FIRE – Fission in r-process elements

Lead: N. Schunck (LLNL)

Sponsors: DOE/NP ($100k), DOE/USNDP ($100k), NNSA/NA221 ($300k)

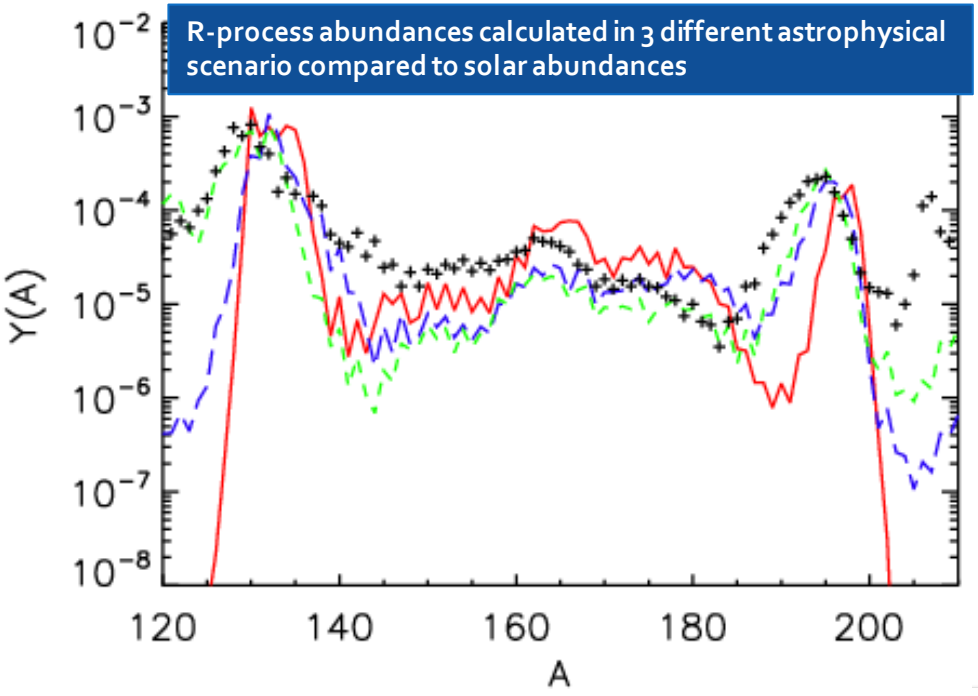
LLNL-PRES-XXXXXX

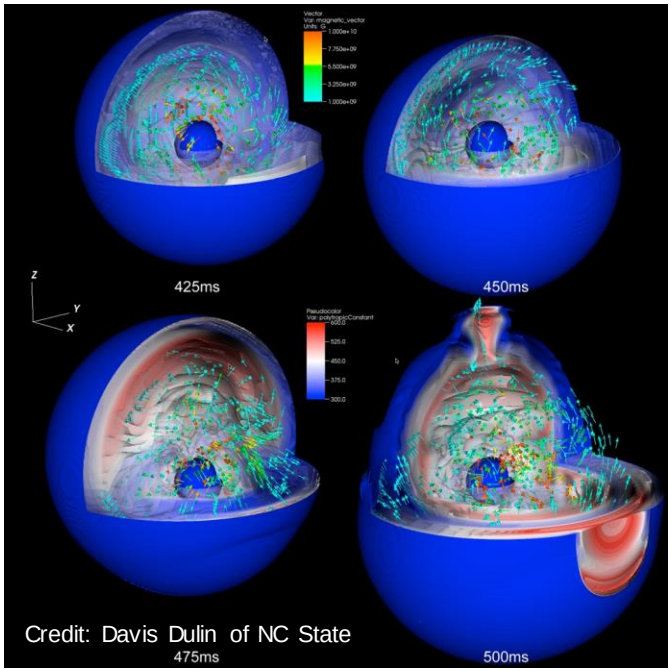
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

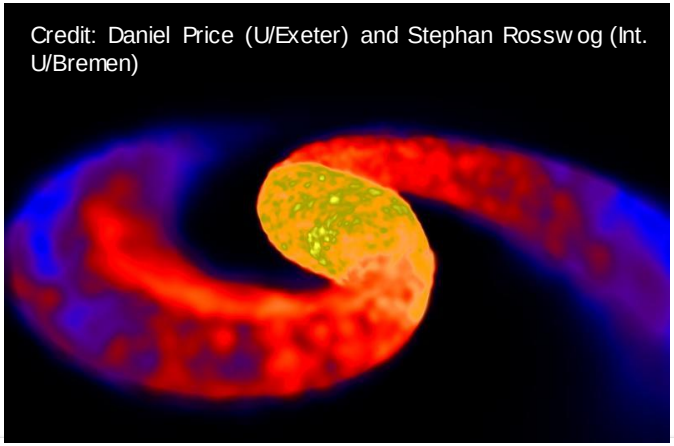
National Nuclear Security Administration

We do not know how the heaviest elements are formed

- Heavy elements are formed by nuclear reactions involving rapid neutron capture (r-process) in stellar environments
- Exact astrophysical conditions of the r-process (neutron star merger? core-collapse supernova?) ~~remain unknown~~ must be tested by nucleosynthesis simulations







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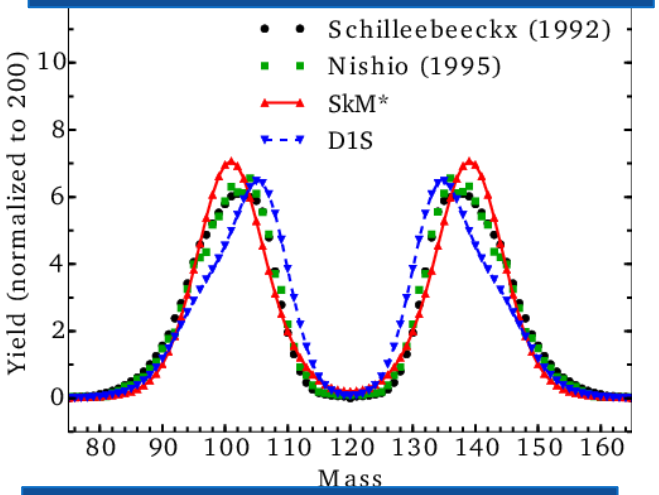
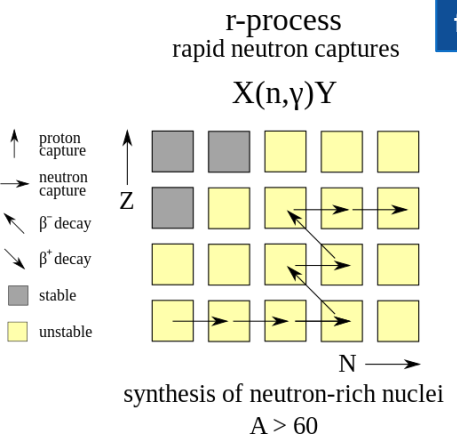
Accurate and reliable nuclear data is essential to model the astrophysical mechanisms of the r-process

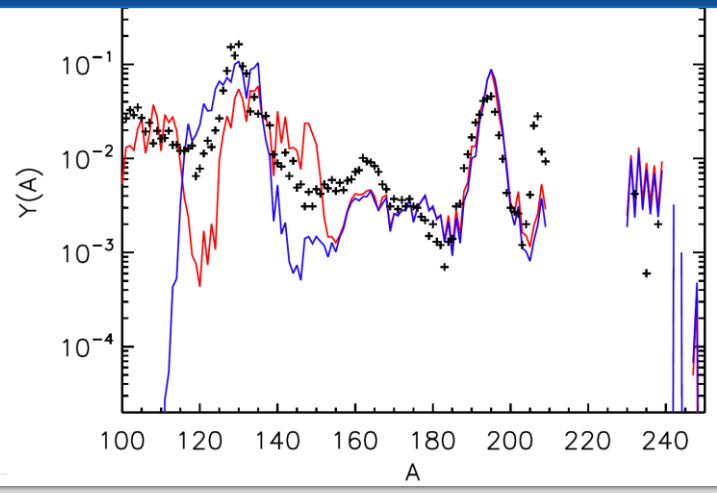
- Calculated r-process abundances depend crucially on masses, separation energies, decay rates (β-decay, γ-emission, fission), capture rates, etc.
- Fission has a major impact on the r-process
  - Fission properties are by far the most uncertain data for r-process simulations
  - NNSA laboratories have developed advanced capabilities to describe fission
  - Fission may be the key to pinpointing the location of the r-process

Predictions of fission fragment mass distributions for ^{239}Pu(n,f) (thermal neutrons)

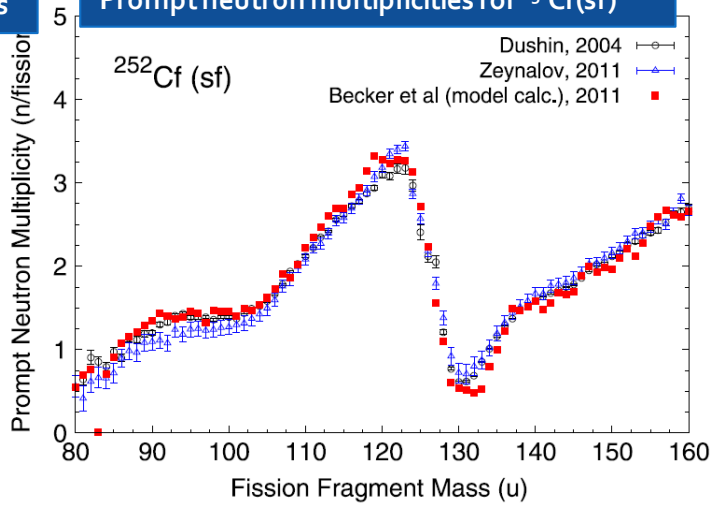




Influence of the shape (symmetric of asymmetric) of fission fragment distributions on r-process abundance predictions



Prompt neutron multiplicities for ^{252}Cf(sf)



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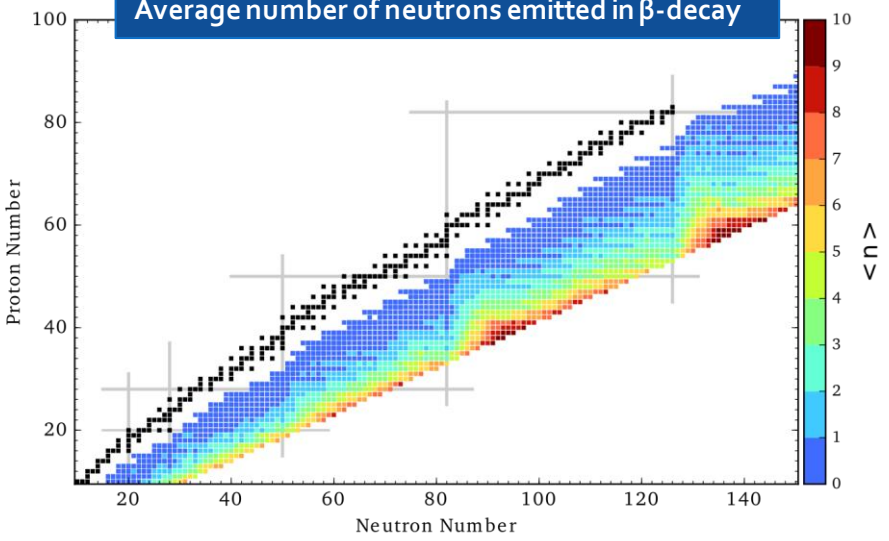
FIRE – Fission In R-process Elements

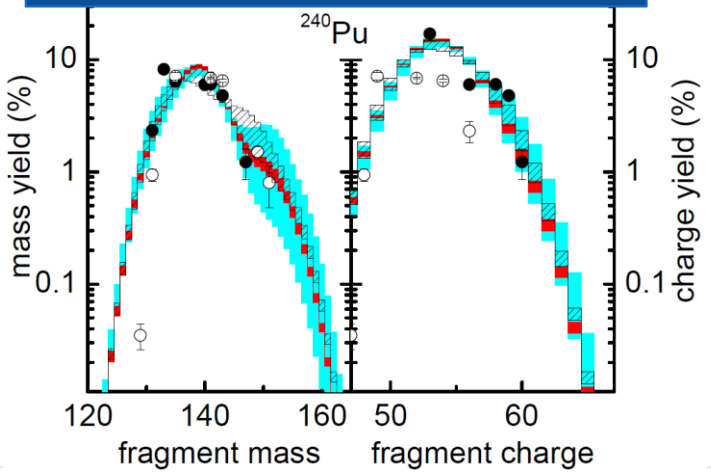
A joint DOE/NP – NNSA/NA221 project to answer fundamental questions about the formation of elements in the universe

- Incorporate for the first time a complete description of fission in astrophysical simulations
  - Spontaneous, induced, beta-delayed fission rates
  - Fission fragment distributions
- Astrophysics goals
  - Develop a new nucleosynthesis code that can incorporate input data on fission decay
  - Determine sensitivity of simulations on nuclear data inputs
- Nuclear physics goals
  - Establish a theoretical database of nuclear properties relevant for astrophysics
  - Improve models of beta-decay and fission

Average number of neutrons emitted in β-decay



Predictions of spontaneous fission fragment distributions for ^{240}Pu with uncertainties



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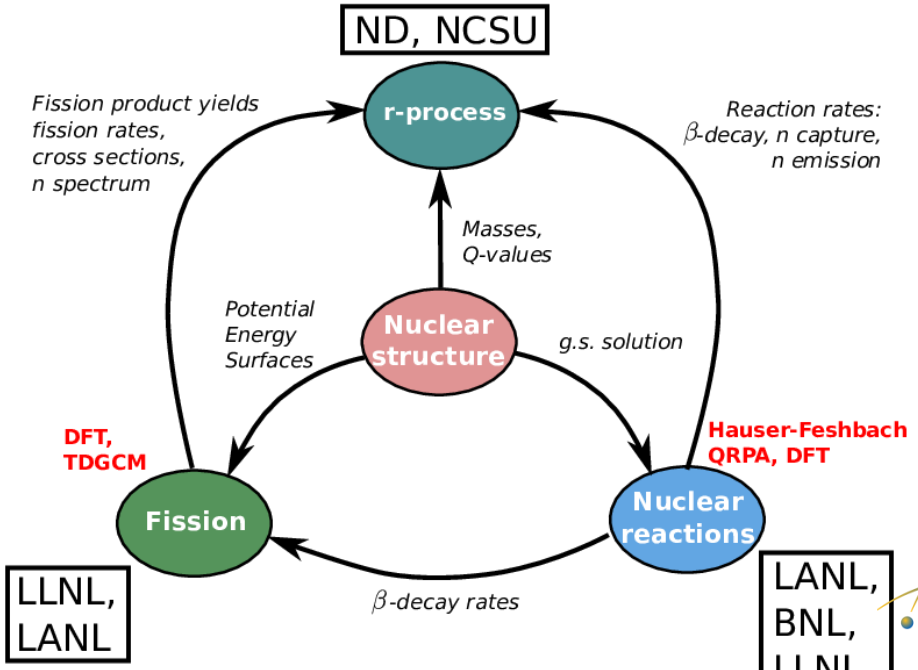
FIRE brings experts in fission theory, nuclear data and nuclear astrophysics



- Project team:
  - LLNL: N.Schunck (PI), R. Vogt
  - LANL: T. Kawano, P. Talou, A. Hayes-Sterbenz
  - BNL: A. Sonzogni, L. McCutchan
  - Notre Dame: R. Surman
  - North Carolina State: G. McLaughlin
- Additional participants
  - 1 postdoc at LANL
  - 1 postdoc at Notre Dame
  - 1 graduate student at NCSU
  - 1 summer student at LLNL

Total Budget: $500k/year

- NA221: LANL ($160k), BNL ($40k), LLNL ($100k) directly funded
- DOE: Notre Dame ($109k) and NCSU ($70k) subcontracted by LLNL

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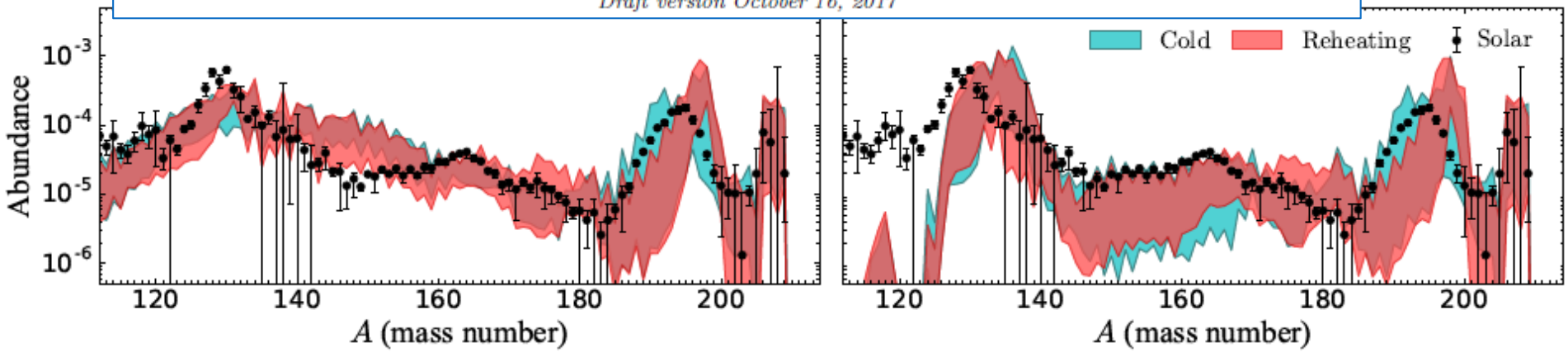
FIRE collaboration participates to analysis of LIGO-VIRGO recent observation of neutron star mergers

- First direct experimental evidence that heavy elements (Au, Pt, Pb, etc.) are produced in neutron star mergers
- Experimental constraints on astrophysical models will reduce uncertainties of computed abundances
- FIRE team (Vassh, Surman, Mumpower, Sprouse) key participants

THE ORIGIN OF R-PROCESS ELEMENTS IN THE MILKY WAY

Benoit Côté[1,7,8], Chris L. Fryer[2,7,8], Krzysztof Belczynski[3], Oleg Korobkin[2,7], Martyna Chruślińska[4], Nicole Vassh[5], Matthew R. Mumpower[2,6,7], Jonas Lippuner[2,7], Trevor M. Sprouse[5], Rebecca Surman[5,7], Ryan Wollaeger[2]

Draft version October 16, 2017



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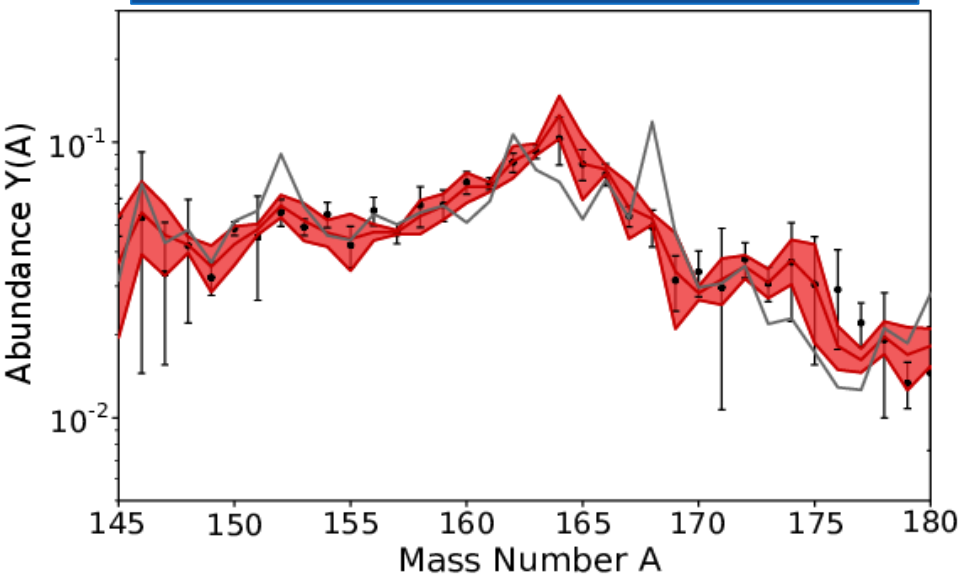
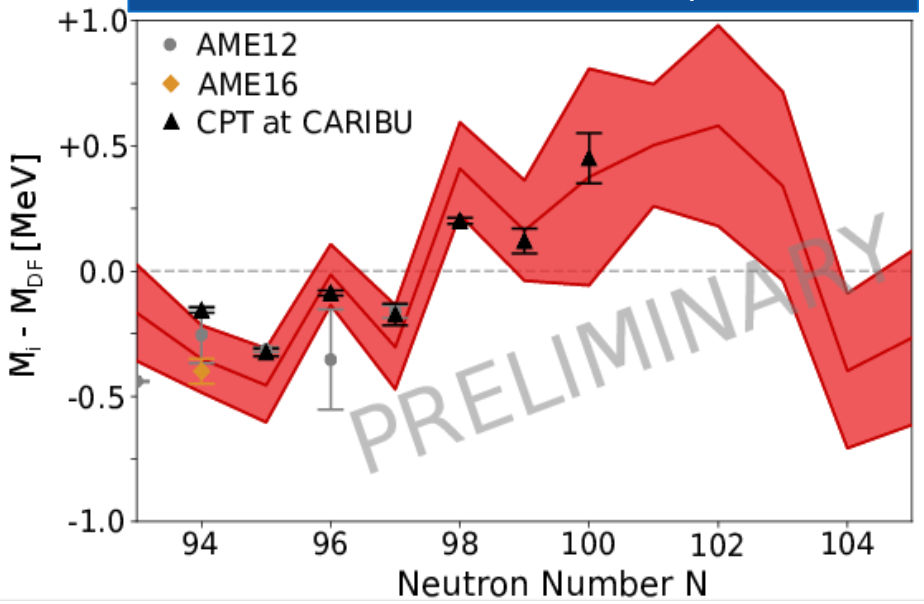
Astrophysical simulations could help make better mass evaluations far from stability (Vashh)

- Reverse engineering of nuclear masses:
  - Start from known mass model
  - Add perturbation controlled by few parameters
  - Sample parameters to reproduce r-process abundances

Abundances of elements near the rare-earth peak obtained with the Duflo-Zuker mass formula (in grey) and for the reversed-engineered masses (red band).



Deviations between reverse-engineered masses and Duflo-Zuker mass formula, with AME (2012 and 20016) and CARIBU measurements for Nd (Z=60) isotopes



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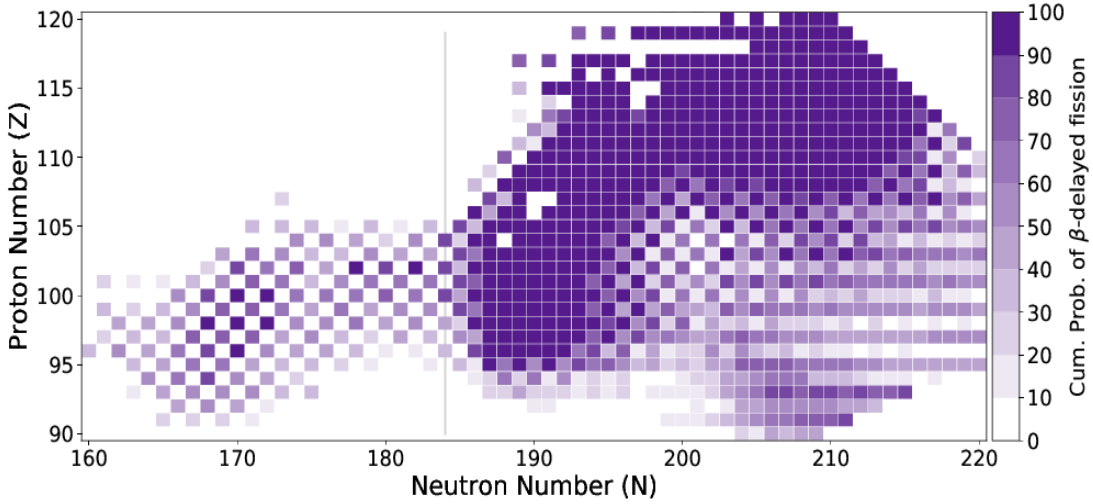
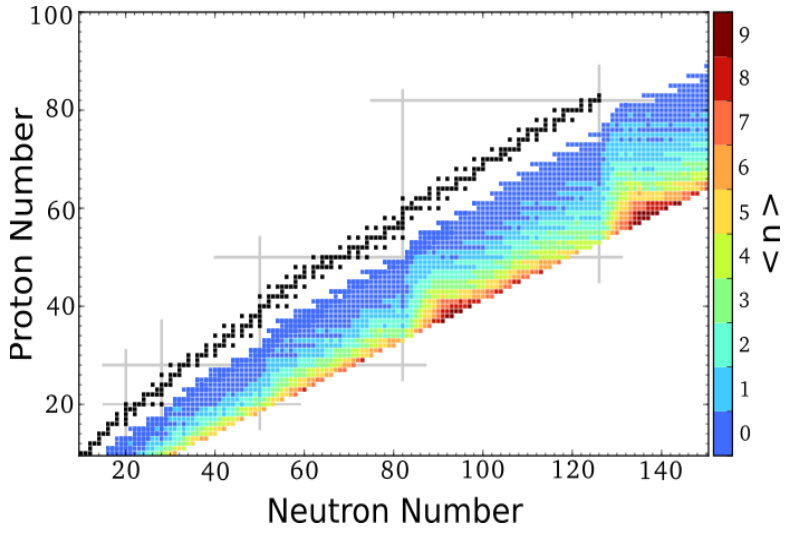
First attempts to simulate all fission channels of neutron-rich nuclei yield surprises (Mumpower)

- Combine estimates of β-decay rates in semi-microscopic model (macro-micro + QRPA with phenomenological interation) with LANL model for induced fission
- Large probability of β-delayed fission in r-process region: one of the driving mechanisms?

Fission probability of heavy, neutron-rich elements after being formed by β-decay (β-delayed fission



Realistic calculation based on QRPA+Hauser-Feshbach formalism of the average number of neutrons emitted after β-decay for all elements in the nuclear chart.



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Metrics

Publications and Invited Talks

- Publications (Cumulative)
  - M.R. Mumpower, T. Kawano, J.L. Ullmann, M. Krtička, and T. M. Sprouse, "Estimation of M1 scissors mode strength for deformed nuclei in the medium- to heavy-mass region by statistical Hauser-Feshbach model calculations," Phys. Rev. C **96**, 024612 (2017)
  - X. B. Wang and A. C. Hayes, "Weak magnetism correction to allowed β-decay for reactor antineutrino spectra", Phys. Rev. C **95**, 064313 (2017)
  - M. Mumpower, T. Kawano, P. Möller, "Neutron-gamma competition for β-delayed neutron emission", Phys. Rev. C **94**, 064317 (2016)
- Talks (Cumulative)
  - P. Jaffke, "Quantifying the Impact of Theoretical Fission Yields on Prompt Particle Observables", FIESTA Workshop, Santa Fe, September 2017
  - M. Mumpower, "Application of LANL Fission models to the Astrophysical R-Process", FIESTA Workshop, Santa Fe, September 2017
  - R. Surman, "Quantifying nuclear physics uncertainties in r-process abundance patterns", invited talk, 16th International Symposium on Capture Gamma-Ray Spectroscopy and Related Topics (CGS16), Shanghai, China, September 2017
  - R. Surman, "Astrophysics and FRIB", invited review talk, FRIB Day 1 Science at the 2017 Low Energy Community Meeting, Argonne National Laboratory, August 2017
  - R. Surman, "Nuclear physics inputs for nucleosynthesis", invited review talk, INT-17-2b Electromagnetic Signatures of r-Process Nucleosynthesis in Neutron Star Binary Mergers, Institute of Nuclear Theory, Seattle, WA, July 2017
  - G. C. McLaughlin, "Neutrino flavor transformation in compact object mergers and reverse engineering the rare earth peak", INT, Seattle, August 2017
  - R. Surman, "Nuclear physics inputs for nucleosynthesis", review talk, INT-17-2b Electromagnetic Signatures of r-Process Nucleosynthesis in Neutron Star Binary Mergers, Institute of Nuclear Theory, Seattle, WA, July 2017
  - P. Jaffke, "Implementing and testing theoretical fission fragment yields in a Hauser-Feshbach statistical decay framework", Scientific Workshop on Nuclear Fission Dynamics and the Emission of Prompt Neutrons and Gama Rays, Varna, Bulgaria, June 2017
  - R. Surman, "Nuclear masses and the site of r-process nucleosynthesis", invited talk, Nuclear Physics in Astrophysics VIII, Catania, Sicily, June 2017
  - G. C. McLaughlin, "Theory Initiatives", NSAC Meeting, June 2017
  - R. Surman, "Astrophysical Alchemy", colloquium, Ball State University, Muncie, IN, April 2017
  - R. Surman, "Astrophysical alchemy", colloquium, Department of Physics, University of Washington in St. Louis, St. Louis, MO, March 2017
  - R. Surman, "Neutron capture rates and r-process nucleosynthesis", workshop talk, INT Program INT-17-1a: Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart, Seattle, WA, March 2017
  - G. C. McLaughlin, "Stellar Explosions and Nucleosynthesis", Colloquium, University of Tennessee, Knoxville, TN, February 2017
  - G. C. McLaughlin, "Stellar Explosions and Nucleosynthesis", Colloquium, Kent State, Kent, OH, February 2017
  - R. Surman, "Nucleosynthesis and neutrino physics in compact object mergers", invited talk, APS April Meeting, Washington, D.C, January 2017

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Plans for FY18

- Cross-validate nuclear data models on very neutron-rich heavy element (^{280}Pu)
  - Fully microscopic approaches based on density functional theory for spontaneous and induced fission, and β-decay
  - Semi-microscopic models with macroscopic-microscopic approach to g.s. properties, residual interaction for β-decay
- Use validation to establish possible systematics (faster calculations)
- Use recent observations of neutron star merger to better constrain r-process scenario
- Evaluate sensitivity of r-process simulations to various nuclear data

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