Fission properties of r-process nuclei predicted with the BCPM EDF

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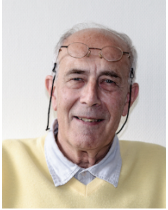
March 23rd, 2023

Conference on Quantum-Many-Body Correlations
In memory of Peter Schuck

21 – 23 March, 2023

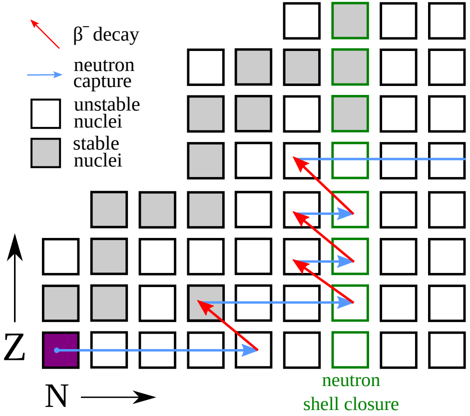
IJCLab, Orsay (FR)



The r process

B[2]FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

r(apid neutron capture) process: $\tau_{(n,\gamma)} \ll \tau_{\beta-}$



- The neutron-to-seed ratio determine how far the r-process can proceed.
- Astrophysical site with high neutron fluxes (e.g., **neutron star mergers**).

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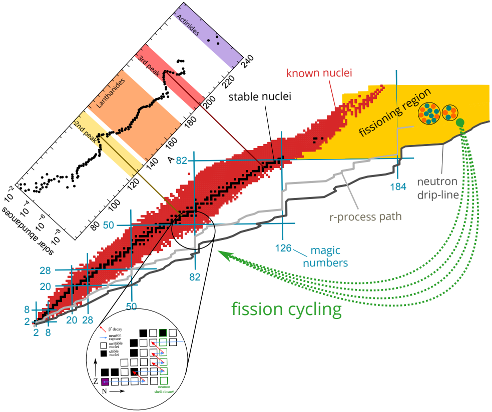

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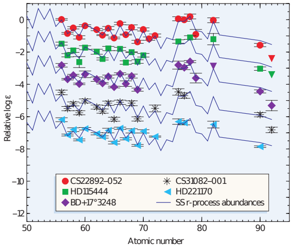
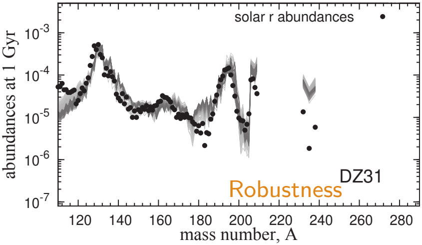
Fission and r process

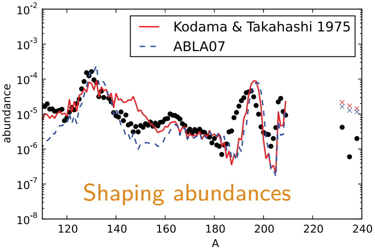
Thielemann+(1983), Panov+(2005), Martinez-Pinedo+(2007), Beun+(2008), Petermann+(2012), Eichler+(2015), Goriely(2015), Mumpower+(2018), Zhu+(2019), Wu+2019, Vassh+(2019), ...

Cowan and Sneden, Nature 440 1151 (2006)

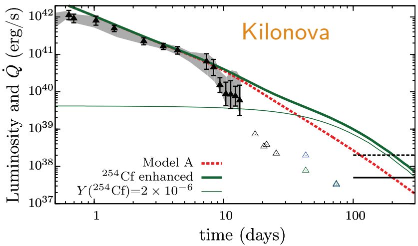


J. Mendoza-Temis *et al.*, PRC **95**, 055805 (2015)



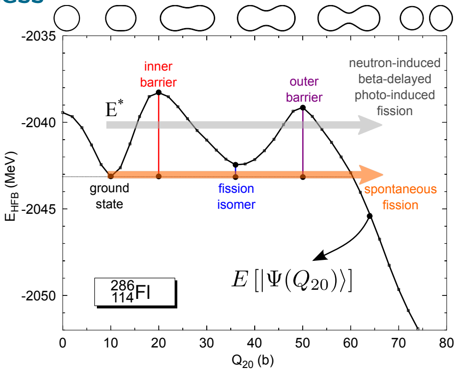


M. Eichler *et al.*, Astrophys. J. **808**, 30 (2015)



M.-R. Wu *et al.*, Phys. Rev. Lett. **122**, 062701 (2019).

The fission process



Potential Energy Surface $\mathcal{V}$

Energy evolution from the initial state to the scission point.

Collective inertias $\mathcal{M}$

Resistance of the nucleus against the deformation forces.

$$P_{\text{fiss}} = \big(1+\exp(-2S[L])\big)^{-1} \rightarrow S[L(Q_{20})] = \int_a^b dQ_{20}\sqrt{\mathcal{M}(Q_{20})[\mathcal{V}(Q_{20}) - E_0]}$$

The Hartree-Fock-Bogolyubov (HFB) formalism

The ground-state wavefunction is obtained by minimizing the total energy:

$$\delta E[|\Psi\rangle] = 0 \quad \text{with} \quad |\Psi\rangle = \prod_{\mu} \beta_\mu |0\rangle \;\Rightarrow\; \beta_\mu |\Psi\rangle = 0 \;\forall\; \mu \,.$$

The energy landscape is constructed by constraining the deformation of the nucleus $\langle \Psi(q)|\hat{Q}|\Psi(q)\rangle = q$:

$$E[|\Psi(q)\rangle] = \langle \Psi(q)|\hat{\mathcal{H}} - \lambda_q \hat{Q}|\Psi(q)\rangle \,.$$

To assess the systematic uncertainties on theoretical fission properties, 4 different EDFs are employed:

- Barcelona-Catania-Paris-Madrid (BCPM) Baldo, Robledo, **Schuck**, Viñas PRC(2013).

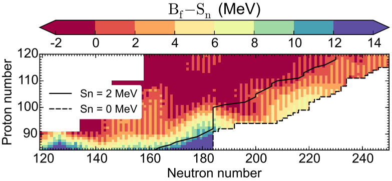
$$E = T_0 + E_{int}^{\infty} + E_{int}^{FR} + E^{s.o.} + E_C + E_{pair} \,;$$

$$E_{int}^{\infty}[\rho_p, \rho_n] = \int d\vec{r} \Big[P_s(\rho)(1-\beta^2) + P_n(\rho)\beta^2 \Big] \rho \,,$$

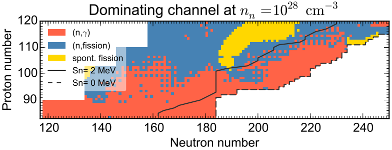
  with P_s and P_n polynomial fits of microscopic EoS in nuclear matter.

- D1S, D1N, and D1M Gogny parametrizations.

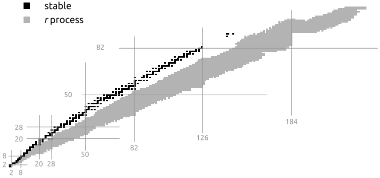
1) Compute fission properties and binding energies using EDF.



2) Calculate stellar reaction rates from Hauser-Feshbach theory.

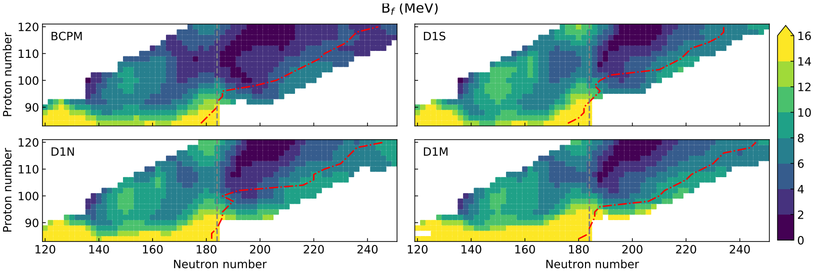


3) Obtain r-process abundances using network calculations.



Systematic of fission barriers B_f

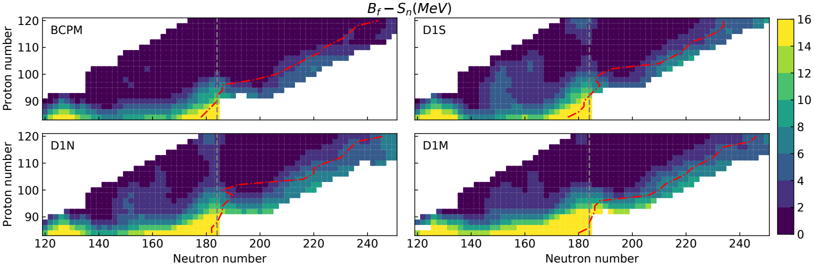
- $B_f \rightarrow$ stability against fission.



- B_f trends qualitatively similar across different D1 interactions:
  - $Z > 94$: systematic deviations $\sim$ 1–2 MeV $\rightarrow m^*/m \sim 0.7 - 0.75$.
  - $Z \leq 94$: deviations up to 10 MeV (but very high B_f).
- BCPM B_f up to 5 MeV smaller for $Z > 94$ $(m^*/m = 1)$.
- Location of the r process differ above $N = 184$.

Systematic of $B_f - S_n$

- For $B_f - S_n \lesssim 2\,\text{MeV}$ (n, fis) dominates over (n, γ).



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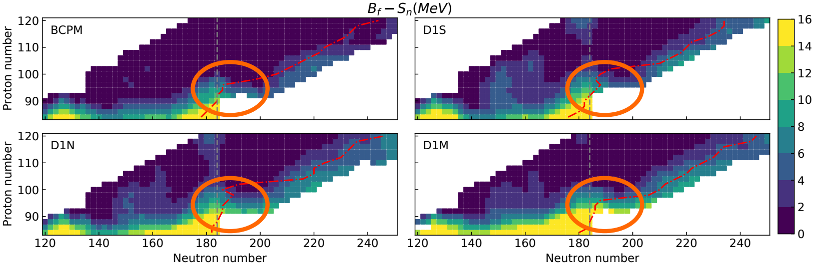

- Production of (super)heavy nuclei requires the overcoming of neutron shell closure at $N = 184$.
- Production of superheavy nuclei more favored with D1M (r-process path proceeds towards lower Z).

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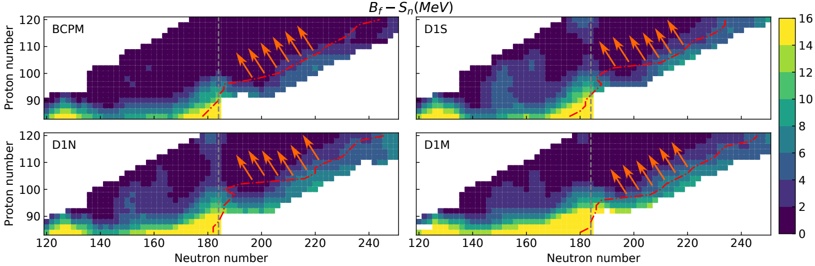

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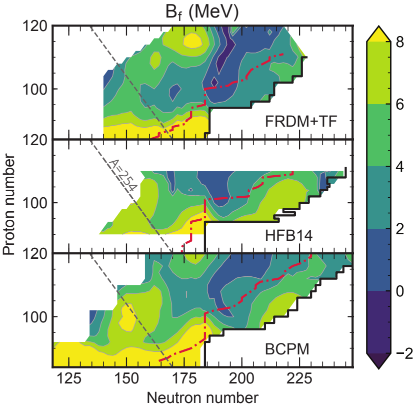
- Production of superheavy nuclei more favored with D1M (r-process path proceeds towards lower Z).
- Path towards stability interrupted by region of low fission barriers.

Impact of fission on the r-process

SAG *et al.*, Phys. Rev. C 102, 045804 (2020)

- Dynamical ejecta: $Y_e \lesssim 0.05$; $n/s \approx 600$
- Accretion disk: $Y_e \lesssim 0.15$; $n/s \approx 120$



BCPM: Giuliani *et al.* (2018); **FRDM+TF**:Panov *et al.* (2010); **HFB14**: Goriely *et al.* (2009).

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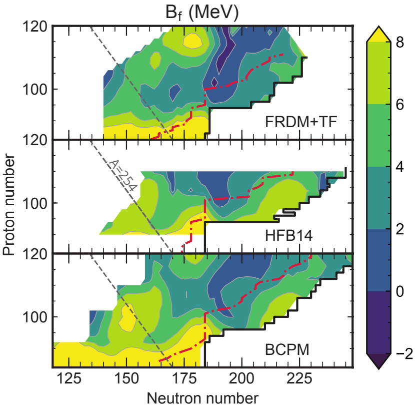

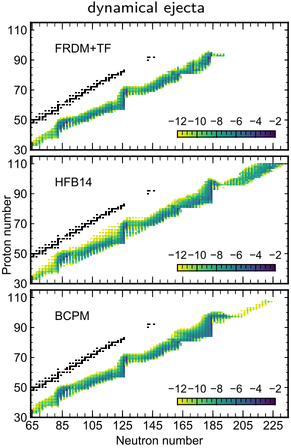

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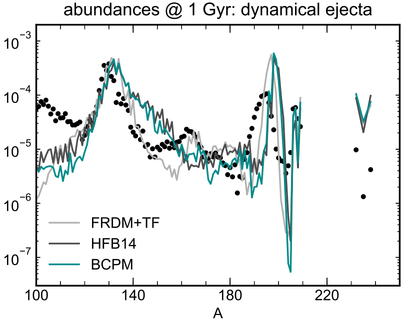

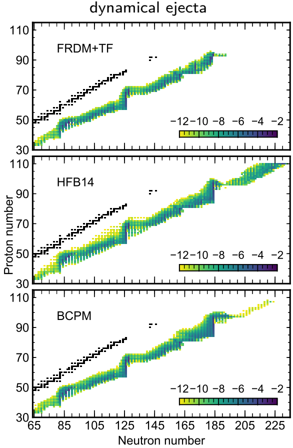

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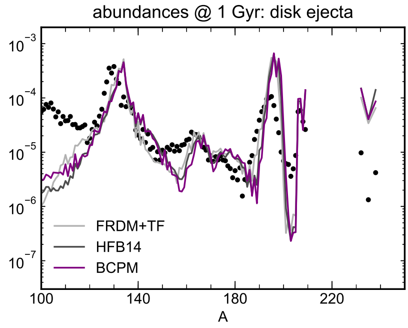

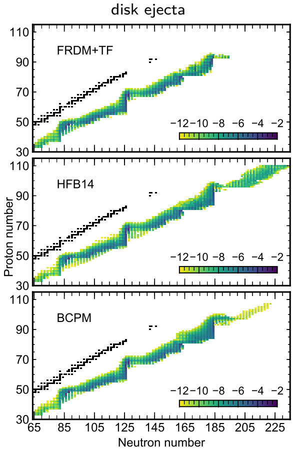

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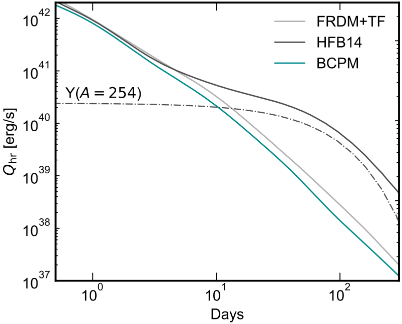
Kilonova: BCPM vs FRDM+TF vs HFB14

Kilonova: EM transient produced by the decay of r-process nuclei.

- HFB14:
  - Large accumulation of ^{254}Cf due to high fission barriers.
- FRDM+TF:
  - ^{254}Cf progenitors destroyed by β-delayed fission.
- BCPM:
  - ^{254}Cf progenitors destroyed by neutrons from fission.

SAG *et al.*, Phys. Rev. C **102**, 045804 (2020)



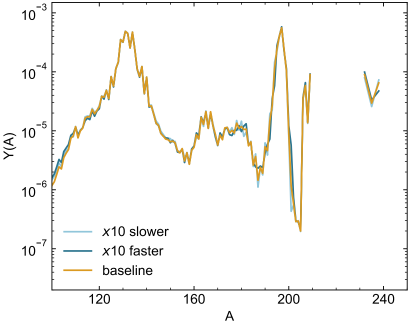
Kilonova light curves sensitive to nuclear properties at $N = 184$ and $A = 254$

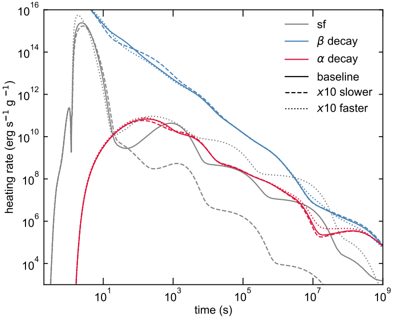
(n, γ) vs (n, fis)

β-delayed and spontaneous fission rates

Impact of β-decay rates on fission

- Impact of β-decay half-lives varies with the observable.
- We modified $t^{\beta}_{1/2} \geq 3\ s$ and study the impact on abundances and heating rates.

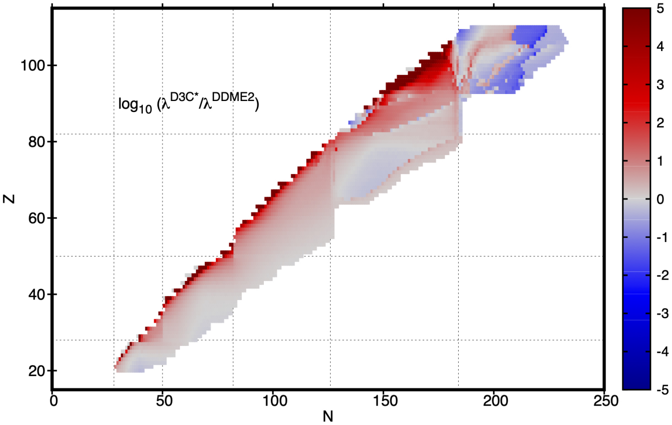




Fission heating rate sensitive to "slow" β-decay rates
($\tau_\beta \gtrsim$ few seconds)

Systematic of β-decay rates

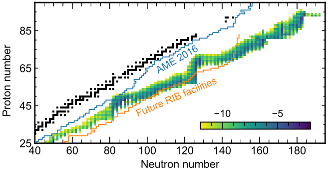
credit: Caroline Robin (U. Bielefeld)



- β-decay rates closer to stability show larger uncertainties → more systematic studies are required (see also E. M. Ney *et al.*, Phys. Rev. C **102**, 034326 (2020)).

Conclusions

- For neutron-rich ejecta, fission plays a crucial role during r-process.
- Global calculations of neutron-rich nuclei show large variations in the predicted fission properties $\rightarrow$ (consistent) sensitivity studies are required.
- r-process abundances and kilonova light curve are strongly affected by fission properties at $N = 184 \rightarrow$ KN window to exotic region?



- Heating rates sensitive to competition between fission and β-decay at $t \gtrsim$ s.
- **Future work/needs:**
  - Sensibility studies exploring the impact of fission rates on nucleosynthesis calculations.
  - Systematic studies of β-decays half-lives and strengths crucial for assessing uncertainties.

Collaborators

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Funding

MINISTERIO DE CIENCIA E INNOVACIÓN

Financiado por la Unión Europea NextGenerationEU

Plan de Recuperación, Transformación y Resiliencia

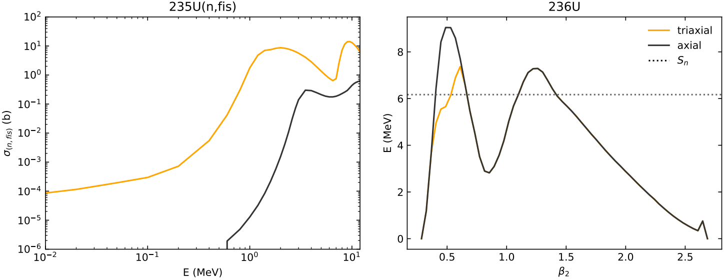
AGENCIA ESTATAL DE INVESTIGACIÓN

UAM Universidad Autónoma de Madrid

Backup

Global calculation of fission nuclear properties

- Model assumptions → systematic uncertainties → impact on nucleosynthesis?
- Relevant physics close to stability ≠ relevant physics in exotic nuclei.



- Systematic deviations close to stability could be compensated in exotic nuclei (and vice versa) → global calculations from different models are required.

Global calculation of fission nuclear properties

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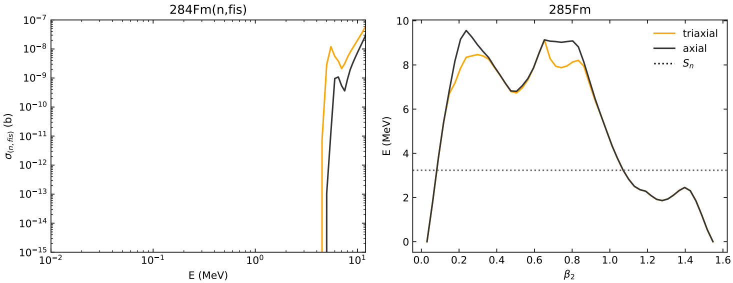

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