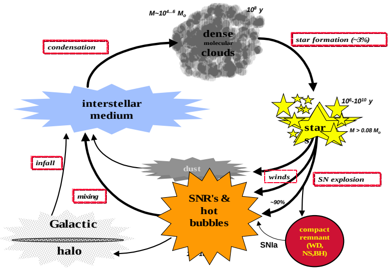
Outline

Signatures and nucleosynthesis processes

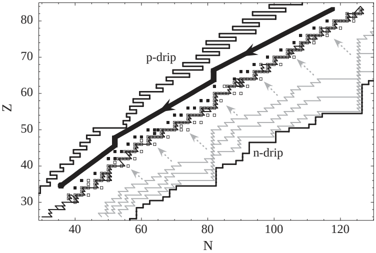
- Solar system abudances contain signatures of nuclear structure and nuclear stability.
- They are the result of different nucleosynthesis processes operating in different astrophysical environments and the chemical evolution of the galaxy.

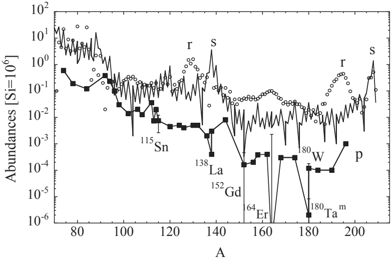




Nucleosynthesis beyond iron (Traditional description)

Three processes contribute to the nucleosynthesis beyond iron: s-process, r-process and p-process (γ-process).

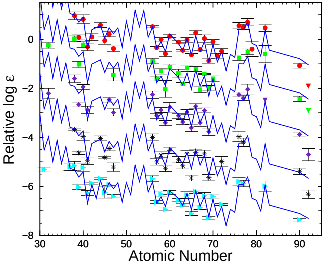




- s-process: relatively low neutron densities, $n_n = 10^{10-12}$ cm^{-3}, $\tau_n > \tau_\beta$
- r-process: large neutron densities, $n_n > 10^{20}$ cm^{-3}, $\tau_n < \tau_\beta$.
- p-process: photodissociation of s-process material.

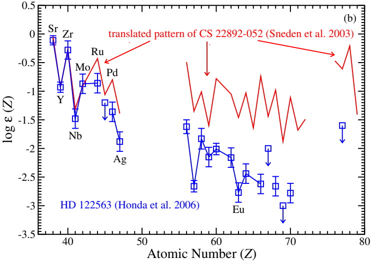
Heavy elements and metal-poor stars

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



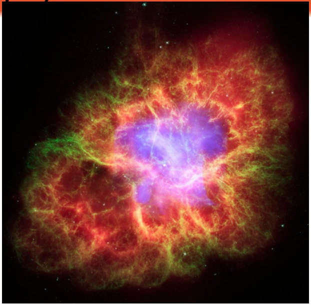
- Stars rich in heavy r-process elements ($Z > 50$) and poor in iron (r-II stars, $[\mathrm{Eu/Fe}] > 1.0$).
- Robust abundance patter for $Z > 52$, consistent with solar r-process abundance.
- These abundances seem the result of events that do not produce iron. [Qian & Wasserburg, Phys. Rept. **442**, 237 (2007)]
- Possible Astrophysical Scenario: Neutron star mergers.

- Stars poor in heavy r-process elements but with large abundances of light r-process elements (Sr, Y, Zr)
- Production of light and heavy r-process elements is decoupled.
- Astrophysical scenario: neutrino-driven winds from core-collapse supernova



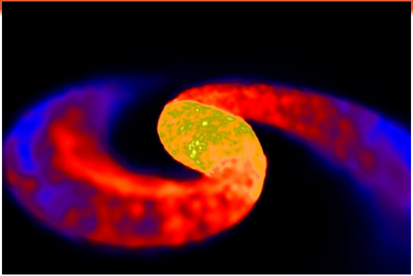
Honda *et al*, ApJ **643**, 1180 (2006)

Astrophysical sites



Core-collapse supernova

- Neutrino-winds from protoneutron stars.
- Aspherical explosions, Jets, Magnetorotational Supernova, …
[Winteler *et al*, ApJ **750**, L22 (2012)]



Neutron star mergers

- Matter ejected ($\sim 0.01\ M_\odot$) dynamically during merger.
- Electromagnetic emission from the decay of r-process nuclei [Kilonova, Metzger et al, MNRAS **406**, 2650 (2010)]
- Winds from accretion disks around black holes [Wanajo & Janka, ApJ **746**, 180 (2012)]

Transients from r-process ejecta

PHYSICAL REVIEW VOLUME 103, NUMBER 5 SEPTEMBER 1, 1956

Californium-254 and Supernovae*

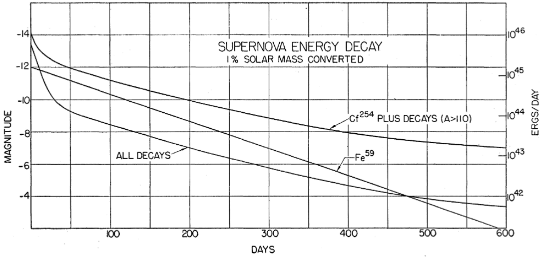
G. R. Burbidge and F. Hoyle,† *Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California*

and

E. M. Burbidge, R. F. Christy, and W. A. Fowler, *Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California*

(Received May 17, 1956)

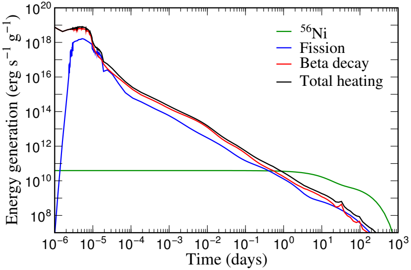
It is suggested that the spontaneous fission of Cf^{254} with a half-life of 55 days is responsible for the form of the decay light-curves of supernovae of Type I which have an exponential form with a half-life of 55 nights. The way in which Cf^{254} may be synthesized in a supernova outburst, and reasons why the energy released by its decay may dominate all others are discussed. The presence of Tc in red giant stars and of Cf in Type I supernovae appears to be observational evidence that neutron capture processes on both a slow and a fast time-scale have been necessary to synthesize the heavy elements in their observed cosmic abundances.

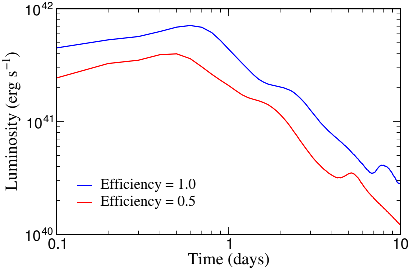


Radioactive heating and light curve

- The r-process heating at late times goes like $t^{-1.3}$.
- Similar to nuclear waste from terrestrial reactors.
- Independent of the ejecta composition.
- Independent of the nuclear mass model.
- Light curve reaches peak brightness at times of 1 day, reaching luminosities 1000 times those of a typical Nova.
- Results are sensitive to photon opacities (Kasen *et al*, 2013)

Metzger, GMP, Darbha, Quataert, Arcones *et al*, MNRAS **406**, 2650 (2010)





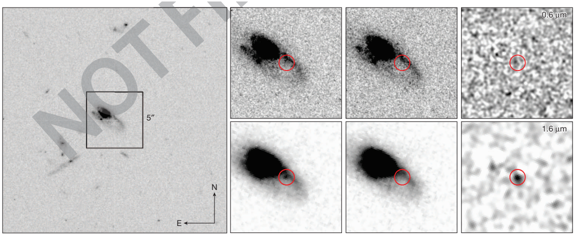
Kilonova Observation

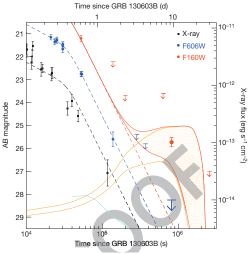
LETTER

doi:10.1038/nature12505

A ‘kilonova’ associated with the short-duration γ-ray burst GRB 130603B

N. R. Tanvir[1], A. J. Levan[2], A. S. Fruchter[3], J. Hjorth[4], R. A. Hounsell[3], K. Wiersema[1] & R. L. Tunnicliffe[2]

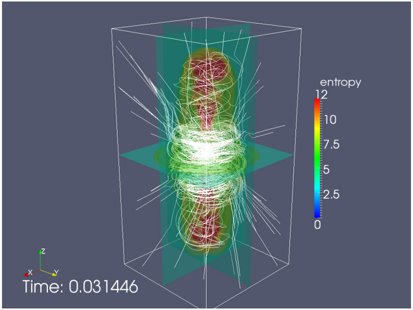


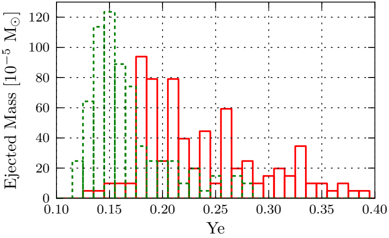


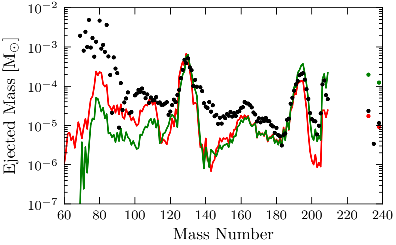
Direct observation of an r-process nucleosynthesis event?

Magnetorotationally Driven Supernovae

Winteller *et al*, ApJ **750**, L22 (2012)

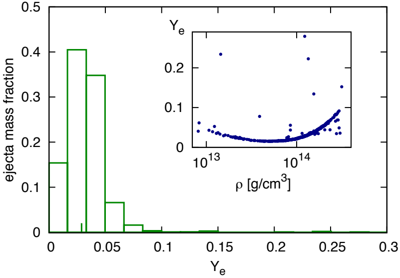


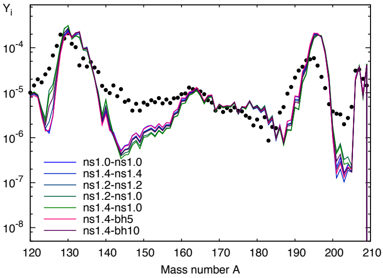




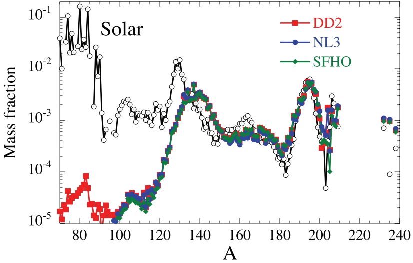
Neutron-star mergers: Astrophysically robust

Korobkin, Rosswog, Arcones, & Winteler, MNRAS **426**, 1940 (2012)

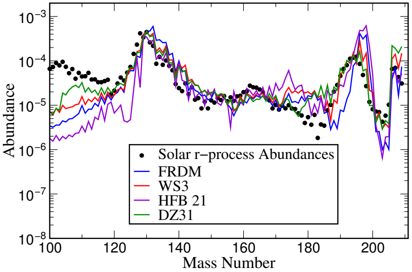




Sensitive to nuclear physics input



Bauswein, Goriely, Janka, ApJ **773**, 78 (2013)



Joel Mendoza-Temis (PhD)

Strong sensitivity nuclear physics input and particularly fission.

Nuclear physics needs

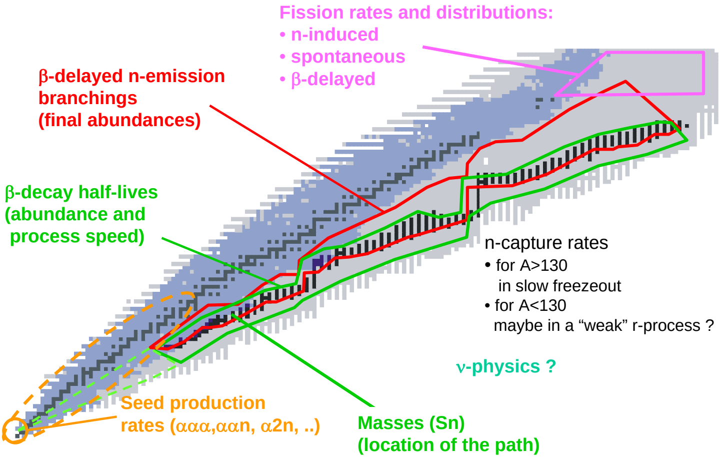


figure from H. Schatz

Fission input in the r-process

R-process simulations require rates for neutron capture, beta-decay (including delayed neutron emission) and alpha-decay. Whenever fission becomes important we also need fission rates and yields (including neutrons produced) for the following fission induced reactions:

- Neutron induced fission
- Beta-delayed fission
- Spontaneous fission
- Gamma induced fission(?)
- Neutrino induced fission(?)

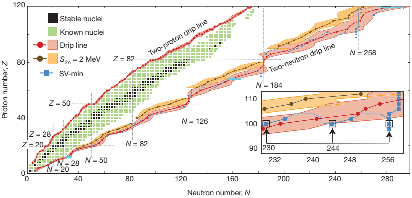
Fission relevance for the r-process

In my opinion these are the questions we need to address:

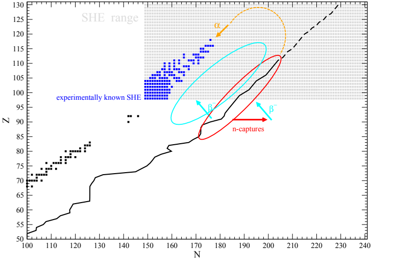
- Where in the (Z, N) plane does fission occur at the different phases of the r-process?
- Does fission constitute a barrier to the production of heavier nuclei or just a “mine field” that can be partly crossed?
- What are the fission yields produced by the fissioning nuclei?
- Are there new magic neutron numbers above $N = 126$? If so, what is their strength?
- Can long live superheavy nuclei be produced in the r-process?

Nuclear Landscape

Erler *et al.*, Nature **486**, 509 (2012)



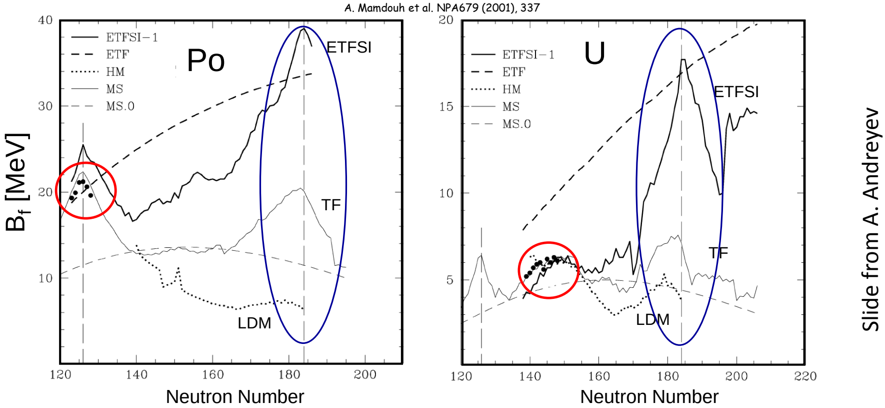
Petermann *et al.*, Eur. Phys. J. A **48**, 122 (2012)



The r-process explores the limits of stability.

Fission Barrier Calculations for the r-process nuclei

Full symbols – experimental data
Lines – calculations (LDM,TF, ETFSI)



- Good agreement between $B_{f,cal}$ and $B_{f,exp}$ for nuclei close to stability
- Large disagreement far of stability (both on n-def. and n-rich sides)
- Need measured fission data far of stability to 'tune' fission models

Evolution fission rates

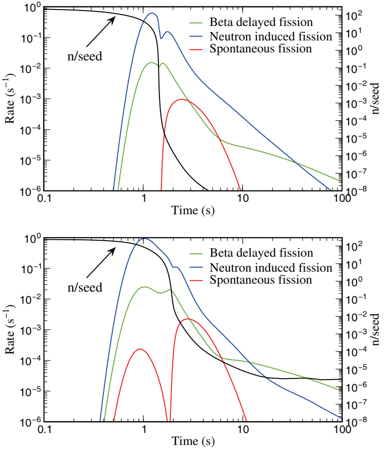


Fig. 9. The evolution of fission rates for the different channels shown for a hot (top) and cold (bottom) r-process with the fission barrier/mass model selection TF/FRDM.

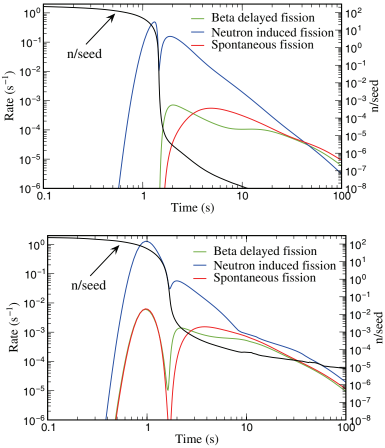


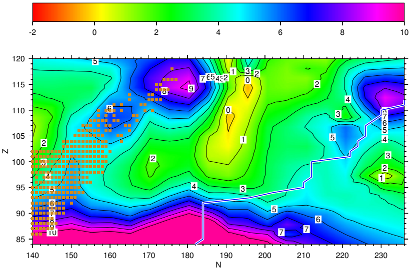
Fig. 10. Similar to fig. 9, the evolution of fission rates for the different channels shown for a hot (top) and cold (bottom) r-process, but with the fission barrier/mass model selection ETFSI/ETFSI.

From Petermann *et al.*, Eur. Phys. J. A **48**, 122 (2012)

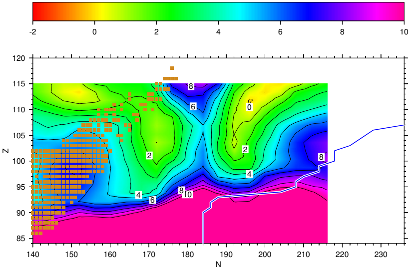
Fission in the r-process

- 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)]

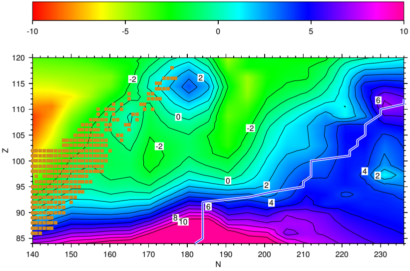


Neutron-induced fission is the dominating process.

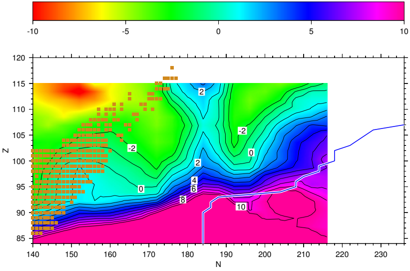
Fission in the r-process

- Depends of 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.

Neutron-induced fission rates

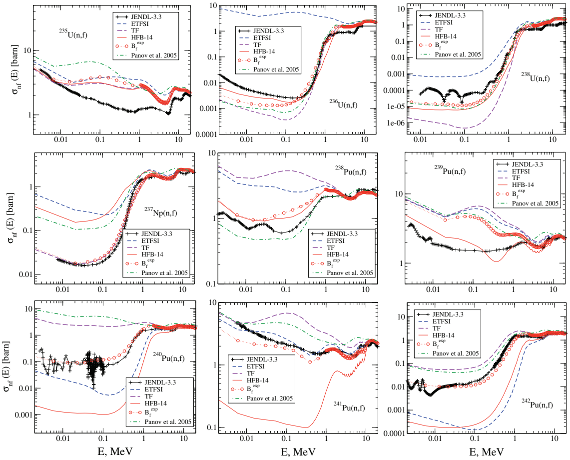


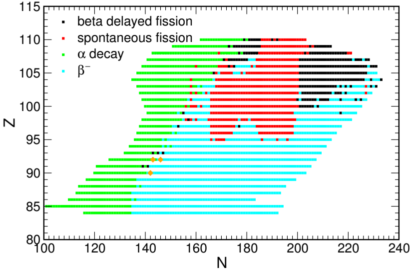
Fig. 1. Present predictions of energy-dependent (n, f) cross sections $\sigma_{nf}(E)$ for some target nuclei of U, Np and Pu calculated in the framework of different mass and fission barrier predictions (ETFSI, TF, HFB-14) and experimental data, marked B_f^{exp} as well. Experimentally measured cross-sections were used after JENDL-3.3 (Nakagawa et al. 2005), averaged by the code JANIS Soppera et al. (2008), displayed by a black line. All the predictions are given for a ground-state population. Our previous results (Panov et al. 2005) are shown as well.

From Panov *et al.*, A&A **513**, A61 (2010)

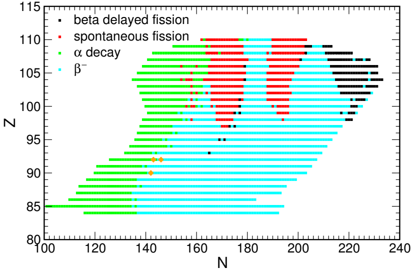
Fission in the r-process

Other fission channels become relevant for small neutron densities.

TF barriers

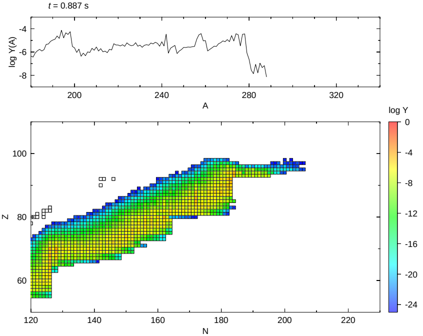


ETFSI barriers

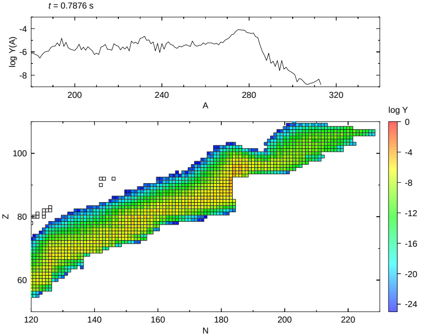


Are super-heavy nuclei produced in the r-process?

FRDM masses plus TF barriers



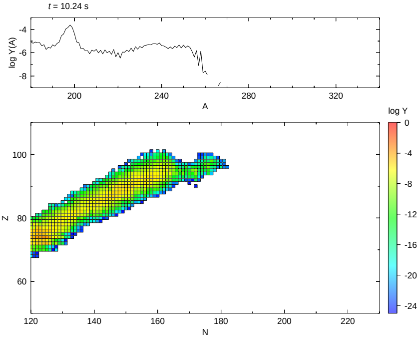
ETFSI masses and barriers



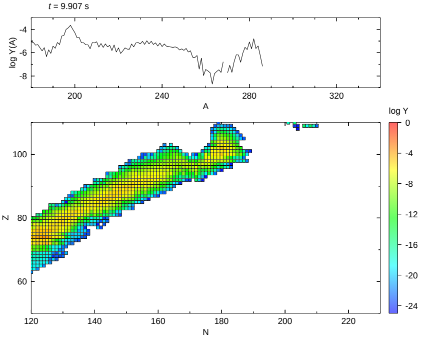
Petermann, *et al.*, Eur. Phys. J. A **48**, 122 (2012)

Are super-heavy nuclei produced in the r-process?

FRDM masses plus TF barriers ($t \approx 10$ s)

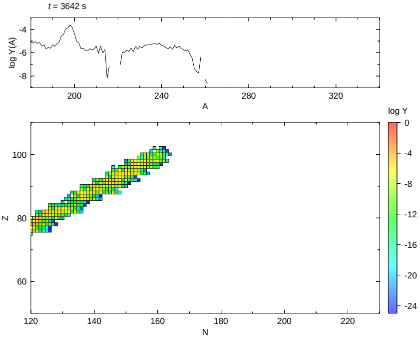


ETFSI masses and barriers

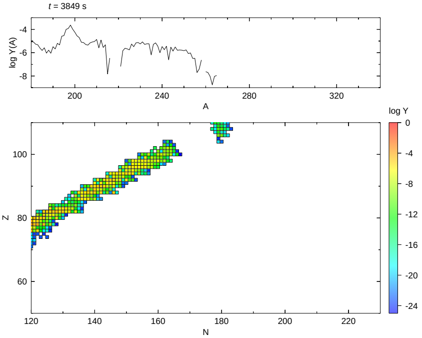


Are super-heavy nuclei produced in the r-process?

FRDM masses plus TF barriers ($t \approx 1$ h)

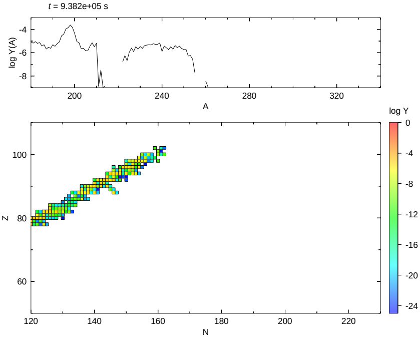


ETFSI masses and barriers

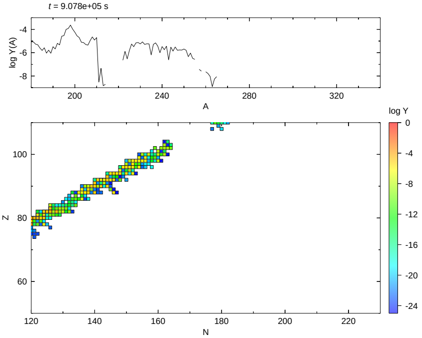


Are super-heavy nuclei produced in the r-process?

FRDM masses plus TF barriers ($t \approx 10$ d)

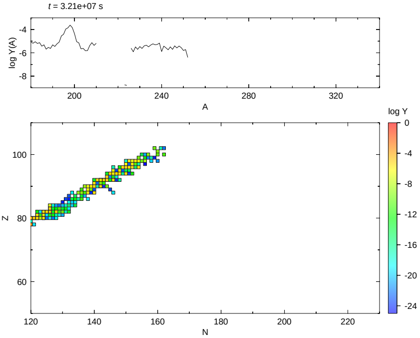


ETFSI masses and barriers

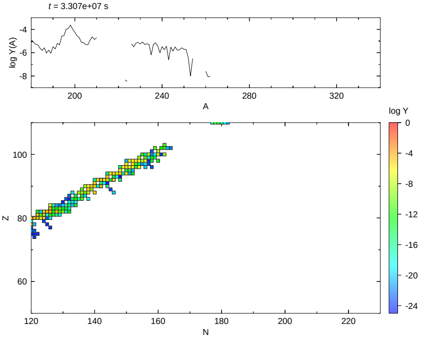


Are super-heavy nuclei produced in the r-process?

FRDM masses plus TF barriers ($t \approx 1$ yr)

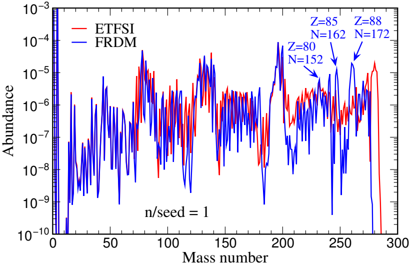


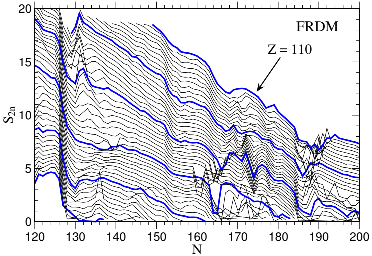
ETFSI masses and barriers



Influence of shell-structure

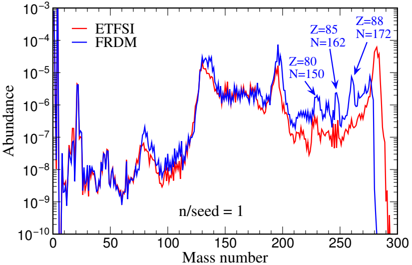
Hot r-process

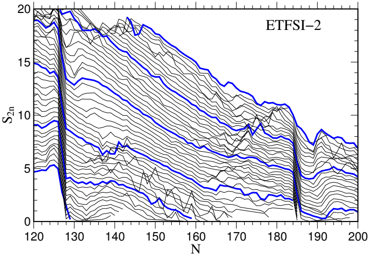




(I. Petermann PhD Thesis)

Cold r-process

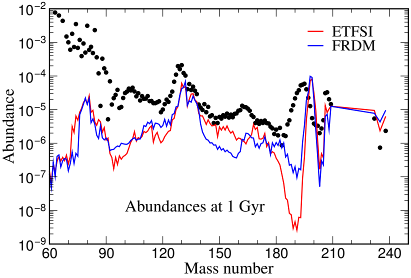




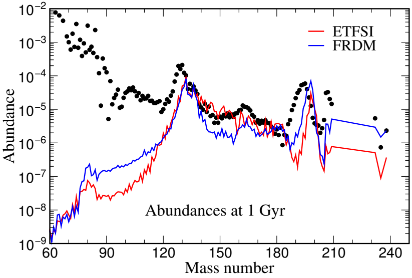
Influence in r-process abundances

- 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

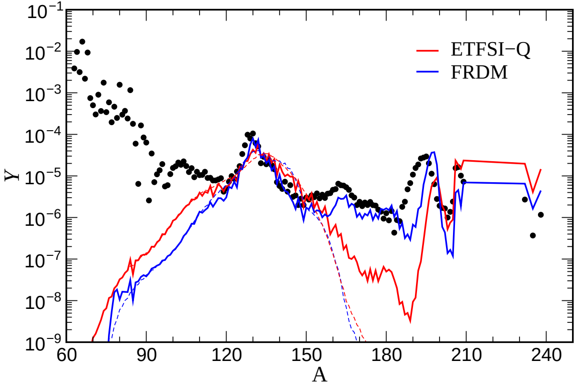


Cold r-process



Role of fission yields

Fission yields are important to determine the final r-process abundance. However, the distribution of produced nuclei is modified by subsequent neutron-captures.



GMP, J. Phys. G **35** 014057 (2008).

Yields used in r-process calculations

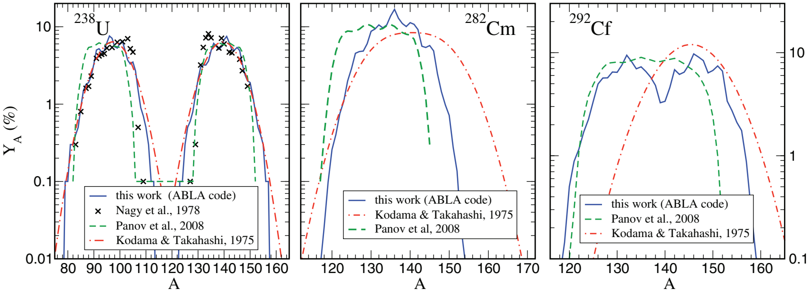
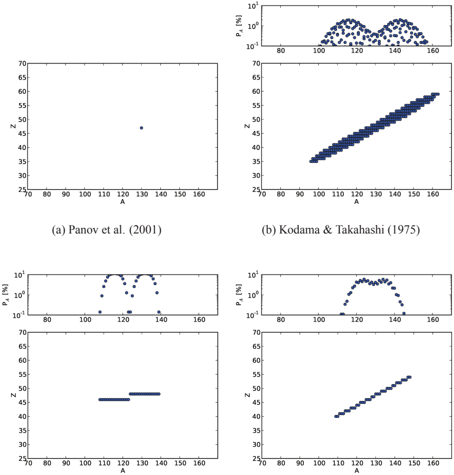


Fig. 10. The final mass distributions of fission fragments for the compound nuclei (after neutron capture) ^{238}U, ^{282}Cm and ^{292}Cf. The distributions were computed with the ABLA code (Kelić et al. 2008) as described in the text. In addition, we show the yields computed with the phenomenological parameterizations of Panov et al. (2008) and Kodama & Takahashi (1975), as well as experimental data (crosses).

From Panov *et al.*, A&A **513**, A61 (2010)

Yields used in r-process calculations

Fission yields for ^{260}Pu:

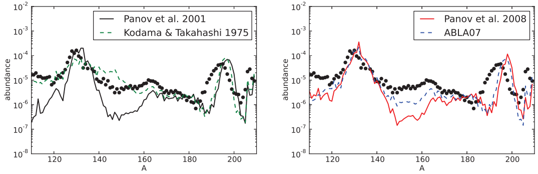


(a) Panov et al. (2001) (b) Kodama & Takahashi (1975)

(c) Panov et al. (2008) (d) ABLA07

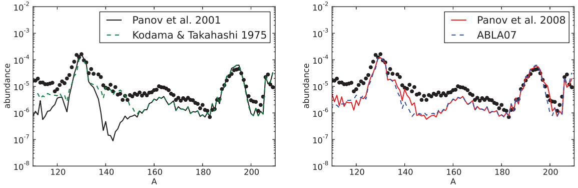
From M. Eichler, *et al.*, Proceedings Nuclear Physics in Astrophysics VI.

Impact in abundances



(a) (b)

Figure 3: Final abundances around the second and third peak for a NSM [1] employing four different fission fragment distribution models. For reasons of clarity the results are presented in two graphs. The black dots represent the solar r-process abundances [14]. The mass model is FRDM in all calculations.



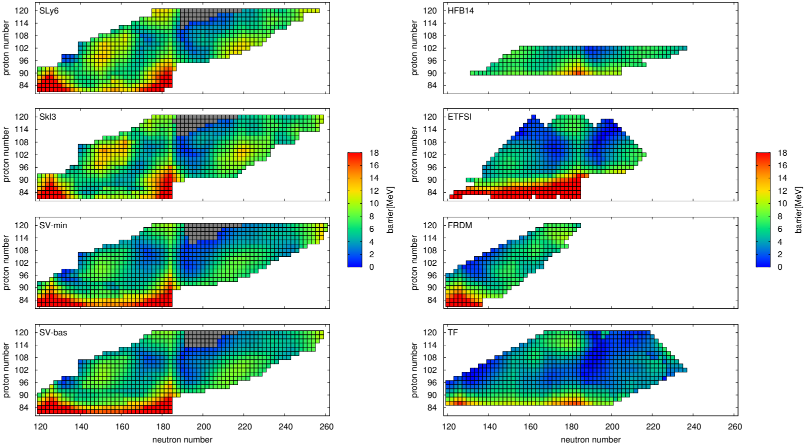
(a) (b)

Figure 4: Same as Figure 3, but for an MHD supernova [2].

From M. Eichler, *et al.*, Proceedings Nuclear Physics in Astrophysics VI.

Can fission produce elements lighter than $A \sim 130$?

Fission barriers systematics based on Skyrme HF-BCS calculations
[Erler, Langanke, Loens, GMP, Reinhard, PRC **85**, 025802 (2012)]



If fission occurs at sufficiently low mass numbers it can produce elements with