Role of fission in r-process nucleosynthesis

Samuel A. Giuliani

NSCL/FRIB, East Lansing

July 12th, 2018

FRIB and the GW170817 kilonova

NSCL/FRIB at MSU

Outline

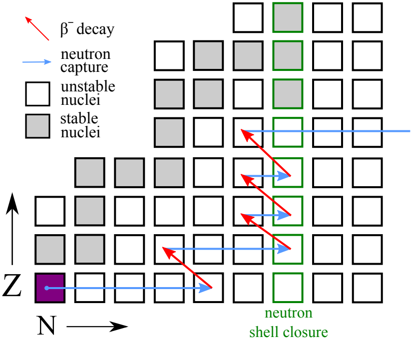
1. **Introduction**
2. **Impact of fission on r-process nucleosynthesis**
3. **Fission fragments distributions**
4. **Conclusions & Outlook**

Outline

1. **Introduction**
2. Impact of fission on r-process nucleosynthesis
3. Fission fragments distributions
4. Conclusions & Outlook

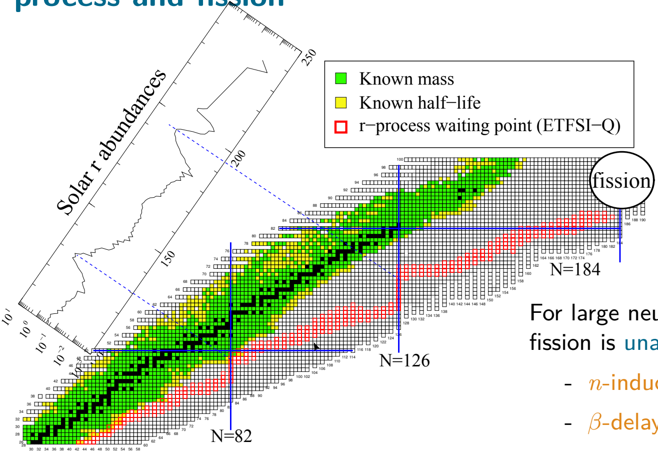
The r process

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



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

r process and fission

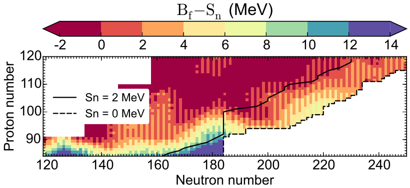


For large neutron-to-seed ratio fission is unavoidable

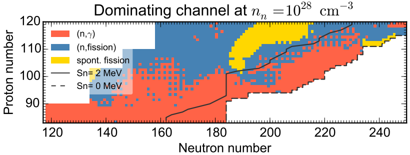
- n-induced fission
- β-delayed fission
- spontaneous fission

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

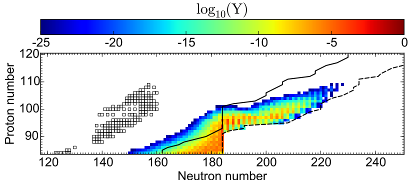
1) Compute fission properties and binding energies using BCPM EDF.



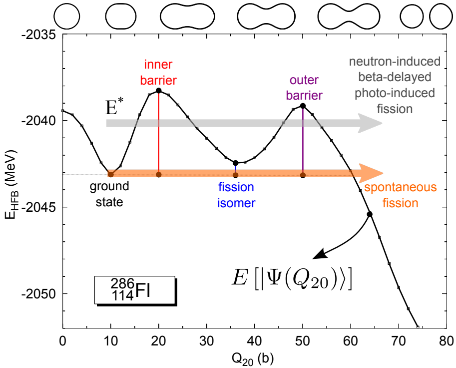
2) Calculate stellar reaction rates from Hauser-Feshbach theory.



3) Obtain r-process abundances using network calculations.



The fission process



Potential Energy Surface

Energy evolution from the initial state to the scission point.

SAG+ PRC90(2014); Sadhukhan+ PRC90(2014)

Collective inertias

Resistance of the nucleus against the deformation forces.

Baran+ PRC84 (2011)

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 (UNEDF1, D1S);
- relativistic EDF.

Outline

1. Introduction

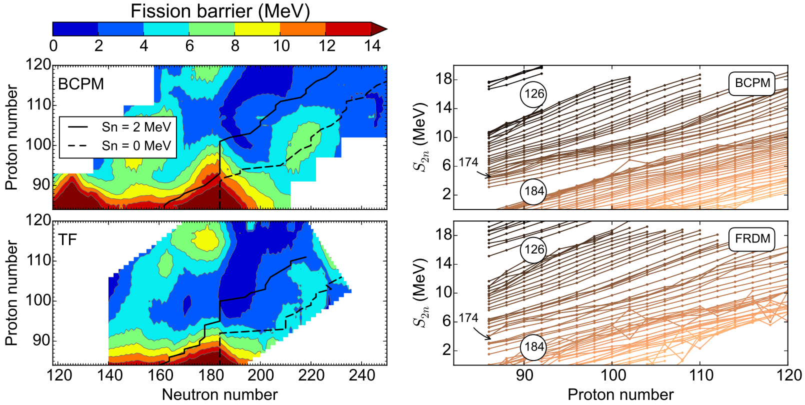
2. **Impact of fission on r-process nucleosynthesis**

3. Fission fragments distributions

4. Conclusions & Outlook

Nuclear inputs from the BCPM EDF

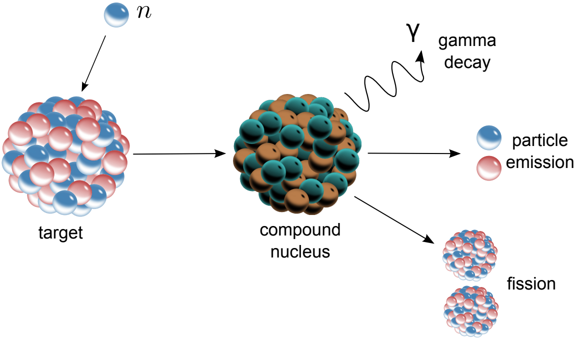
We study the impact of fission in the r process by comparing BCPM with previous calculations based on Thomas-Fermi (TF) barriers and Finite Range Droplet Model (FRDM) masses.



BCPM: Giuliani *et al.* (2018); **TF**: Myers and Świątecky (1999); **FRDM**: Möller *et al.* (1995).

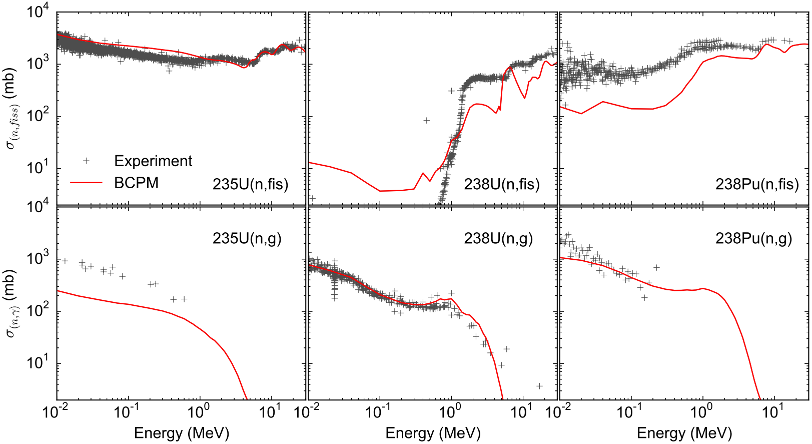
Compound reactions

Reaction rates computed within the Hauser-Feshbach statistical model.

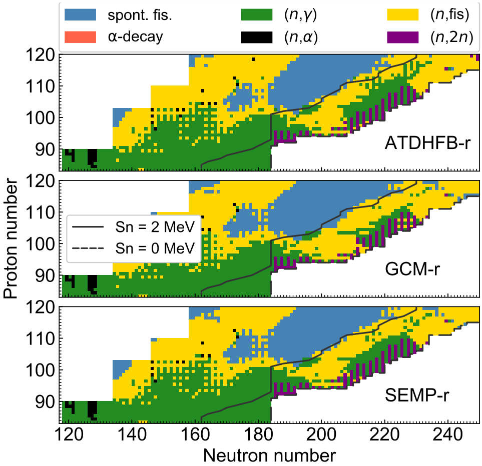


- Based on the Bohr independence hypothesis: the decay of the compound nucleus is independent from its formation dynamics.
- BCPM nuclear inputs implemented in TALYS reaction code to compute n-induced fission and n-capture rates.

Cross sections from BCPM



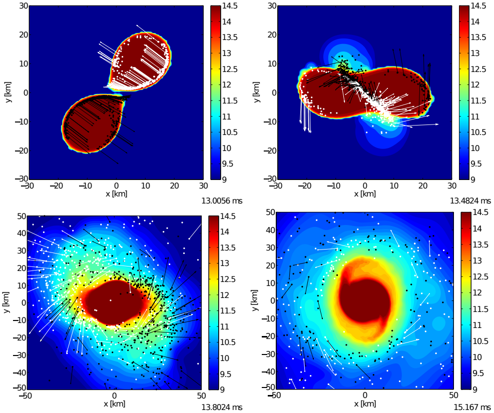
Stellar reaction rates - impact of collective inertias?



SAG, Martínez-Pinedo and Robledo, Phys. Rev. C 97, 034323 (2018)

The dynamical ejecta in neutron mergers

Trajectory from 3D relativistic simulations of $1.35\,\mathrm{M}_\odot$-$1.35\,\mathrm{M}_\odot$ NS mergers.

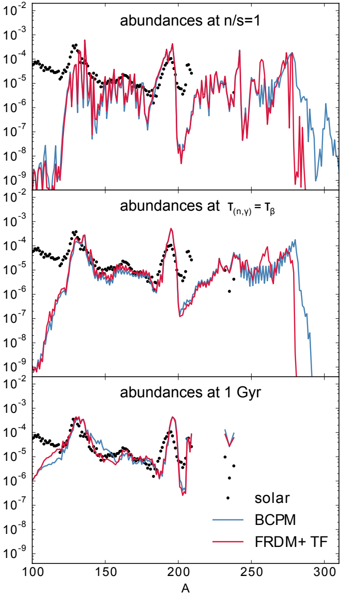


Bauswein et al., ApJ 773, 78 (2013).

- Large amount of ejecta (0.001-$0.01\ \mathrm{M}_\odot$).
- Material extremely neutron rich ($R_{n/s} \gtrsim 600$).
- Role of weak interactions?

r-process abundances: BCPM vs FRDM+TF

- Trajectory: 3D relativistic simulations from $1.35\,\mathrm{M}_\odot$-$1.35\,\mathrm{M}_\odot$ NS mergers [Bauswein+(2013)].
- BCPM Giuliani+(2017) vs TF+FRDM Panov+(2010).
- We changed the rates of nuclei with $Z \geq 84$.
- Same β-decay rates [Möller *et al.* PRC67(2003)].



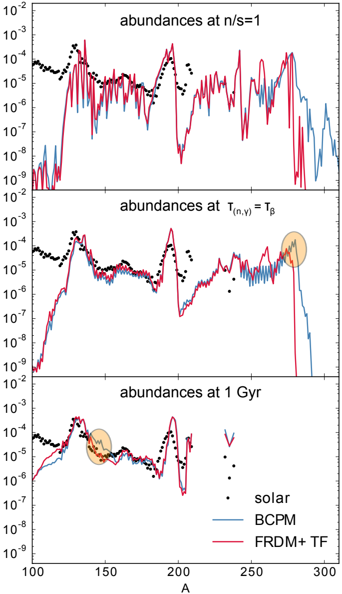
r-process abundances: BCPM vs FRDM+TF

- Trajectory: 3D relativistic simulations from $1.35\,\mathrm{M}_\odot$-$1.35\,\mathrm{M}_\odot$ NS mergers [Bauswein+(2013)].
- BCPM Giuliani+(2017) vs TF+FRDM Panov+(2010).
- We changed the rates of nuclei with $Z \geq 84$.
- Same β-decay rates [Möller *et al.* PRC67(2003)].

- BCPM barriers larger than TF:
  - nuclei around $A > 280$ longer lifetimes ,
  - accumulation above 2nd peak.

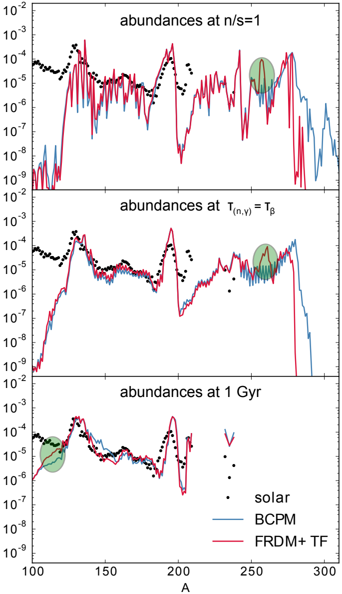
- BCPM shell gap smaller than FRDM at $N = 174$:
  - FRDM-TF peak at $A \sim 257$,
  - impact on final abundances at $A \sim 110$.

- Same ^{232}Th/^{238}U ratio: progenitors of actinides have $Z < 84 \Rightarrow$ can initial nuclei with $Z \geq 84$ survive to fission?



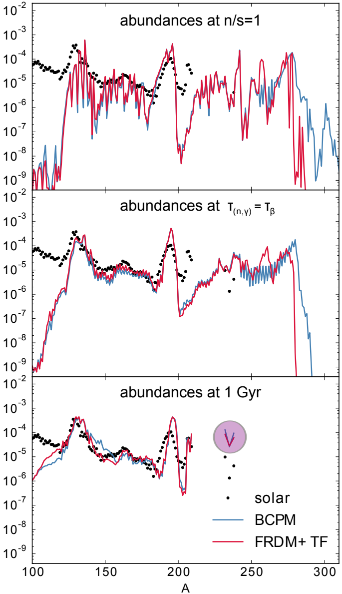
r-process abundances: BCPM vs FRDM+TF

- Trajectory: 3D relativistic simulations from $1.35\,M_{\odot}$-$1.35\,M_{\odot}$ NS mergers [Bauswein+(2013)].
- BCPM Giuliani+(2017) vs TF+FRDM Panov+(2010).
- We changed the rates of nuclei with $Z \geq 84$.
- Same β-decay rates [Möller *et al.* PRC67(2003)].
- BCPM barriers larger than TF:
  - nuclei around $A > 280$ longer lifetimes ,
  - accumulation above 2nd peak.
- BCPM shell gap smaller than FRDM at $N = 174$:
  - FRDM-TF peak at $A \sim 257$,
  - impact on final abundances at $A \sim 110$.
- Same ^{232}Th/^{238}U ratio: progenitors of actinides have $Z < 84 \Rightarrow$ can initial nuclei with $Z \geq 84$ survive to fission?

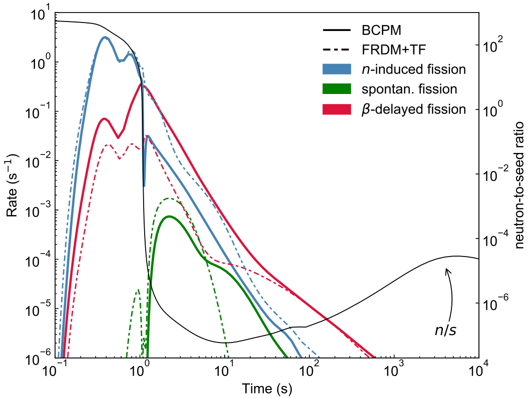


r-process abundances: BCPM vs FRDM+TF

- Trajectory: 3D relativistic simulations from $1.35\,\mathrm{M}_\odot$-$1.35\,\mathrm{M}_\odot$ NS mergers [Bauswein+(2013)].
- BCPM Giuliani+(2017) vs TF+FRDM Panov+(2010).
- We changed the rates of nuclei with $Z \geq 84$.
- Same β-decay rates [Möller *et al.* PRC67(2003)].
- BCPM barriers larger than TF:
  - nuclei around $A > 280$ longer lifetimes ,
  - accumulation above 2nd peak.
- BCPM shell gap smaller than FRDM at $N = 174$:
  - FRDM-TF peak at $A \sim 257$,
  - impact on final abundances at $A \sim 110$.
- Same ^{232}Th/^{238}U ratio: progenitors of actinides have $Z < 84 \Rightarrow$ can initial nuclei with $Z \geq 84$ survive to fission?



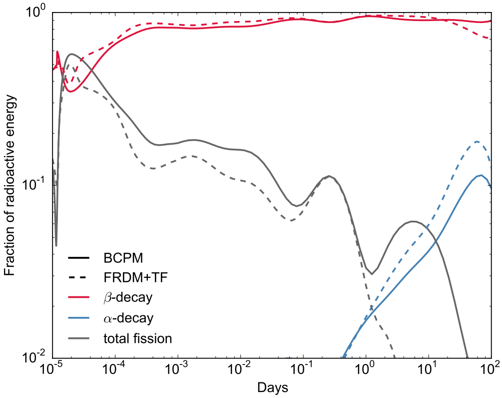
Averaged fission rates



- n-induced dominates until freeze-out and revived by β-delayed neutrons $\Rightarrow$ β-delayed fission rates from BCPM barriers required!
- decay of material to stability triggers spontaneous fission.

Emitted radioactive energy

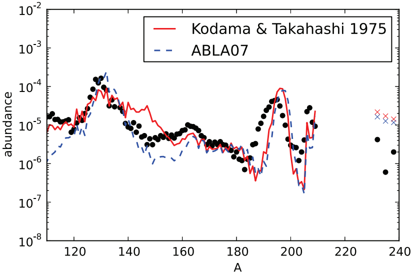
Energy emitted by radioactive products in NSM crucial for predicting kilonova light curves [J. Barnes et al., ApJ **829** 110 (2016)].



- Minor impact in the radioactive energy production $\Rightarrow$ progenitors of actinides from $Z < 84$ [Mendoza-Temis et al., Phys. Rev. **C92**, 055805 (2015)].
- Fission subdominant $\rightarrow$ impact of multi-chance bdf [Mumpower *et al.*, arXiv:1802.04398]?

Outline

Impact of fission yields on r process

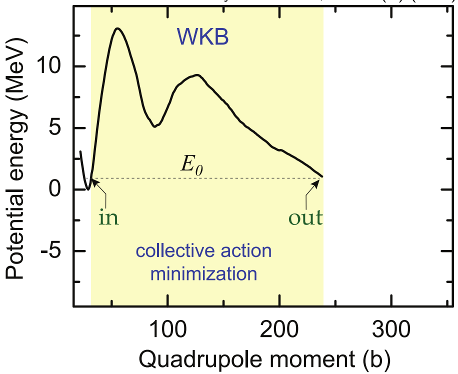


M. Eichler *et al.*, Astrophys. J. **808**, 30 (2015).

- Final abundances strongly affected by fragments distributions
  [see also B. Côté *et al.*, Astrophys. J. **855**, 99 (2018)].
- Most of the models are parametrizations/phenomenological $\rightarrow$ validity far from stability?
- This talk: compute fission yields (FY) using DFT+Langevin.

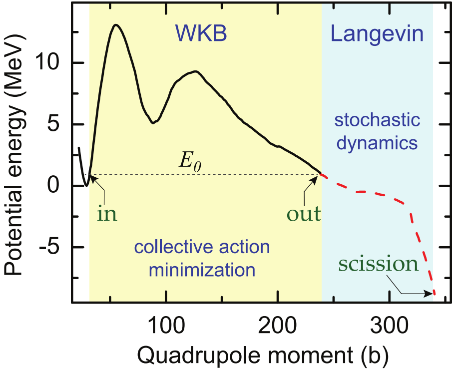
The fission process

J. Sadhukan *et al.* Phys. Rev. C **93**, 011304(R) (2016)



The fission process

J. Sadhukan *et al.* Phys. Rev. C **93**, 011304(R) (2016)



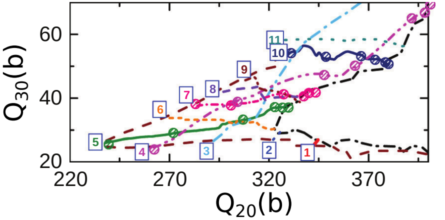
The stochastic Langevin framework

Path from outer turning point to scission given by dissipative Langevin:

$$\frac{dp_i}{dt} = -\frac{p_j p_k}{2}\frac{\partial}{\partial x_i}(\mathcal{M}^{-1})_{jk} - \frac{\partial V}{\partial x_i} - \underbrace{\eta_{ij}}_{\text{friction}}(\mathcal{M}^{-1})_{jk}p_k + \underbrace{g_{ij}\Gamma_j(t)}_{\text{random force}}$$

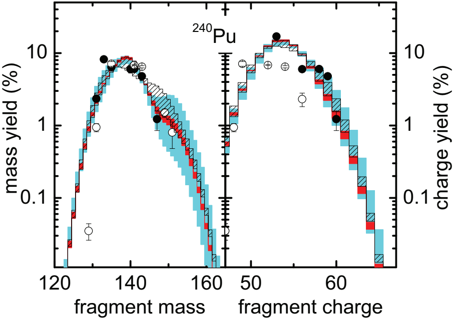
$$\frac{dx_i}{dt} = (\mathcal{M}^{-1})_{ij}p_j$$

J. Sadhukan *et al.* Phys. Rev. C **96**, 061301(R) (2017)



^{240}Pu: Fission yields

J. Sadhukan *et al.* Phys. Rev. C **96**, 061301(R) (2017)



- Good agreement with experimental data (circles).
- Results are robust against variations in theoretical quantities (η_{ij}, E_0,...).
- Random force responsible for the tails of the distribution.

Fission yields of ^{294}Og

How robust is the method against:

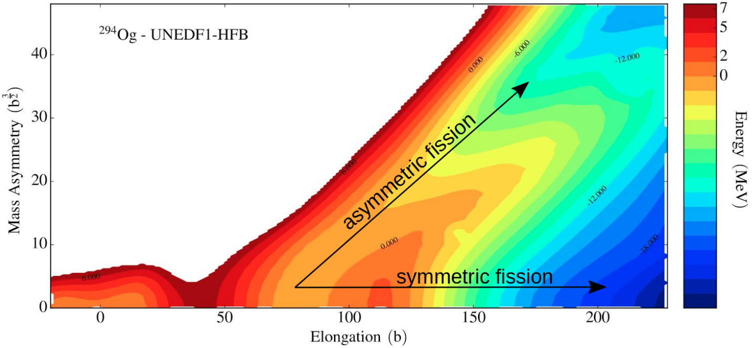
- Choice of collective variables?
- Choice of collective inertias?
- Choice of functional?

Testground: $^{294}_{118}\mathbf{Og}_{176}$ [Oganessian *et al.*, PRC **74** (2006)]

- Heaviest element produced on Earth (2005-2010 JINR, Dubna).
- $\tau \sim 0.7\,$ms.
- Very few events (1-2 fission?).

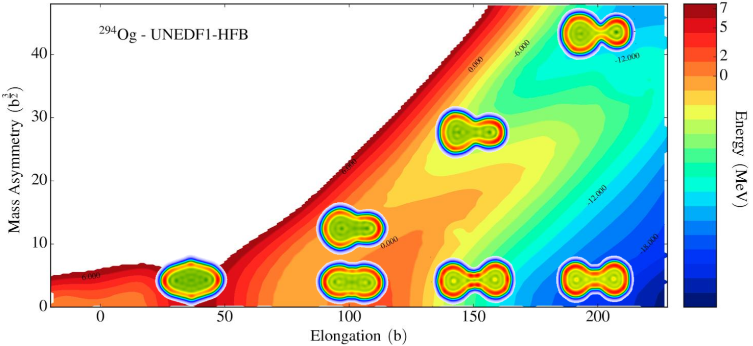
Very **exotic nucleus** → "blind" EDF calculation...

^{294}Og: potential energy surface



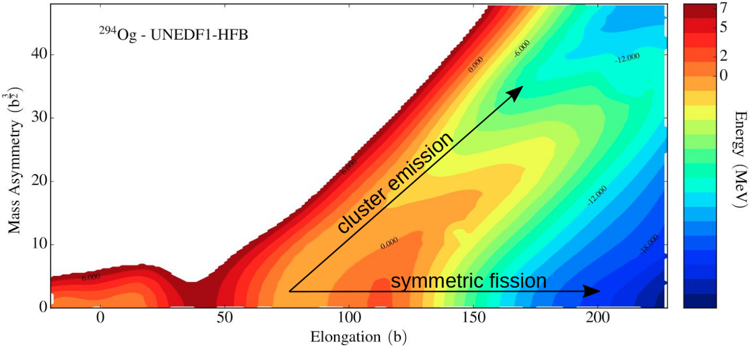
- Two competing fission modes: symmetric ($Q_{30} = 0$) vs asymmetric ($Q_{30} \neq 0$).

^{294}Og: potential energy surface



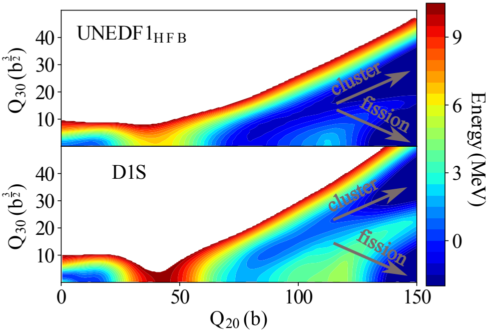
- Two competing fission modes: symmetric ($Q_{30} = 0$) vs asymmetric ($Q_{30} \neq 0$).
- From localization functions: ${}^{294}_{118}\mathrm{Og}_{176} \longrightarrow {}^{208}_{82}\mathrm{Pb}_{126} + {}^{86}_{36}\mathrm{Kr}_{50}$.

^{294}Og: potential energy surface



- Two competing fission modes: symmetric ($Q_{30} = 0$) vs asymmetric ($Q_{30} \neq 0$).
- From localization functions: $^{294}_{118}\mathrm{Og}_{176} \longrightarrow {}^{208}_{82}\mathrm{Pb}_{126} + {}^{86}_{36}\mathrm{Kr}_{50}$.
- ^{294}Og decays via cluster emission.

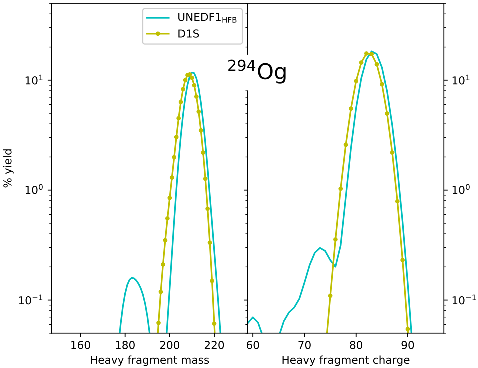
^{294}Og barriers: UNEDF1 vs D1S



Matheson *et al.* (in preparation)

UNEDF1 and D1S predict similar evolution of the potential energy surface, but D1S has larger barrier → impact on yields?

^{294}Og fission yields: UNEDF1 vs D1S



Matheson *et al.* (in preparation)

Outline

1. Introduction

2. Impact of fission on r-process nucleosynthesis

3. Fission fragments distributions

4. **Conclusions & Outlook**

Conclusions & Outlook

- HFB + Hauser-Feshbach are valuable tools for studying the role of fission in the r-process nucleosynthesis.
- New set of stellar rates suited for r-process calculations:
- Abundances sensitive to height of fission barriers and local changes in neutron separation energies around $A = 257$ and $A > 280$.
- No impact on radioactive energy generation and ^{232}Th/^{238}U ratio: progenitors of actinides have $Z < 84 \Rightarrow$ no nuclei with $Z \geq 84$ survive to fission?
- EDF + Langevin is a useful method to compute fission yields $\rightarrow$ small sensitivity on choice of the functional.

- **Future work:**
  - β-delayed fission rates from BCPM barriers;
  - calculation of fission fragments distributions using EDFs;
  - explore different initial astrophysical conditions;
  - extend calculations using different EDF.

Some questions

- Which observables could prove the production of actinides/SHE during the r process? (see Y. Zhu *et al.*, arXiv:1806.09724 and Nicole's talk)
- How shall we conciliate consistency and accuracy in the calculations of nuclear inputs? (Nicolas' talk)
- Is it time for new sensitivity studies of r-process abundances? (see L. Neufcourt *et al.*, arXiv:1806.00552 Witek's talk)

Collaborators

- G. Martínez Pinedo (TUD/GSI, Darmstadt)
- **Z. Matheson** and W. Nazarewicz (NSCL/FRIB, East Lansing)
- L. Robledo (UAM, Madrid)
- J. Sadhukhan (VECC, Kulkata)
- N. Schunck (LLNL, Livermore)
- M.-R. Wu (Sinica, Taiwai)

Thank you!

The dynamic description of spontaneous fission

$$t_{SF} \sim \exp(2S) \quad \Leftarrow \quad S(L) = \int_a^b ds \sqrt{2 \times B(s)\left[E(s) - E_0\right]}$$

Expand the multidimensional PES: relevant d.o.f. in s?

- Deformation multipoles: $Q_{20}, Q_{22}, Q_{30}, \ldots$
- Pairing correlations Δ (Babinet and Moretto, PLB 49 (1974)).

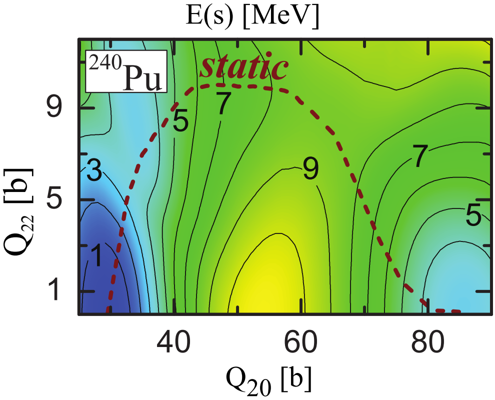
How to determine the fission path $L(s)$?

- Minimizing the energy $E(s)$: *static approximation*.
- Minimizing the action $S(L)$: *dynamic approach*.

State-of-the-art SF calculations:
Sadhukhan et al, PRC88(2013) and PRC90(2014); SAG et al, PRC90(2014); Zhao et al, PRC92(2015) and PRC93(2016).

Static vs dynamic fission: ^{240}Pu and ^{234}U

Triaxial case: ^{240}Pu - SkM* interaction



from Shadukhan et al., PRC90(2014),

see also Zhao et al., PRC93(2016).

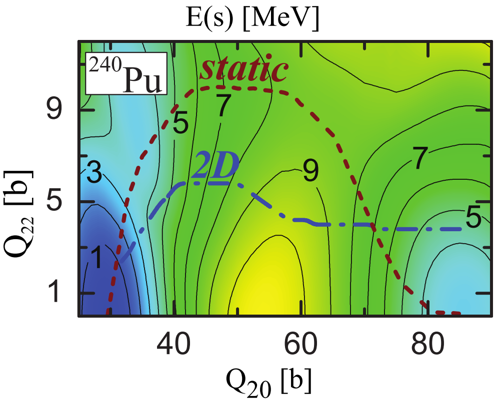
dynamic paths:

2D: $s = \{Q_{20}, Q_{22}\}$

3D: $s = \{Q_{20}, Q_{22}, \Delta N^2\}$

Static vs dynamic fission: ^{240}Pu and ^{234}U

Triaxial case: ^{240}Pu - SkM* interaction



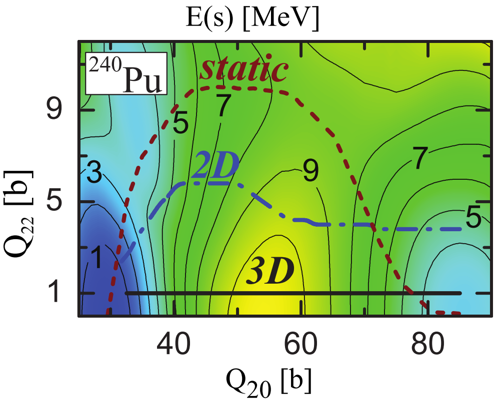
from Shadukhan et al., PRC90(2014),
see also Zhao et al., PRC93(2016).

dynamic paths:

2D: $s = \{Q_{20}, Q_{22}\}$
3D: $s = \{Q_{20}, Q_{22}, \Delta N^2\}$

Static vs dynamic fission: ^{240}Pu and ^{234}U

Triaxial case: ^{240}Pu - SkM* interaction



from Shadukhan et al., PRC90(2014),

see also Zhao et al., PRC93(2016).

dynamic paths:

2D: $s = \{Q_{20}, Q_{22}\}$
3D: $s = \{Q_{20}, Q_{22}, \Delta N^2\}$

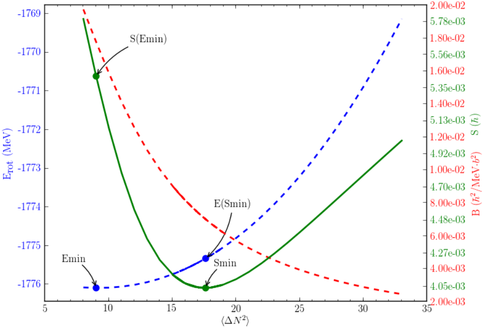
Pairing fluctuations restore the axial symmetry! Artifact?

Static vs dynamic fission: ^{240}Pu and ^{234}U

Axial case: ^{234}U - BCPM interaction

Method	t_{sf} (s)
E_{min} (static)	0.81×10^{43}
$S_{min}(Q_{20}, Q_{30})$	0.44×10^{42}
$S_{min}(Q_{20}, Q_{40})$	0.12×10^{43}
$S_{min}(Q_{20}, \Delta N^2)$	0.18×10^{23}
Experiment	7.8×10^{23}

SAG, Robledo and Guzmán-Rodriguez PRC90(2014).



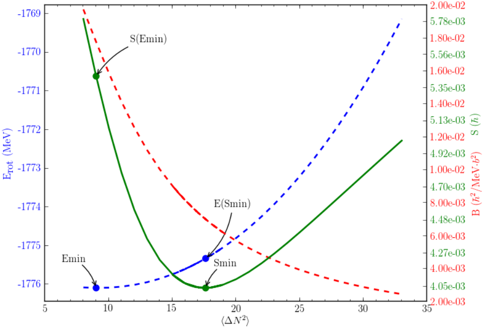
- Pairing correlations reduce collective inertias → spontaneous fission lifetimes decrease when pairing is included as d.o.f.

Static vs dynamic fission: ^{240}Pu and ^{234}U

Axial case: ^{234}U - BCPM interaction

Method	t_{sf} (s)
E_{min} (static)	0.81×10^{43}
$S_{\text{min}}(Q_{20}, Q_{30})$	0.44×10^{42}
$S_{\text{min}}(Q_{20}, Q_{40})$	0.12×10^{43}
$S_{\text{min}}(Q_{20}, \Delta N^2)$	0.18×10^{23}
Experiment	7.8×10^{23}

SAG, Robledo and Guzmán-Rodriguez PRC90(2014).



- Pairing correlations reduce collective inertias → spontaneous fission lifetimes decrease when pairing is included as d.o.f.

Conclusion

Spontaneous fission dynamics strongly modified by pairing fluctuations!