Neck Rupture and Scission Neutrons in Nuclear Fission

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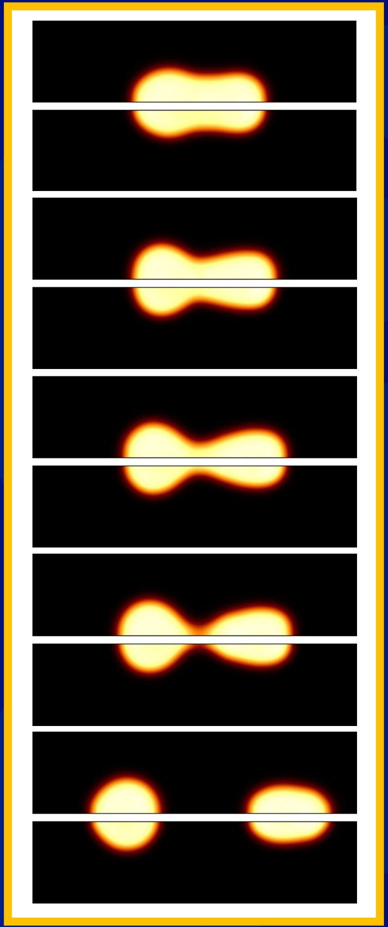
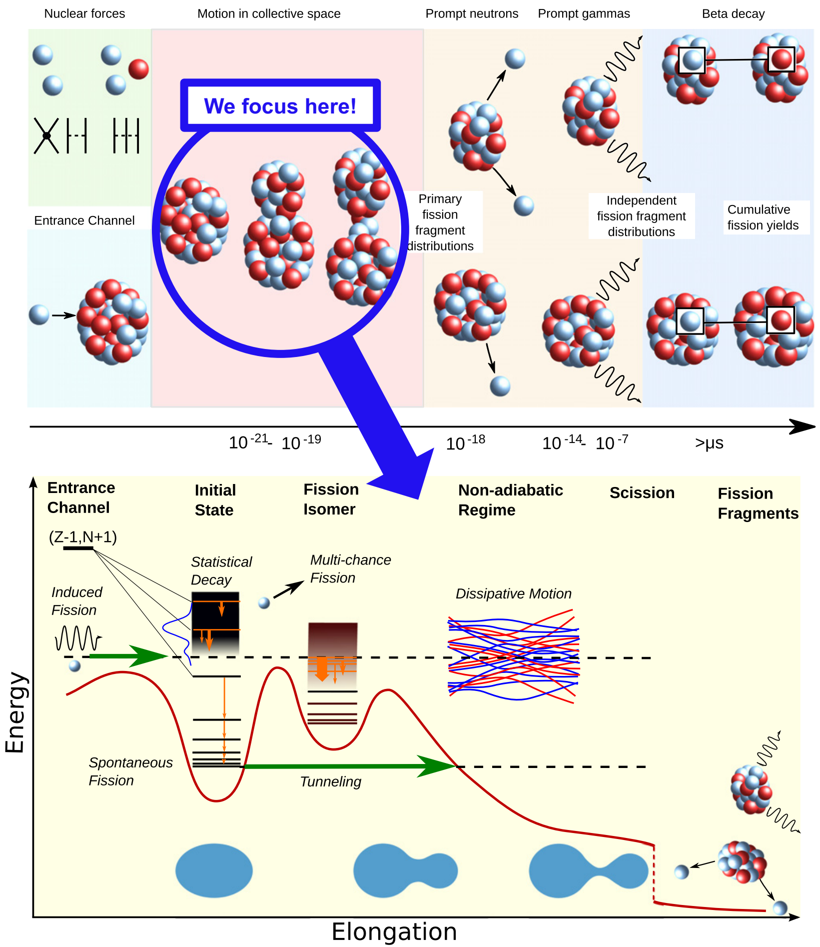


Motivation

- Fission was discovered in 1938, and its main mechanism explained a few months later by Lise Meitner and Otto Frisch.
- It is a highly complicated quantum many-body process, with various distinct stages, occurring at vastly different timescales.
- Surprisingly, the idea of scission neutrons (SNs) is almost as old as the discovery of fission itself, first being considered by Bohr and Wheeler in 1939.
- Ever since, the existence of SNs and their potential properties have been hotly debated over the years, and their experimental confirmation is still an open question.
- This work represents a small contribution towards the overarching goal in fission theory: to develop a consistent microscopic framework that describes all stages of fission and can accurately predict all relevant fission observables for all nuclei across the nuclear chart.



Source: Bender, Michael, et al. "Future of nuclear fission theory." *Journal of Physics G: Nuclear and Particle Physics* **47**, 113002 (2020).

Theoretical Framework

- We used the time-dependent superfluid local density approximation (TDSLDA), or, equivalently, time-dependent density functional theory (TDDFT) extended to superfluid systems, to simulate fission.
- This allows for the treatment of dynamics from saddle to scission, the most non-equilibrium part of fission, under realistic initial conditions.
- Two key points are required for any theory to model this stage of fission correctly:
  - The evolution from saddle to scission should be dissipative.
  - A correct description of pairing is essential.
- To allow for SNs to separate from fission fragments, runs became very computationally expensive.
  - We used either 48x48x120 or 48x48x100 point lattices.
  - Required all of Summit and Sierra to run.
  - Larger boxes are still required.

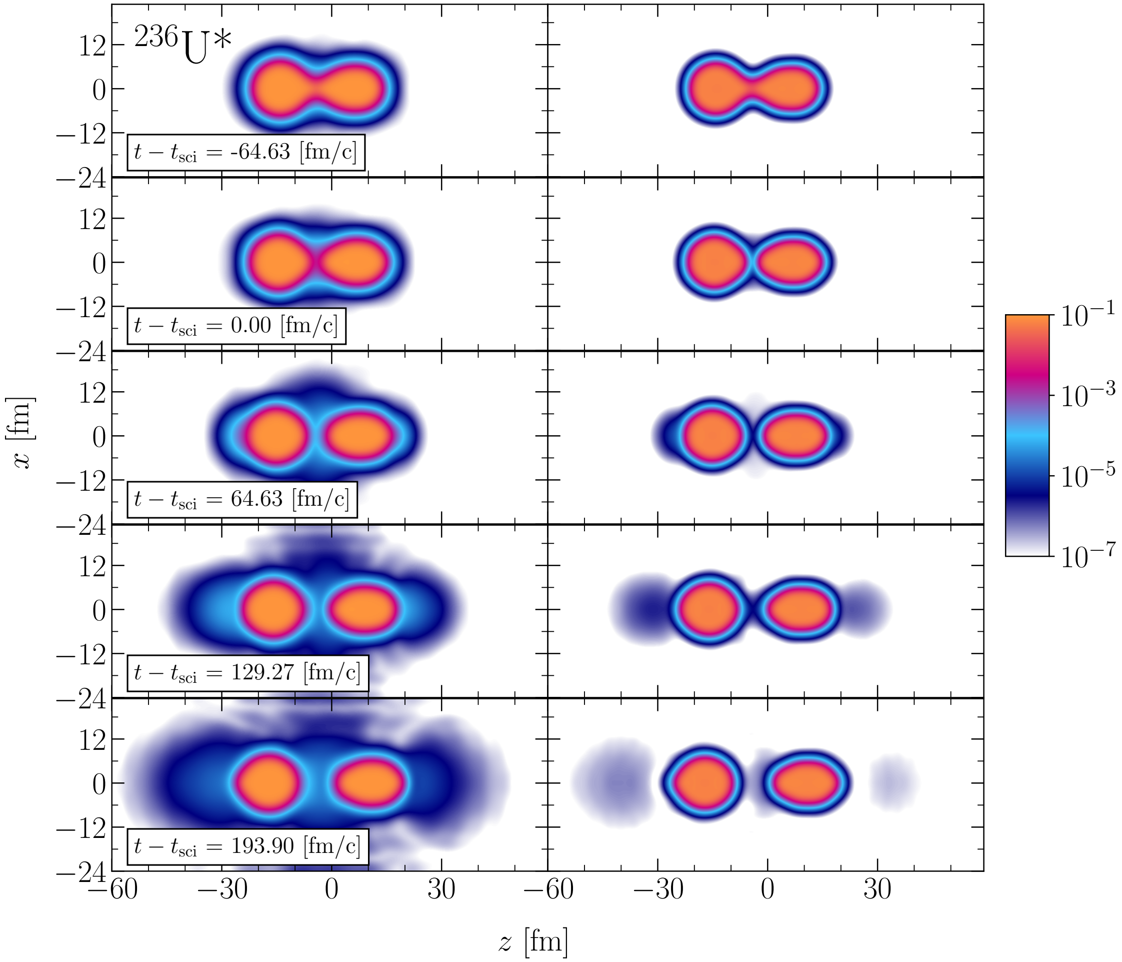
Considered Runs

Run #	Nucleus	Q_{20} [b]	Q_{30} [$b^{3/2}$]	β_2	β_3
1	^{236}U	184.33	19.66	1.88	0.86
2	^{236}U	159.64	17.80	1.63	0.77
3	^{236}U	135.25	12.74	1.38	0.55
1	^{240}Pu	157.20	20.18	1.56	0.85
2	^{240}Pu	153.11	18.34	1.52	0.77
3	^{240}Pu	140.08	10.6	1.39	0.45
4	^{240}Pu	141.85	8.56	1.40	0.36
5	^{240}Pu	144.71	6.63	1.43	0.28
6	^{240}Pu	145.64	6.63	1.44	0.28
1	^{252}Cf	240.80	36.53	2.20	1.39
2	^{252}Cf	227.19	32.50	2.07	1.24
3	^{252}Cf	199.17	23.52	1.82	0.90
4	^{252}Cf	168.29	13.44	1.54	0.51

Source: Ibrahim Abdurrahman, Matthew Kafker, Aurel Bulgac, and Ionel Stetcu, " Neck Rupture and Scission Neutrons in Nuclear Fission," *Phys. Rev. Lett.* **132**, 242501 (2024).

What do We See?

- At the neck rupture neutron clouds are emitted perpendicular and parallel to the axis of fission.
- Some charged particle emission as well.



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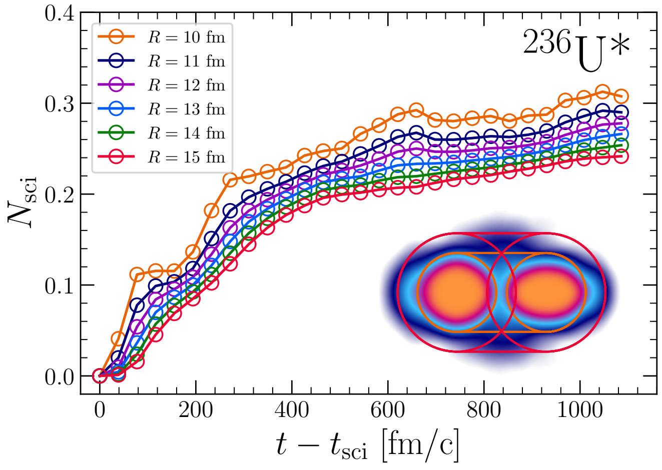
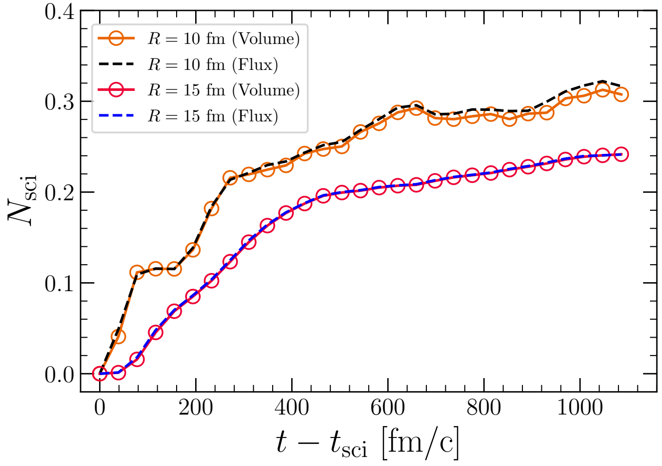
Consistency Checks

- Regardless of the specific selection criteria, we always see scission neutrons, with the amount varying by 20 % at most.
- Neutrons are free and remain free:
  - The interaction energy of the cloud is 1 % of its kinetic energy.

$$E_n^{\text{int}} = \int dV \left[a_n n_n^{5/3} + b_n n_n^2 + c_n n_n^{7/3}\right] \ll E_n^{\text{kin}}$$

  - After fully accelerating, the nucleons in LFF have an average of ~1/3rd the kinetic energy as nucleons in the cloud.





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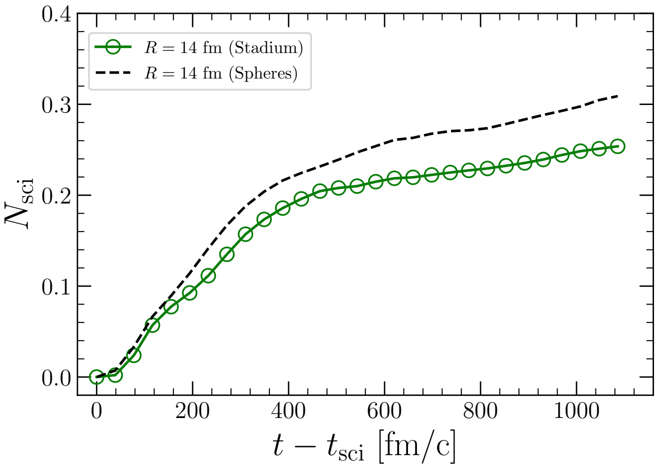

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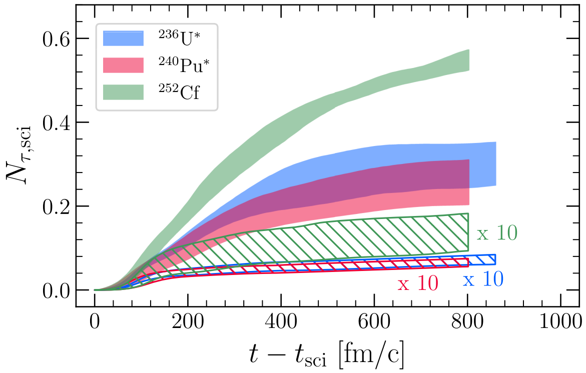
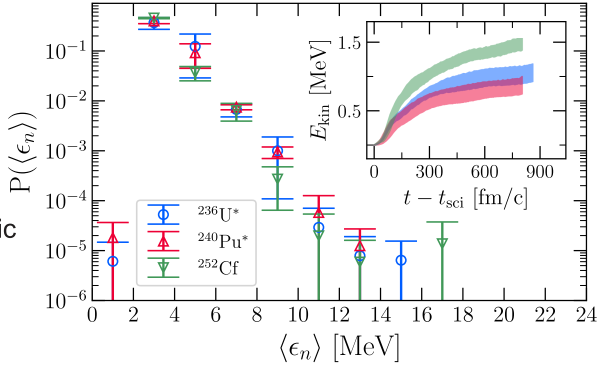
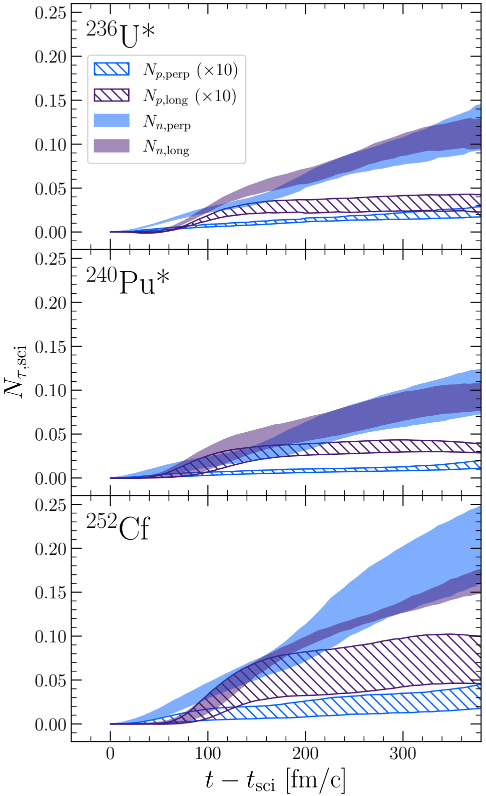
Amounts and Kinetic Properties

- Numbers:
  - The total number of emitted neutrons is about 0.30 ± 0.05, 0.26 ± 0.05, and 0.55 ± 0.02 per fission event for ^{236}U, ^{240}Pu, and ^{252}Cf, respectively.
  - This corresponds to roughly 9%–14% of the total emitted prompt neutrons.
  - Estimates are conservative.
  - In comparison, Carjan and collaborators estimated an upper bound of 25%–50% of prompt fission neutrons are emitted during scission.
  - Roughly equal number of perpendicular and longitudinal neutrons.
- Kinetic Properties:
  - The average kinetic energies of the SNs are given by 3.51 ± 0.25 MeV, 3.42 ± 0.27 MeV, and 2.67 ± 0.24 MeV for ^{236}U, ^{240}Pu, and ^{252}Cf, respectively.
  - Faster than typically considered prompt neutrons.
  - Some neutrons are emitted with much higher kinetic energies.







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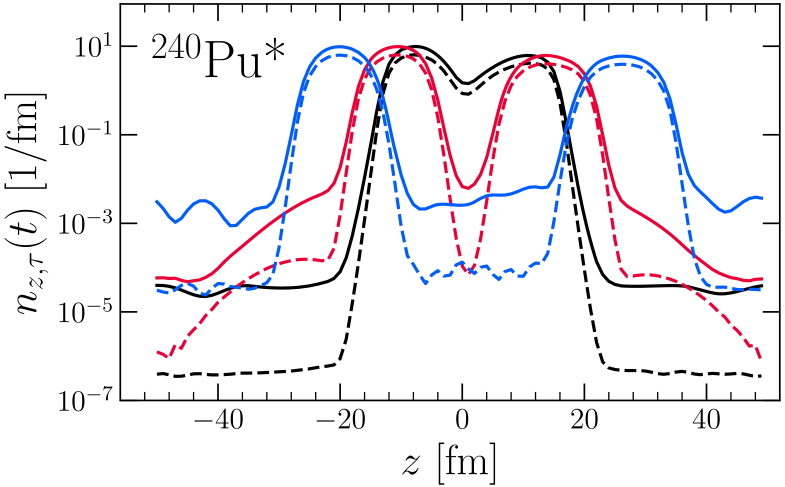
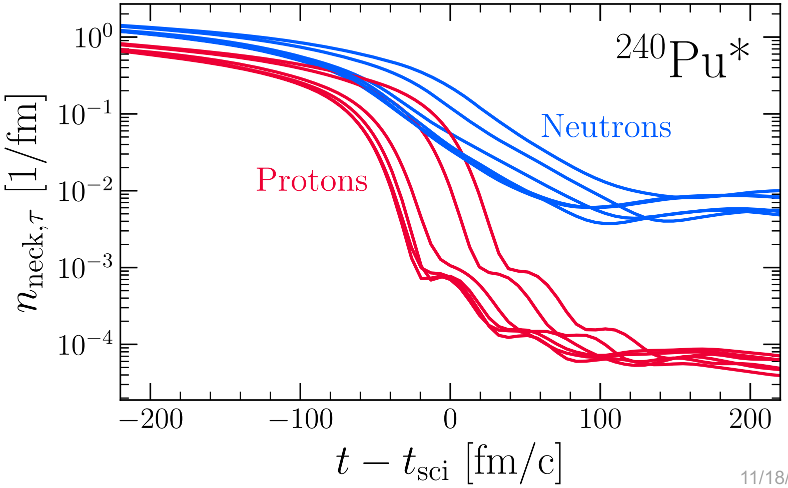
Emission Mechanism and the Neck Rupture

- Neck rupture behavior is universal for large class of asymmetric fission trajectories.
  - The number density decays exponentially, with a decay time of τ ≈ 35.0 ± 2.2 fm/c for neutrons and 15.3 ± 0.3 fm/c for protons.
  - It is not random, once a wrinkle forms at the outer saddle it does not move.
  - Still needs to be tested for symmetric or close to symmetric fission and more nuclear systems.
- Catapult mechanism (more like a slingshot), suggested by Mädler in 1984, is responsible for longitudinal emission.





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Conclusions

This study represents the first fully microscopic evidence for the emission of scission neutrons in quantum many-body theory.

Key takeaways:

- Neutrons make up reasonable portion of prompt neutron emission.
- They appear in three signals, two in front of each fragment, and one perpendicular to the fission axis.
- The dispersion of these signals at later times is unclear.
- Scission neutrons have higher average energies than prompt neutrons, with some carrying up to 17 MeV of kinetic energy.
- Neck rupture is not a random, with the point of rupture defined at the outer saddle.
- Universality of rupture needs to be tested for larger class of fission trajectories.
- Larger lattice are still required to extract angular distributions and potentially see the termination of scission neutron emission.

Thank you!
Any questions?