Microscopic fission models

State of the art and future opportunities

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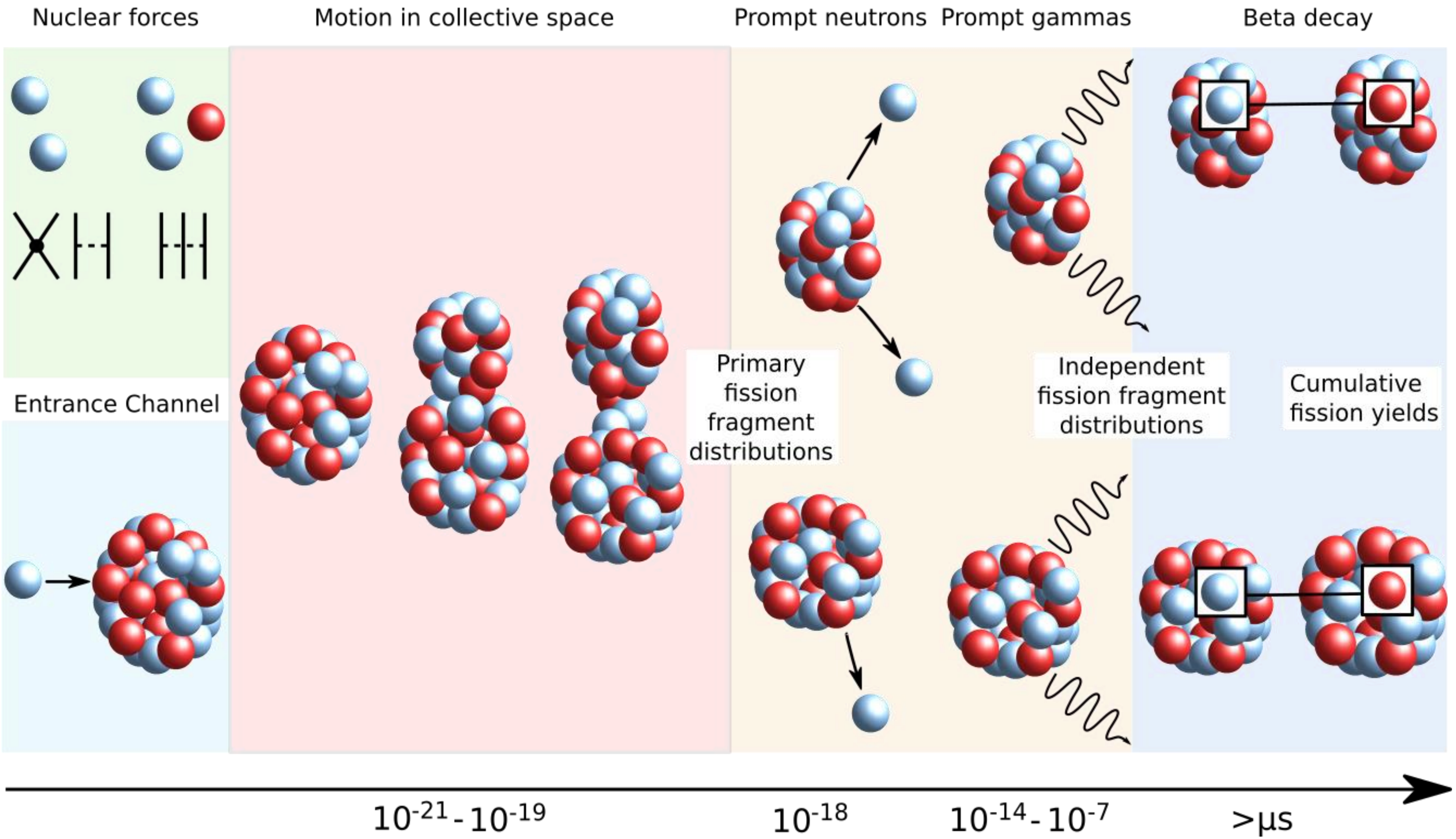
From Scission to Cumulative Fission Product Yields

Two major research areas for fission theory: cross sections (~ probabilities that fission happens) and fission products (includes neutrons, gammas, fragments, etc.)



Microscopic fission models?

The most significant progress of the last 2 decades has been on describing the evolution "from saddle to scission" and extract the initial conditions of the fission fragments

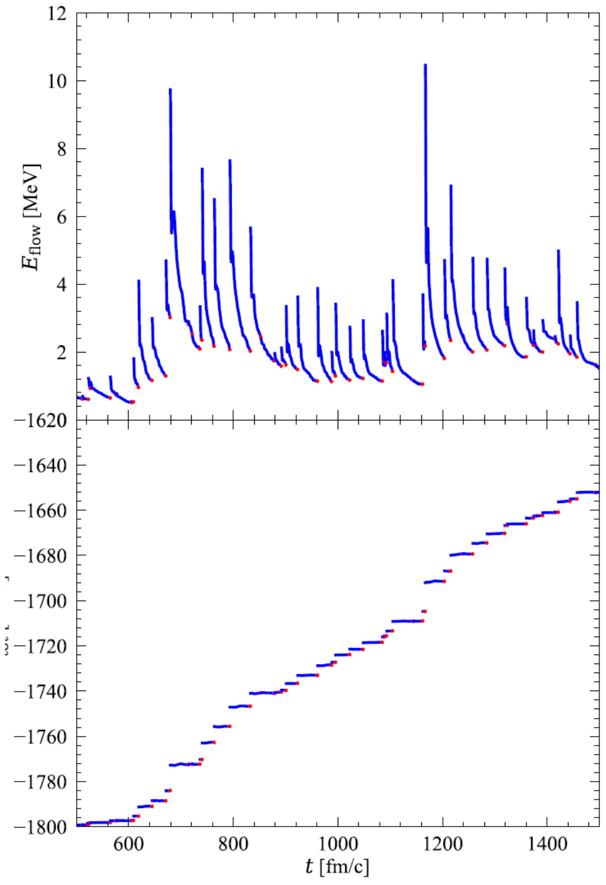
- Global framework of nuclear density functional theory (DFT), aka self-consistent mean-field theory (and beyond mean field)
- Current hierarchy of methods:
  - Hartree-Fock-Bogoliubov (HFB): deformation properties, potential energy surfaces
  - Projection techniques (PNP and AMP): quantum numbers of compound nucleus or of fission fragments
  - Time-dependent density functional theory (TDHF, TDHFB, TDDFT, etc.): excitation energy of fission fragments
  - Time-dependent generator coordinate method (TDGCM): fission fragment distributions
  - QRPA/linear response theory: γ- and β-decay of fission fragments
- Inputs: model of nuclear forces + quantum many-body methods
- Outputs: distributions $Y(Z,A;E_n)$, spin distribution $p(I,\pi)$, excitation energy E^*, level density $\rho(U)$, etc.

DFT provides a consistent theoretical framework to predict the initial conditions of the fission fragments for deexcitation codes

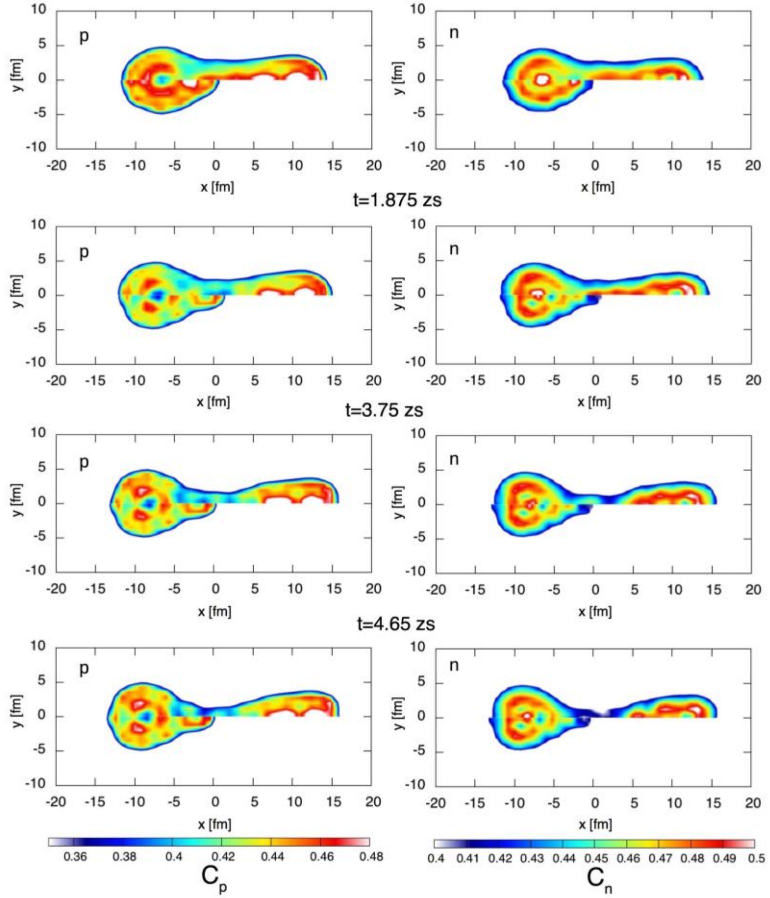
New insights

Microscopic methods have explained why fission is dissipative and why the most likely heavy fragment in actinide fission is not ^{132}Sn

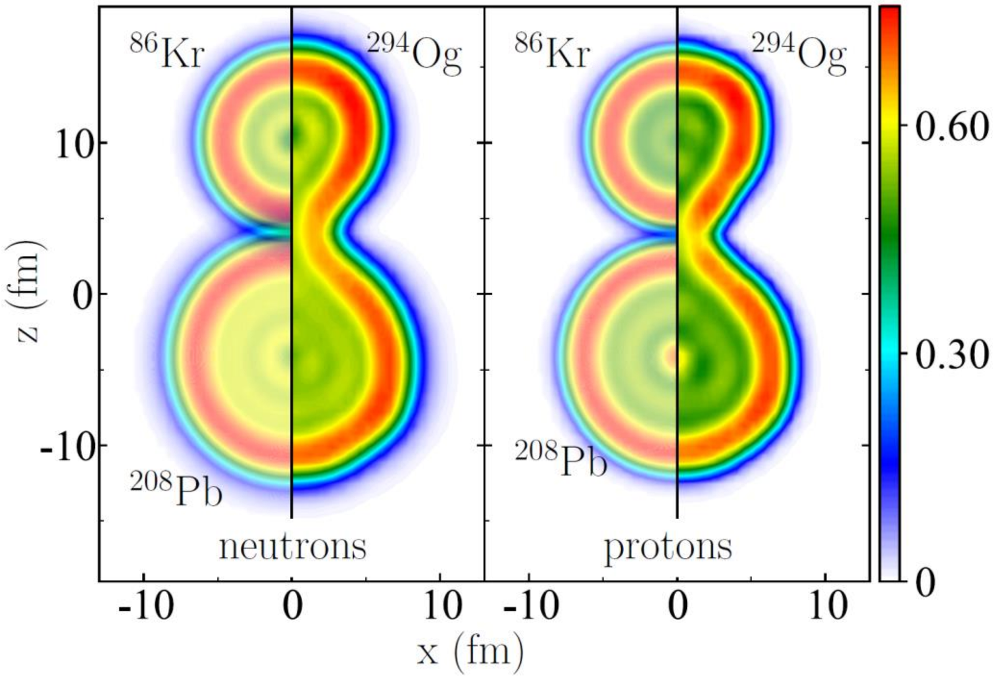
PRC **104**, L021601 (2021)



Nature **104**, L021601 (2019)



PRC **99,** 041304(R) (2019)



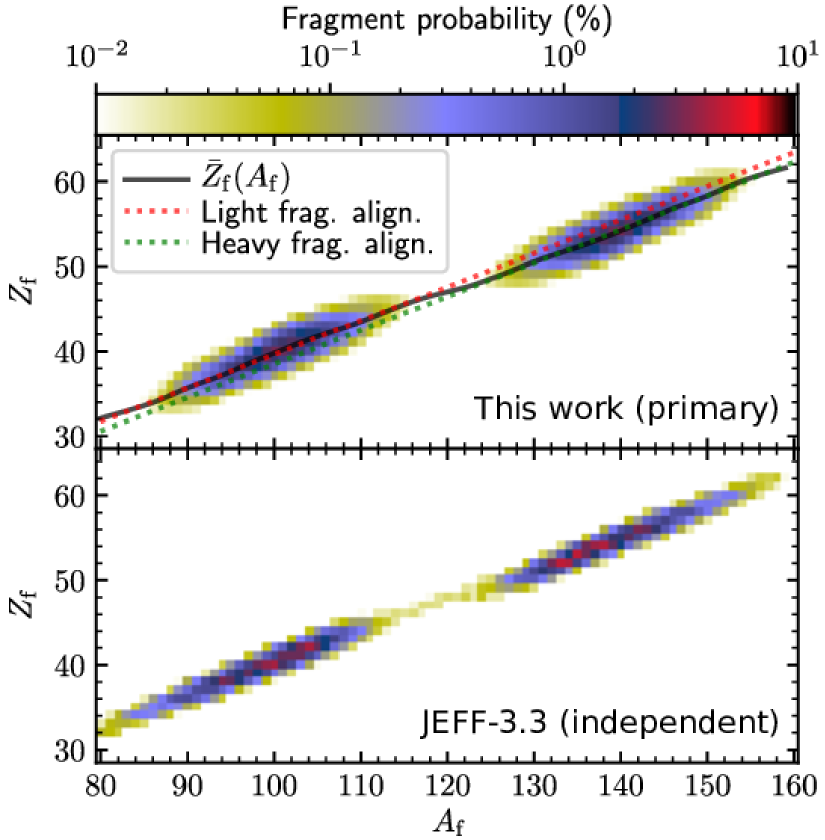
New predictions of cluster radioactivity in superheavy elements

Fundamental theories give a better understanding of the physics of the fission process

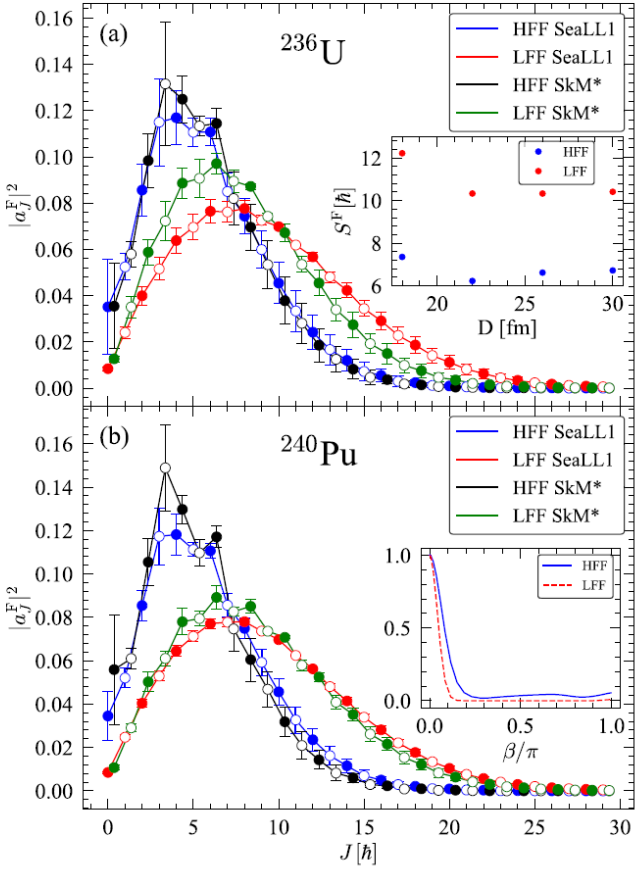
New constraints

Projection techniques have provided unique insights into the odd-even staggering effect and spin distributions in the fragments that inform phenomenological models

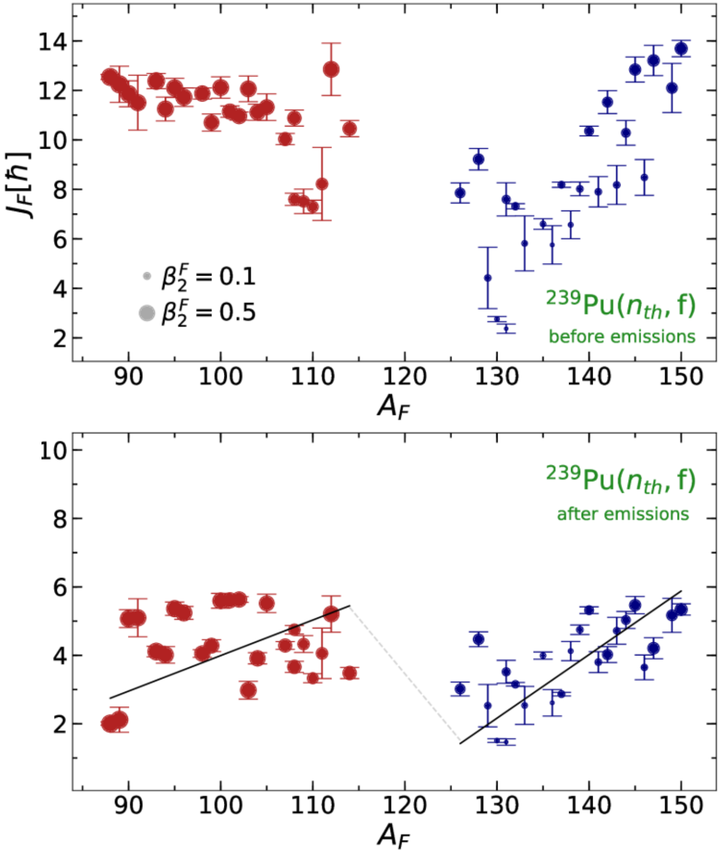
PRC **103**, 054602 (2021)



PRL **126**, 142502 (2021)



PRC **104**, L021601 (2021)

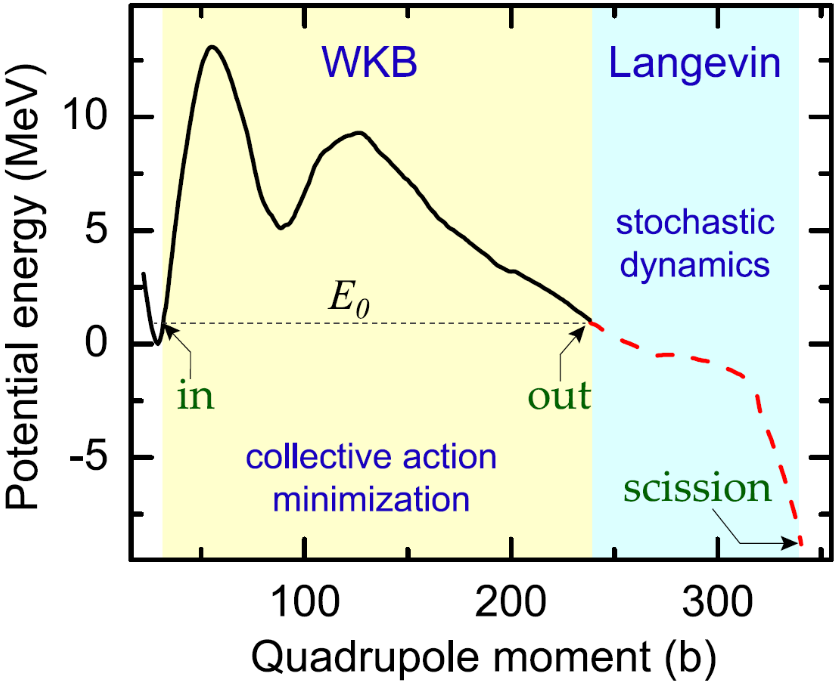


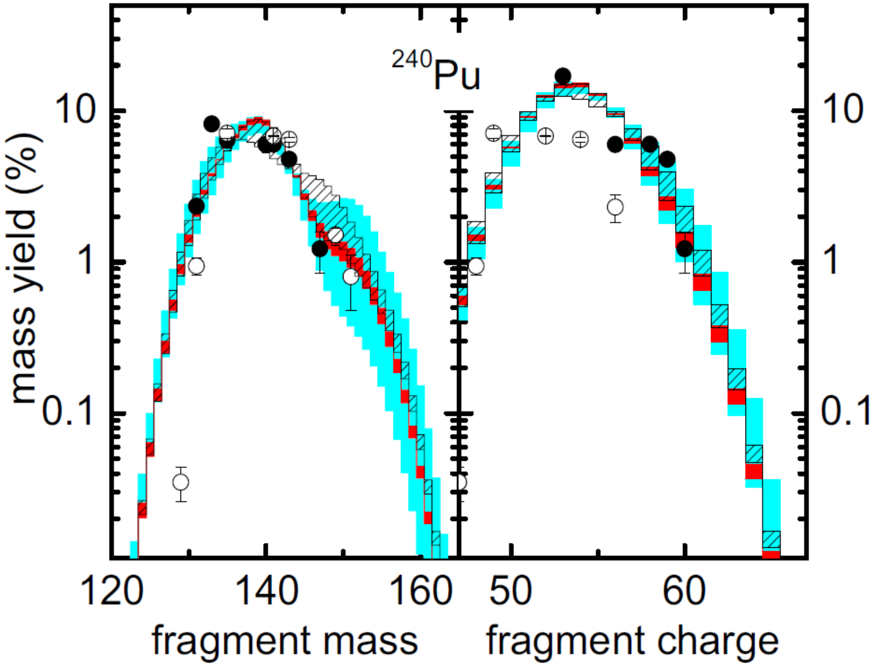
Fundamental theories inform phenomenological models

Spontaneous Fission

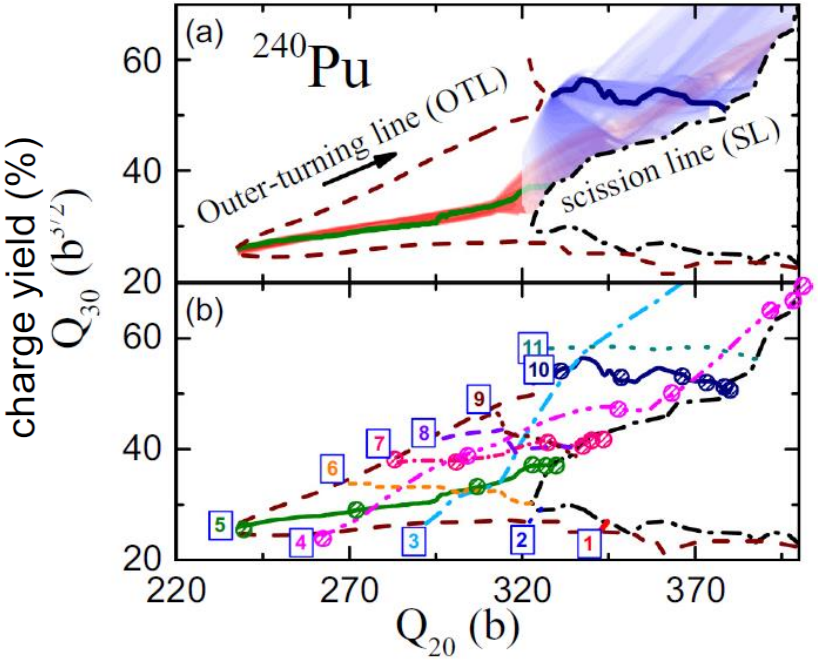
The same techniques used for induced fission are readily applicable to study spontaneous fissions, including half-lives and distributions

PRC **96**, 061301 (2017)





PRC **93**, 011304 (2016)



- Microscopic methods give realistic description of multi-dimensional tunneling
- Semi-classical methods still needed to describe late evolution to scission

Outlook

Microscopic models of fission provide insights into the fundamental mechanisms of the process that help inform and constrain more phenomenological models used in evaluations

- Short term
  - Combine recent methods for higher-fidelity description of initial conditions and couple with deexcitation codes: validate in major actinides and predict minor actinides
  - Systematic calculations of FPY across the mass table (=microscopic equivalent of LANL FRLDM+Langevin) for applications such as astrophysics or nuclear forensics
    - Neutron-induced fission: programmatic applications
    - Spontaneous fission: programmatic and basic science (superheavies, astrophysics)
    - β-delayed fission: basic science (astrophysics)
- Longer term
  - A unified theory of fission that includes dissipation, fluctuations and collectivity is still needed
    - Basic building blocks are here: time-dependent DFT (dissipation), time-dependent RPA (fluctuations), TDGCM (collectivity)
    - How to combine them into consistent theory?
  - Uncertainty quantification and propagation
    - All predictions depend on a dozen of parameters of the energy functional – that are calibrated on some experimental data
    - Framework for UQ is straightforward but implementation is beyond exascale unless ML/AI techniques are used

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