Microscopic Description of the Fission Process
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The neutron strikes the nucleus and is absorbed.

The absorbed neutron causes the nucleus to undergo deformation.

In about 10^{-14} second, one of the deformations is so drastic that the nucleus cannot recover.

The nucleus fissions, releasing two or more neutrons.

In about 10^{-12} second, the fission fragments lose their kinetic energy and come to rest, emitting a number of gamma rays. Now the fragments are called fission products.

The fission products lose their excess energy by radioactive decay, emitting beta particles and gamma rays over a lengthy time period (transuranium elements).
Theoretical Description of the Fission Process

The Team

PI: Witold Nazarewicz

PhD students:
- Daniel Lay
- Joshua Wylie
- Zachary Matheson (now NNSA graduate fellow)

Post Docs: Samuel Giuliani
  + Jhilam Sadhukhan (Kolkata)
  + Nicolas Schunck (LLNL)
  + NUCLEI (SciDAC-4)
  + Statistics and Probability at MSU

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- Most practical applications have been based on simplified theories tuned to existing data
- We are developing a microscopic model that will be predictive

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https://people.nscl.msu.edu/~witek/fission/fission.html
Five components of our program

I. Quantified input (optimized energy density functional)

II. Microscopic model based on a quantified input
   - Density functional theory
   - Stochastic Langevin framework

III. Confrontation with experiment
   - Actinides and transfermiums (superheavy nuclei)
   - Pt-Po region

IV. Systematic predictions
   - Superheavy elements
   - Astrophysical applications: r-process

V. Uncertainty quantification
   - Linear regression
   - Bayesian machine learning
   - Bayesian model averaging
Fission fragment yields


**Graphs and Data**

- **Prefragment Z**: Shows data points for different isotopes, indicated by symbols like squares and circles, labeled with elements like Pt, Fm, and others.
- **Prefragment N**: Similar setup with additional data points for isotopes like Pu and Fm.
- **Yield (%)**: Plots showing the percentage yield against fragment mass and charge for isotopes labeled with 178Pt, 240Pu, 254Fm, and 256Fm.

**Key Observations**

- The graphs illustrate the distribution of prefragments with respect to Z and N.
- The yield values are plotted against fragment mass and charge, highlighting the spread of different isotopes.

**References**

- The data is likely derived from experimental results or simulations related to nuclear physics or a specific reactor's performance.
Heavy Cluster Decay


$^{294\text{Og}} \rightarrow ^{208\text{Pb}} + ^{86\text{Kr}}_{50}$

DFT+Langevin Robust prediction: extremely asymmetric fission
Synthesis of elements during the r-process is sensitive to fission properties of (super)heavy nuclei, particularly in neutron star mergers where the flux of free neutrons is high.

Abundances (in log scale) at freeze-out
Uncertainty Quantification and Bayesian Machine Learning

Residual of an observable $O$:

$$\delta_O(Z, N) = O^{\text{exp}}(Z, N) - O^{\text{th}}(Z, N)$$

Estimate of an observable $O$:

$$O^{\text{est}}(Z, N) = O^{\text{th}}(Z, N) + \delta^{\text{em}}_O(Z, N)$$

Emulator of the residual

Supervised learning: the nuclear modeling and the choice of priors represent two aspects of the supervision.
11 global nuclear mass models: Skyrme, Gogny D1M, BCPM, HFB-24, FRDM-2012

rms mass deviation $\sim 0.6 – 6$ MeV

• Machine Learning: The emulators of separation-energy residuals and confidence intervals defining theoretical error bars are constructed using Bayesian Gaussian processes.

• After establishing statistical methodology and parameters, we carried out extrapolations towards particle driplines.

• We carry out Bayesian Model Averaging to make quantified predictions using several models.

$$p(M_k | y) = \frac{p(y | M_k) \pi(M_k)}{\sum_{\ell=1}^{K} p(y | M_\ell) \pi(M_\ell)}$$
Beyond the proton drip line: Bayesian analysis of proton-emitting nuclei

"0" corresponds to the neutron number of the lightest isotope for which an experimental separation energy value is available.

\[ p_{2p} := p( S_{2p}^* < 0 \cap S_{1p}^* > 0 | S_{1p}/2p ) \]

Quantified limits of the nuclear landscape
“0” corresponds to the neutron number of the heaviest isotope for which an experimental separation energy value is available.
Prospects

Current Status:
• Sophisticated calculations of spontaneous fission lifetimes: more collective degrees of freedom taken into account (currently 4D); the fission path determined by minimizing the collective action.
• Fission yield distributions explained by a statistical treatment with diffusive dynamics.
• Identification of pre-fragments through nucleon localizations.
• Ability to carry out reliable extrapolations in mass and isospin through Gaussian processes/neural networks and Bayesian model averaging.

Challenges:
• Extension of the framework to induced fission.
• Consistent description of various experimental fission data, including TKEs
• Global calculations of fission yields for r-process simulations.
• Quantification of uncertainties in fission observables using Bayesian Machine Learning techniques
• Deliverables since the last Symposium
  • 4 publications
  • 3 papers submitted
  • 1 program report
  • 16 presentations
  • 1 postdoc, another postdoc will join us soon
  • 3 students involved. Zach Matheson received NGFP fellowship.

• Quantification of margins and uncertainties is important
• Ongoing collaboration with LLNL
• Fission is a perfect problem for the extreme scale computing. Our project is well aligned with NUCLEI SciDAC-4 ASCR project.
BACKUP
The most promising new candidates for the true 2p radioactivity:

$^{30}$Ar, $^{34}$Ca, $^{39}$Ti, $^{42}$Cr, $^{58}$Ge, $^{62}$Se, $^{66}$Kr, $^{70}$Sr, $^{74}$Zr, $^{78}$Mo, $^{82}$Ru, $^{86}$Pd, $^{90}$Cd, $^{103}$Te