Panoramica processo r

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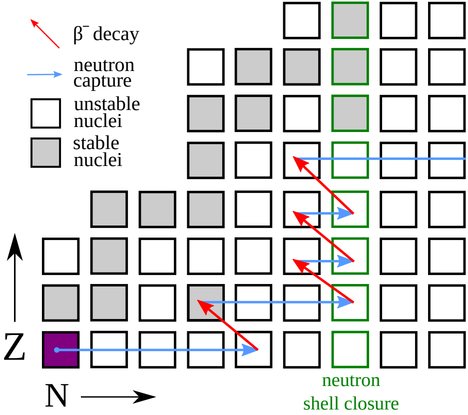
n_TOF Meeting

The r process

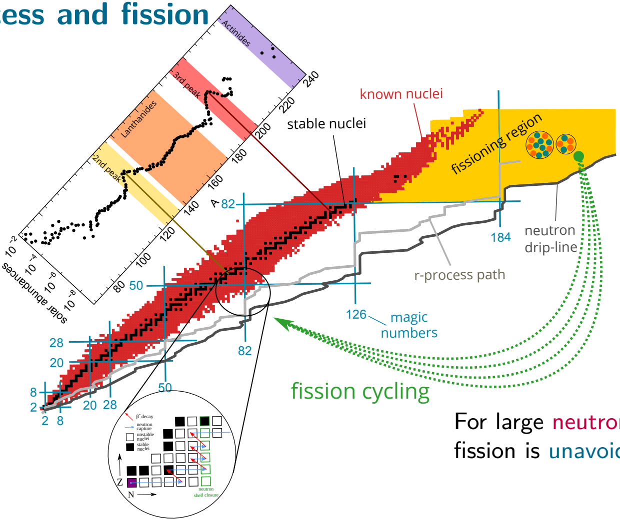
B^{2}FH, Rev. Mod. Phys. 29, 547 (1957) ; A. Cameron, Report CRL-41 (1957)

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



- How far can the r process proceed? Number of free neutrons that seed nuclei can capture (neutron-to-seed ratio).

r process and fission



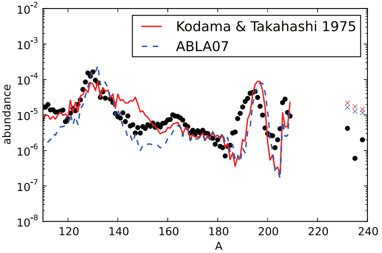
For large neutron-to-seed ratio fission is unavoidable.

- Where does fission occur?
- How much material accumulates in fissioning region?
- What are the fission yields?

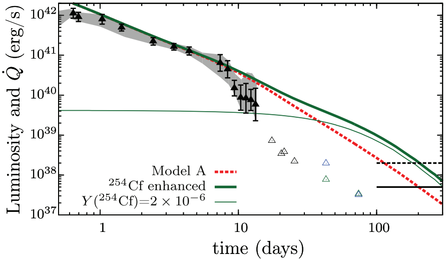
Fission and r process

- Fission plays a crucial role during the r-process nucleosynthesis
  Thielemann+(1983), Panov+(2005), Martinez-Pinedo+(2007), Korobkin+(2012), Petermann+(2012), Eichler+(2015), Goriely(2015), Mumpower+(2018), Vassh+(2019)...

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

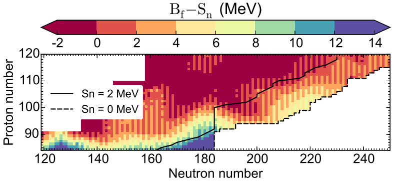


M.-R. Wu *et al.*, Phys. Rev. Lett. **122**, 062701 (2019)

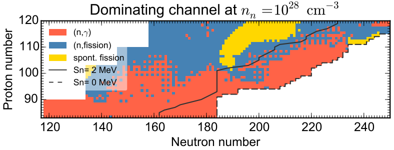


- Many models are parametrizations/phenomenological → validity far from stability?
- Long-term goal: compute reaction rates and fission properties from consistent (EDF) nuclear input.

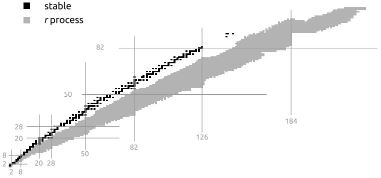
1) Compute fission properties and binding energies using EDF.



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



3) Obtain r-process abundances using network calculations.



The Hartree-Fock-Bogolyubov (HFB) formalism

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

$$\delta E[|\Psi\rangle] = 0\,,$$

where $|\Psi\rangle$ is a quasiparticle (β) vacuum:

$$|\Psi\rangle = \prod_{\mu} \beta_\mu |0\rangle \quad \Rightarrow \quad \beta_\mu |\Psi\rangle = 0\,.$$

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

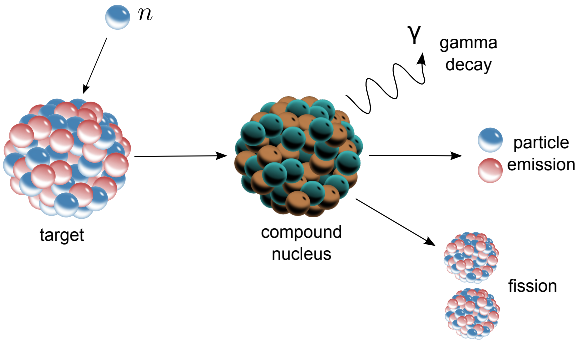
$$E[|\Psi(q)\rangle] = \langle\Psi(q)|\hat{\mathcal{H}} - \lambda_q \hat{Q}|\Psi(q)\rangle\,.$$

The energy density functionals (EDF) provide a phenomenological ansatz of the effective nucleon-nucleon interaction:

- Barcelona-Catania-Paris-Madrid (BCPM);
- Skyrme and Gogny interactions;
- relativistic EDF.

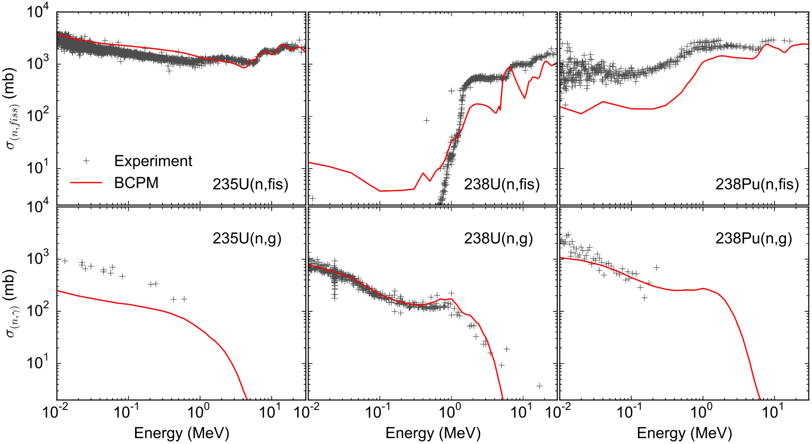
Compound reactions

Reaction rates computed within the Hauser-Feshbach statistical model.



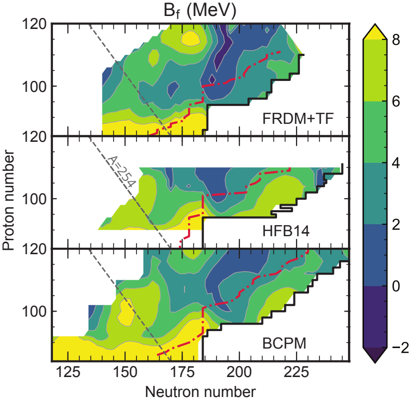
- Based on the Bohr independence hypothesis: the decay of the compound nucleus is independent from its formation dynamics.
- BCPM nuclear inputs implemented in TALYS reaction code to compute n-induced fission and n-capture stellar rates.

Cross sections from BCPM



Results: BCPM vs FRDM+TF vs HFB14

SAG *et al.*, PRC 102, 045804 (2020)



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

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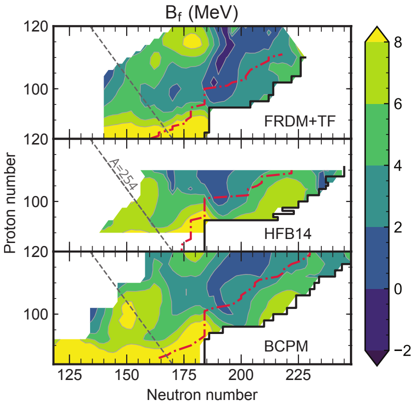

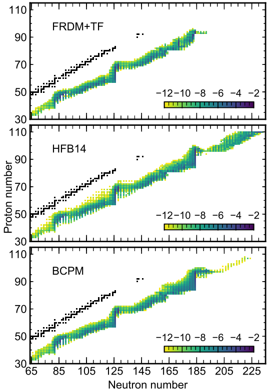

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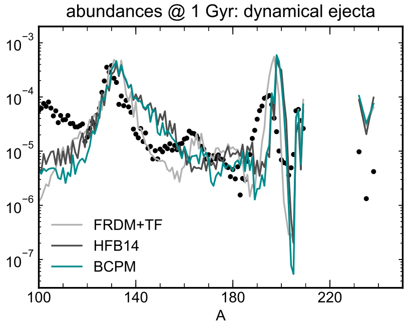

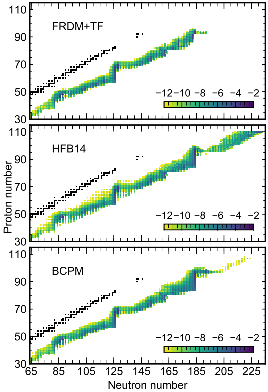

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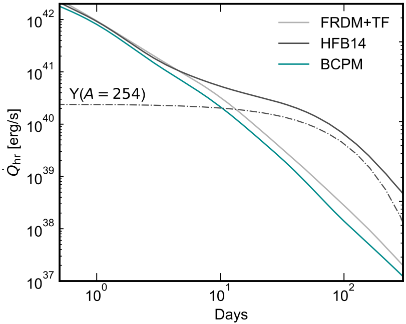
Kilonova: BCPM vs FRDM+TF vs HFB14

- 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 sensible to neutron-rich $A = 254$ nuclei

(n, γ) vs (n, fis)

β-delayed and spontaneous fission rates

Kilonova: BCPM vs FRDM+TF vs HFB14

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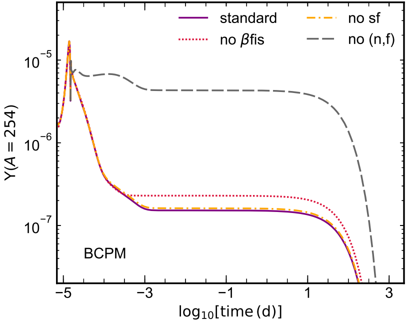


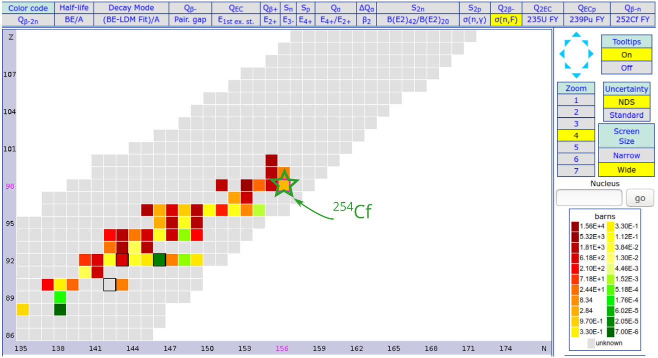
Kilonova light curves sensible to neutron-rich $A = 254$ nuclei

(n,γ) vs (n,fis)

β-delayed and spontaneous fission rates

Experimental (n, fis) cross sections

Credit: NuDat 2.8 (https://www.nndc.bnl.gov/nudat2/)

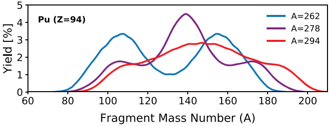


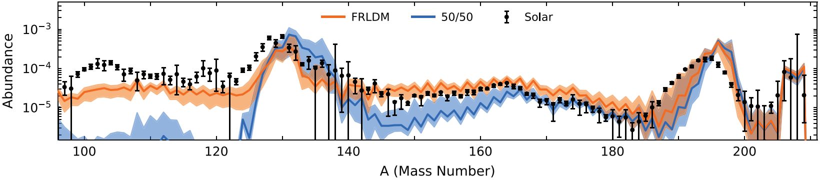
Evolution of $\sigma_{n,f}$ ($E_n \sim 100\,\mathrm{keV}$) with isospin asymmetry?

Fission yields and r process

Fission fragments distributions can substantially impact r-process abundances distributions (Panov+2008, Goriely+2013, Eichler+2015, Vassh+2018, Lemaître+2021...).

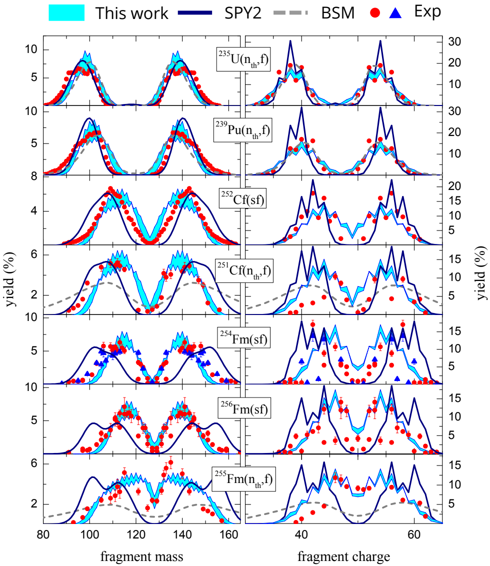
N. Vassh *et al.*, Astrophys J. **896**, 28 (2020)





Ffds: Theory vs Experiment

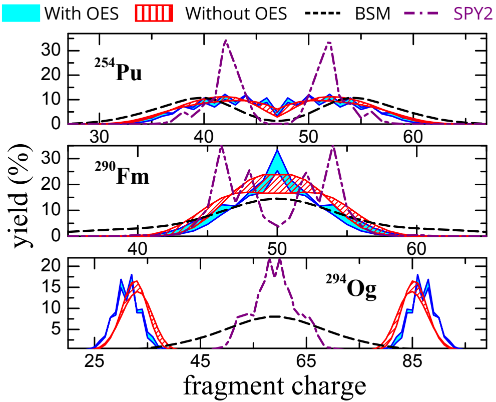
J. Sadhukhan, SAG, W. Nazarewicz (submitted)



- Models agree with experimental data close to stability.
- Larger discrepancies for increasing mass number:
  - BSM (Mumpower+(2020)) broad distributions not supported by data.
  - SPY2 (Lemaître+(2019)) large discrepancies for Fm isotopes.

OES in exotic nuclei

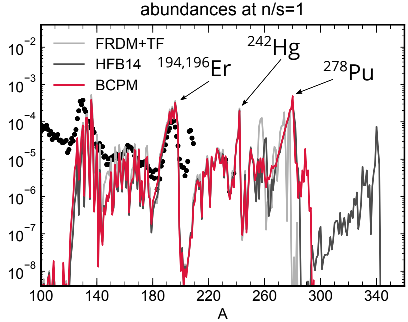
J. Sadhukhan, SAG, W. Nazarewicz (submitted)

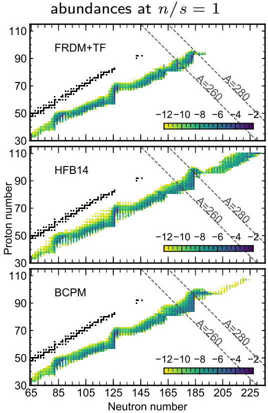


- Larger discrepancies with BSM and SPY2 for more exotic nuclei.

Excursus: β-decay studies

in collaboration with S. Taioli



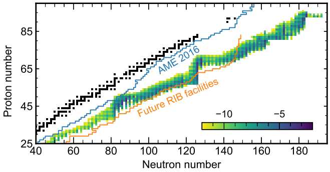


	^{194}Er	^{196}Er	^{242}Hg	^{278}Pu
FRDM	50.15	60.64	30.09	32.47
D3C*	26.79	12.69	1.32	0.46

Table 1: β-decay half-live (in ms) predicted by FRDM (Moller+ PRC2003) and D3C* (Marketin+ PRC2016)

Conclusions & Outlook

- Fission plays a crucial role during strong r-process nucleosynthesis.
- Systematic studies are required to understand the impact on abundances and kilonova light curves.
- Experimental data is required to validate/calibrate theoretical models:
  - (n,γ) vs (n,fis) cross sections;
  - β-delayed and spontaneous fission rates;
  - fission fragment distributions;
  - evolution with isospin asymmetry.



- Region around $A \sim 254$ particularly important for kilonova observations.

Collaborators and founding

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