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Fission In R-process Elements - FY2020

N. Schunck

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DOE Annual Report: Fiscal Year 2020

Project: Fission in R-processes Elements (FIRE)

Project Number: LL16-V-FIRE-PD3Za

Principal Investigator: Nicolas Schunck, LLNL, 925-422-1621
HQ Project Manager: George Fai (DOE), Donald Hornback (NA22)
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Project Summary

The goal of the FIRE topical collaboration in nuclear theory is to determine the astrophysical conditions of the rapid neutron capture process (r-process), which is responsible for the formation of heavy elements. This will be achieved by including in r-process simulations the most advanced models of fission (spontaneous, neutron-induced, β-delayed) that have been developed at LLNL and LANL. The collaboration is composed of LLNL (lead) and LANL for work on nuclear data (ground-state properties, fission, β-decay), BNL for nuclear data management, and the university of Notre Dame and North Carolina State University for r-process simulations. Under DOE/NNSA agreement, both universities receive funds from the DOE Office of Science, while national laboratories receive funds directly from NA221.

Project Achievements: FY2020

Microscopic Approaches to Nuclear data (LLNL)

B-decay rates – Graduate student Evan Ney, from UNC Chapel Hill (PhD supervisor: Prof. Jon Engel), worked with FIRE PI Nicolas Schunck on developing and applying an automated workflow of β-decay calculations for the entire chart of nuclides within a microscopic approach based on nuclear density functional theory (DFT). Such calculations are a three-step process, as shown in Figure 1 –: (i) first use nuclear DFT to determine the ground-state properties of the nucleus of interest; (ii) use the DFT solution to solve the quasiparticle random phase approximation (QRPA) equation with the finite-amplitude method and extract strength functions for the operators of interest (iii) calculate the β-decay rate from the strength functions. The computational framework is built upon the HFBTHO DFT solver developed at LLNL and the pnFAM solver for charge-exchange linear response theory developed at UNC Chapel Hill. Preliminary studies done within a UNC/Notre-Dame/NCSU collaboration in 2014-2017 demonstrated the potential of this approach for even-even nuclei. For the past 2 years, Evan considerably extended these calculations by including all odd and odd nuclei and developing additional diagnostic tools to estimate uncertainties. Among the new development this year are (i) the automatically calculation of different blocking configurations for odd and odd-odd nuclei to properly identify the ground state of these nuclei (ii) the discovery that contour integrations of the FAM sometimes fail for poles lying close to zero, and the development of correction techniques to mitigate these failures (iii) the quantification of theoretical uncertainties of the calculation with a Monte Carlo analysis of the theoretical error. Figure 2 shows the scale of the calculations, which include all nuclei from the valley of stability up to the neutron dripline. The results, with their uncertainty, are shown in Figure 3 – Ratio r . Quantitatively, the quality of the results is comparable with the calculations by Möller et al.: T_{comp}/T_{exp} ~5.3 versus T_{comp}/T_{exp} ~4.8 (Möller). This work was submitted to publication in Phys. Rev. C and is under review at the time of writing.

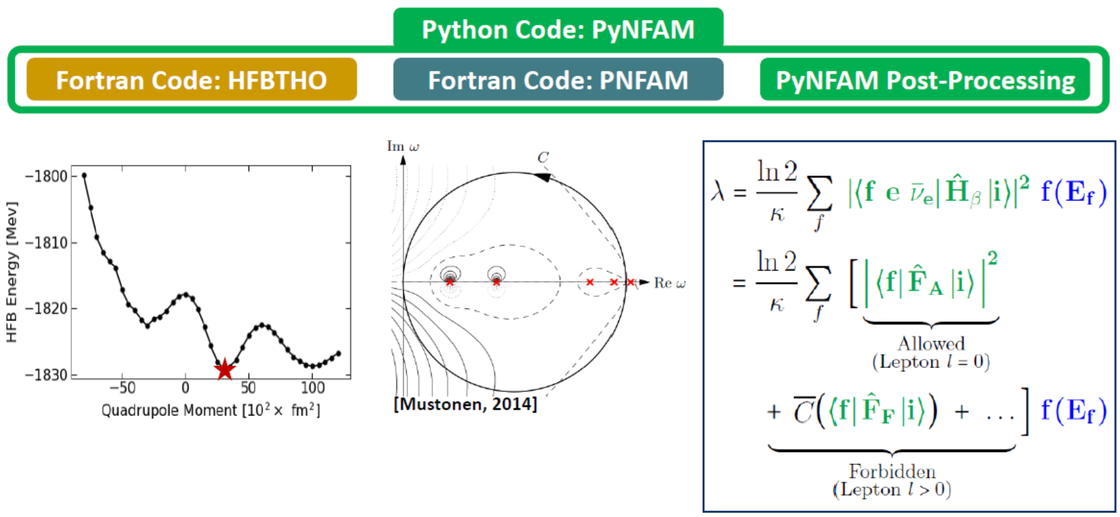

Figure 1 – Automated workflow to generate β-decay rates from self-consistent DFT calculations (QRPA theory). The HFBTHO program solves the HFB equation that provides the basis to solve the QRPA equation with the PNFAM code. A Python wrapper extracts the rates from the strength functions.

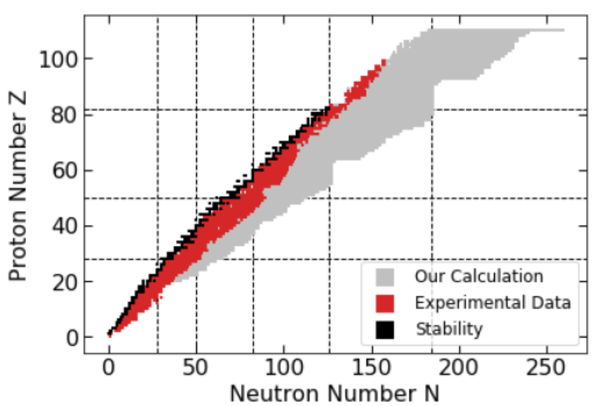

Figure 2 – Position of the nuclei, even-even, odd-even and even-odd, and odd-odd, for which the β-decay rate was computed

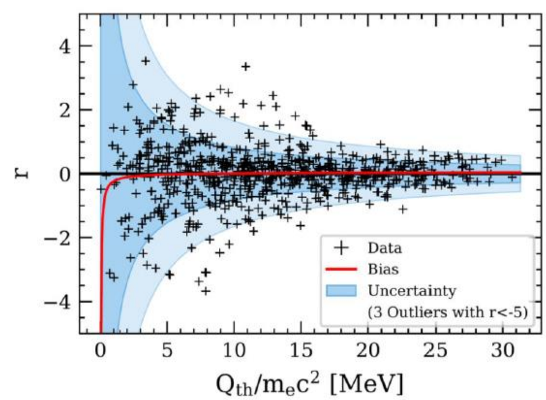

Figure 3 – Ratio r between the theoretical and experimental β-decay rate. The red line is a Bayesian estimate of the bias of the calculation, while the blue shaded bands represent the uncertainty of this bias estimate.

Nuclear Data and Applications (LANL, LLNL, BNL)

Complete Table of Fission Product Yields – The LANL team, led by M. Mumpower and Marc Verrière employed the Finite-Range Liquid-Drop Model (FRLDM) to perform the first systematic calculation of fission fragment yields across the entire chart of nuclides, see Figure 4 for elements heavier than Mercury. The yield of each fissioning system is calculated using a discrete random walk, under the assumption of strong dissipation, across static potential energy surfaces calculated within the macroscopic-microscopic method. This procedure produces over 3800 fission yields at excitation energies suitable for possible applications of neutron-induced and β-delayed fission.

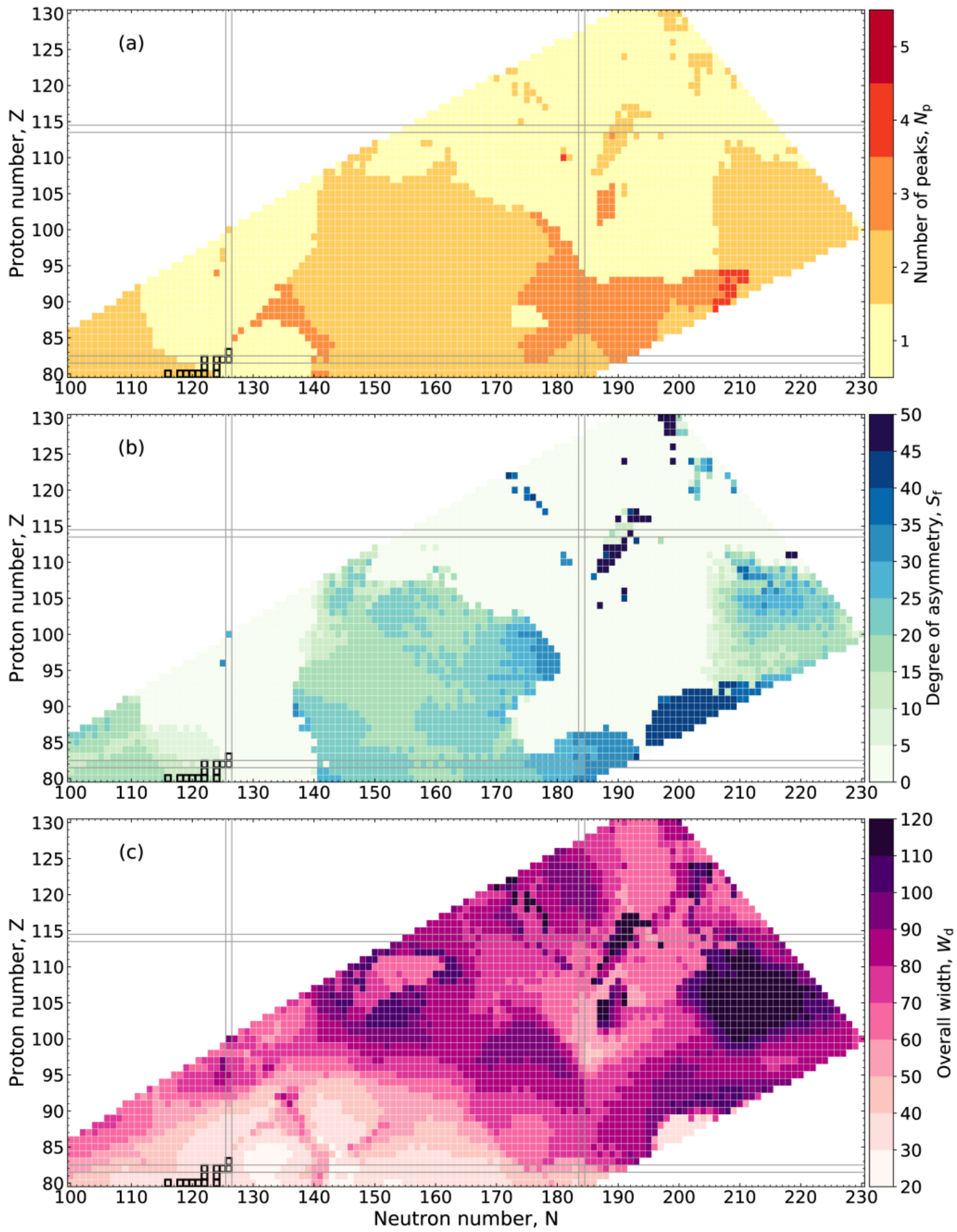

Figure 4 - The (a) number of peaks (b) asymmetry factor and (c) distribution width for the primary fragment mass yields Y(A), for the heavy fissioning system with Z protons and N neutrons. For reference, the black bounding squares indicate extremely long-lived and stable nuclei up to Z= 83 and closed shells are shown by solid parallel lines.

This first-ever systematic calculation of fission product yields by explicit, time-dependent simulation of fission dynamics reveals several regions of asymmetric and symmetric fission, regions where both modes co-exist, and even several exotic cases where two different asymmetric modes are present, leading to fragment distributions with up to four peaks in the mass yield. The width of the fission yields shows a propensity to expand with increasing neutron-excess of the fissioning system. For these super-heavy systems, the difference between splitting symmetrically versus asymmetrically is not as crucial as the spread of fragments across a large mass region in the NZ-plane. Such yields will naturally spread material in a fission recycling r-process and thus produce a wider range of elements in neutron-rich ejecta than modern simulations currently exhibit. This work was published in Phys. Rev. C and the data made available to the nuclear science community at www.matthewmumpower.com/data/table/frldm-fragment-yields-2020.

Astrophysical Simulations (ND, NCSU, LANL, LLNL)

R-process simulation workflow – Fission cycling as an explanation for the so-called universality, or robustness, of abundance patterns seen in metal-poor stars as compared to our Sun remains an intriguing prospect. A collaborative effort led by N. Vassh (Notre Dame) and involving T. Sprouse, R. Surman (Notre Dame), G. McLaughlin (NCSU) and M. Mumpower (LANL) applied for the first time the fission yields determined across the chart of nuclides from the macroscopic-microscopic theory of the Finite Range Liquid Drop Model (FRLDM) to simulations of rapid neutron capture (r-process) nucleosynthesis; see Figure 5.

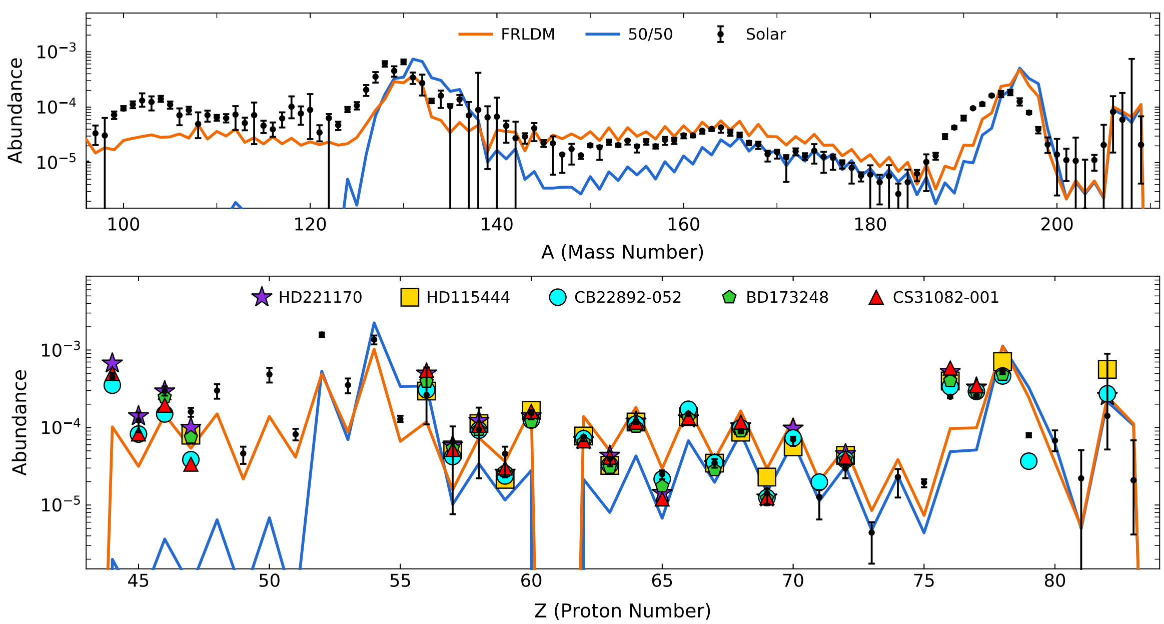

Figure 5 - Top panel: theoretical r-process mass abundances for A>100 computed with the new FRLDM fission product yields (orange curve), compared with schematic 50-50 split scenario where all nuclei fission by producing only 2 fragments of identical mass A/2 (blue curve) and observations in the solar system (black squares). Bottom panel: charge abundances compared with observations in the solar system (black squares) and in a few metal-poor stars (colored symbols).

With the fission rates and yields derived within the same theoretical framework utilized for other relevant nuclear data, there results are the most self-consistent r-process calculations to date. The team demonstrated that the FRLDM fission yields deposit a wide range of product nuclei from the light precious metal region leading into the lanthanides. This wide range of deposition is key to stabilizing r-process pattern against fluctuations in the specifics of the astrophysical scenario, such as the exact ratio of wind to dynamical ejecta. These findings demonstrate the value of theoretical efforts to understand the fission properties of neutron-rich nuclei. The large width of the fission product yields predicted by the FRLDM need to be further validated, either by comparing with other theoretical models such as, e.g., based on density functional theory, or by direct experimental measurements when possible. This work was published in the Astrophysical Journal.

Kilonova light curves – Graduate student Yonglin Zhu at North Carolina State has been studying the importance of fission as a source of heat that drives kilonova light curves. The kilonova light curve is the electromagnetic signal from the merger of two neutron stars and is thought to be powered by the radioactive decay of r-process elements. Yonglin has been investigating the fraction of heating that comes from various decay channels (see Figure 6 below). In particular, since much of the nuclear input entering calculations of the r-process is as yet unmeasured, he has been looking at the spread of possibilities that comes from considering various models of nuclear masses, fission rates, and fission daughter product distributions. At times less than one day after the merger, the effective heating rate due to β-decay contributes on average (=across models) more than half of the heating. However, the relative contribution of β-decay falls off, and a combination of spontaneous fission and α-decay takes over on a timescale of days. At around 100 days, spontaneous fission dominates the heating for almost all nuclear inputs.

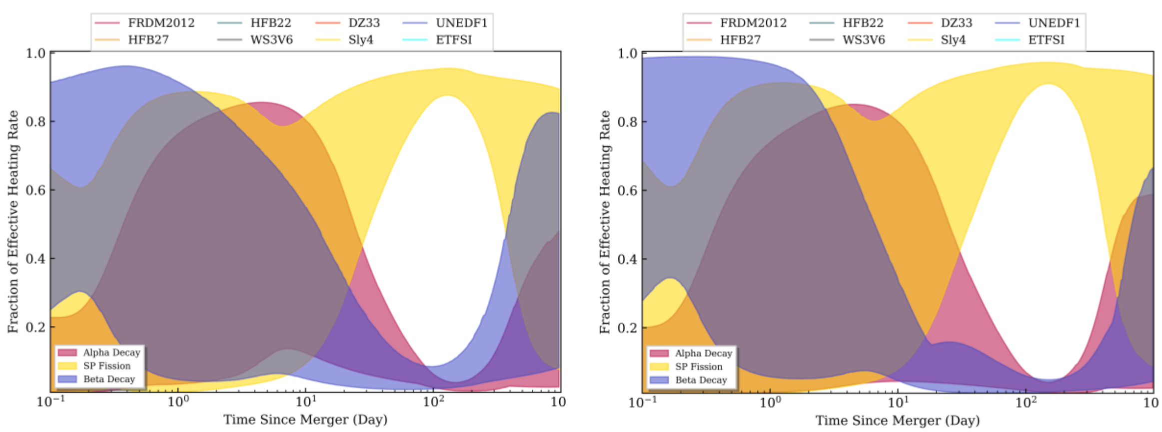

Figure 6 - Fraction of effective heating rate (erg/s) vs time since the merger in days. In both figures, the shaded color regions show the spread of the fraction of effective heating rates from different reaction channels. The figures were generated with data from 8 calculations each using a different mass model. All the nucleosynthesis calculations use the same astrophysical trajectory with initial electron fraction Ye = 0.16. Wherever experimental fission data is not available, we have used symmetric fission yields (left panel) and Kodoma fission yields (right panel). Both panels use theoretical fission rates from Karpov et al 2012, where experimental rates are not available. The effective heating rates were calculated with analytical thermalization efficiencies as in Figure 9 from Barnes et al 2016.

Metrics

Publications (submitted)

1. Erika M. Holmbeck, Rebecca Surman, Anna Frebel, G. C. McLaughlin, Matthew R. Mumpower, Trevor M. Sprouse, Toshihiko Kawano, Nicole Vassh, Timothy C. Beers, *"Characterizing r-Process Sites through Actinide Production"*, Submitted to ApJ (2020) [arXiv:2001.08792]
2. B. Côté, M. Eichler, A. Yagüe, N. Vassh, M.R. Mumpower, B. Világos, B. Soós, A. Arcones, T.M. Sprouse, R. Surman, M. Pignatari, B. Wehmeyer, T. Rauscher, and M. Lugaro, *"Constraining the Rapid Neutron-Capture Process with Meteoritic I-129 and Cm-247"*, Submitted to Science (2020), [arXiv:2006.04833]

3. N. Vassh, G.C. McLaughlin, M.R. Mumpower, and R. Surman, *"Markov Chain Monte Carlo Predictions of Neutron-rich Lanthanide Properties as a Probe of r-process Dynamics",* Submitted to ApJ (2020) [arXiv:2006.04322]
4. E. M. Ney, J. Engel, and N. Schunck, "Global Description of Beta Decay with the Axially-Deformed Skyrme Finite Amplitude Method: Extension to Odd-Mass and Odd-Odd Nuclei", Submitted to Phys. Rev. C (2020) [arXiv:2005.12883]

Publications (cumulative list)

1. M. R. Mumpower, P. Jaffke, M. Verriere, J. Randrup, "*Primary fission fragment mass yields across the chart of nuclides*", Phys. Rev. C **101**, 054607 (2020)
2. X. Wang, B.D. Fields, M.R. Mumpower, T.M. Sprouse, R. Surman, and N. Vassh, "*Sandblasting the r-process: Spallation of Ejecta from Neutron Star Mergers",* ApJ **893,** 92, (2020)
3. M. Verriere and D. Regnier, "*The Time-Dependent Generator Coordinate Method in Nuclear Physics",* Front. Phys. **8**, 233 (2020)
4. T. M. Sprouse, R. Navarro Perez, R. Surman, M. R. Mumpower, G. C. McLaughlin, N. Schunck, "*Propagation of Statistical Uncertainties of Skyrme Mass Models to Simulations of r-Process Nucleosynthesis*", Phys. Rev. C **101**, 055803 (2020)
5. N. Vassh, M.R. Mumpower, G.C. McLaughlin , T.M. Sprouse, and R. Surman, "*Coproduction of Light and Heavy r-process Elements via Fission Deposition",* ApJ **896,** 28, (2020)
6. Marc Verriere, Nicolas Schunck, Toshihiko Kawano, "*Number of Particles in Fission Fragments*", Phys. Rev. C **100**, 024612 (2019)
7. Erika M. Holmbeck, Anna Frebel, G. C. McLaughlin, Matthew R. Mumpower, Trevor M. Sprouse and Rebecca Surman, *Actinide-rich and Actinide-poor r-process-enhanced Metal-poor Stars Do Not Require Separate r-process Progenitors*, ApJ **881**, 5 (2019)
8. Nicole Vassh, Ramona Vogt, Rebecca Surman, Jorgen Randrup, Trevor Sprouse, Matthew Mumpower, Patrick Jaffke, David Shaw, Erika Holmbeck, Yonglin Zhu, Gail McLaughlin, "*Using excitation-energy dependent fission yields to identify key fissioning nuclei in r-process nucleosynthesis*", J. Phys. G: Nucl. Part. Phys. **46**, 065202 (2019)
9. Erika M. Holmbeck, Trevor M. Sprouse, Matthew R. Mumpower, Nicole Vassh, Rebecca Surman, Timothy C. Beers and Toshihiko Kawano, "*Actinide Production in the Neutron-rich Ejecta of a Neutron Star Merger*", ApJ **870**, 23 (2019)
10. A.A. Sonzogni, M. Nino, E.A. McCutchan, "*Revealing fine structure in the antineutrino spectra from a nuclear reactor*", Phys. Rev. C **98**, 014323 (2018)
11. Y. Zhu, R.T. Wollaeger, N. Vassh, R. Surman, T.M. Sprouse, M.R. Mumpower, P. Moeller, G.C. McLaughlin, O. Korobkin, T. Kawano, P.J. Jaffke, E.M. Holmbeck, C.L. Fryer, W.P. Even, A.J. Couture, J.Barnes, "*Californium-254 and Kilonova Light Curves*" ApJL **23**, 863 (2018)
12. M. R. Mumpower, T. Kawano, T. M. Sprouse, N. Vassh, E. M. Holmbeck, R. Surman, and P. Möller, "*β-delayed Fission in r-process Nucleosynthesis*", ApJ **869**, 14 (2018)
13. Shin Okumura and Toshihiko Kawano and Patrick Jaffke and Patrick Talou and Satoshi Chiba, "*235U(n,f) Independent Fission Product Yield and Isomeric Ratio Calculated with the Statistical Hauser-Feshbach Theory*", J Nucl. Sci. Technol. **55**, 1009 (2018)
14. Benoit Côté, Chris L. Fryer, Krzysztof Belczynski, Oleg Korobkin, Martyna Chruślińska, Nicole Vassh, Matthew R. Mumpower, Jonas Lippuner, Trevor M. Sprouse, Rebecca Surman, and Ryan Wollaeger, "*The Origin of r-process Elements in the Milky Way*", ApJ **855**, 99 (2018)

15. R. Orford, N. Vassh, J. A. Clark, G. C. McLaughlin, M. R. Mumpower, G. Savard, R. Surman, A. Aprahamian, F. Buchinger, M. T. Burkey, D. A. Gorelov, T. Y. Hirsh, J. W. Klimes, G. E. Morgan, A. Nystrom, and K. S. Sharma, "*Precision Mass Measurements of Neutron-Rich Neodymium and Samarium Isotopes and Their Role in Understanding Rare-Earth Peak Formation*" Phys. Rev. Lett. **120**, 262702 (2018)
16. A.C. Hayes, Gerard Jungman, E.A. McCutchan, A.A. Sonzogni, G.T. Garvey, X.B. Wang, "*Analysis of the Daya Bay Reactor Antineutrino Flux Changes with Fuel Burnup*" Phys. Rev. Lett. **120**, 022503 (2018)
17. X. B. Wang and A. C. Hayes, *"Weak magnetism correction to allowed β-decay for reactor antineutrino spectra*", Phys. Rev. C **95**, 064313 (2017)
18. M. R. Mumpower, T. Kawano, J. L. Ullmann, M. Krtička, 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)
19. A.A. Sonzogni, E.A. McCutchan, T.D. Johnson, P. Dimitriou, "*Effects of Fission Yield Data in the Calculation of Antineutrino Spectra for 235U (n, fission) at Thermal and Fast Neutron Energies*", Phys. Rev. Lett. **116**, 132502 (2016)
20. M. Mumpower, T. Kawano, P. Möller, "*Neutron-gamma competition for β-delayed neutron emission*", Phys. Rev. C **94**, 064317 (2016)

Talks

1. N. Vassh, "*Exposing the astrophysical conditions of r-process events through observable signatures of lanthanide and actinide production"*, Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS) Collaboration Online Seminar, Jun. 2, 2020
2. N. Vassh, "*Impact of examining neutron-rich lanthanides and pushing the bounds into neutron-rich actinides on r-process nucleosynthesis calculations"*, FRIB First Experiments: Proposal Preparation Workshop, JINA-CEE organized event, May 5, 2020
3. N. Vassh, "*The impact of fissioning nuclei on r-process nucleosynthesis observables"*, APS Virtual April Meeting 2020, L04 Invited Session: Sensitive Reaction Studies for Nuclear Astrophysics, Apr. 19, 2020
4. N. Schunck, "*The FIRE (Fission In R-process Elements) Topical Collaboration*", DOE/NSF Nuclear Science Advisory Committee Meeting, Washington DC, Mar. 2, 2020
5. N. Vassh, "*Examining lanthanide production in merger accretion disk winds: nuclear masses and the rare-earth peak"*, Argonne National Laboratory, Physics Division Seminar, Feb. 24, 2020
6. R. Vogt, "*Modeling fission events in the lab and the universe"*, Physics Department Colloquium, San Diego State University, Jan. 4, 2020
7. N. Vassh, "*r-process nucleosynthesis studies meet the next generation of observation and experiment*", Michigan State University, FRIB Theory Seminar, Dec. 2, 2019
8. M. Mumpower, "*FRLDM fission yields for r-process nucleosynthesis*", Workshop on Nuclear Astrophysics, Beihang University, China, Nov. 28, 2019
9. Rebecca Surman, "*r process: synthesizing observations, simulation, and nuclear physics"*, RPA workshop, MIT, Nov. 21, 2019
10. Rebecca Surman, "*Nuclear structure of exotic nuclei and astrophysical nucleosynthesis*", Gogny 2019, LLNL, Nov. 12, 2019
11. N. Vassh, "*Potential signatures of fission in the r-process*", Washington University, Nuclear Theory Seminar, Nov. 8, 2019

12. M. Mumpower, "*Fission across the chart of nuclides and implications for the r-process*", Workshop on Nuclear Fission Dynamics, Kyoto University, Oct. 28, 2019
13. Rebecca Surman, "*Neutron star mergers and the origins of the heaviest elements"*, colloquium, Penn State University, Oct. 24, 2019
14. Rebecca Surman, "*Forging the heaviest elements"*, colloquium, Illinois State University, Oct. 22, 2019
15. N. Vassh, "*Macroscopic-Microscopic fission yields for nucleosynthesis"*, APS DNP 2019 Fall Meeting, Oct. 16, 2019
16. N. Vassh*, "Examining lanthanide production in merger accretion disk winds: nuclear masses and the rare-earth peak"*, APS DNP 2019 Fall Meeting, Oct. 16, 2019
17. R. Vogt, "*Employing FREYA as a tool for fission product yield evaluations*", Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
18. T. Sprouse, "*Following fission products in explosive astrophysical environments*", Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
19. R. Surman, "*Fission and the origins of the heaviest element*", Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
20. N. Vassh, "*Fission and lanthanide production in r-process nucleosynthesis"*, Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
21. R. Vogt, *Fission Modeling for Correlated Observables*, Notre Dame nuclear physics seminar, 09/16/2019
22. N. Vassh*, "r-process nucleosynthesis in compact object mergers"*, Microphysics In Computational Relativistic Astrophysics (MICRA) Workshop, August 12-16, 2019
23. G. McLaughlin, "*Nuclear Physics of Neutron Star Mergers*", FRIB Low-Energy Community Meeting, August 8, 2019
24. R. Vogt, *Detailed Modeling of Fission and Some Implications for the Astrophysical r process*, Frankfurt Institute for Advanced Study colloquium, July 3, 2019
25. N. Vassh, "*Fission and lanthanide production in r-process nucleosynthesis"*, Institute for Nuclear Theory, S@INT Seminar, June 6, 2019
26. N. Vassh, *"Identifying the neutron-rich nuclei that most influence heavy element abundances: fission and the rare-earth peak*", JINA Frontiers Conference, May 22-24, 2019
27. N. Vassh, "*Fission and lanthanide production in r-process nucleosynthesis"*, SouthEast Laboratory Astrophysics Community (SELAC) Conference, May 13-16, 2019
28. N. Vassh*, "Fission and lanthanide production in r-process nucleosynthesis"*, R-process Sources in the Universe JINA-CEE conference, March 27-30, 2019
29. N. Vassh, *"Fission and lanthanide production in r-process nucleosynthesis"*, University of Maryland, Nuclear Physics Seminar, March 6, 2019
30. N. Vassh, *"Fission and lanthanide production in r-process nucleosynthesis"*, University of California - San Diego, Astrophysics Seminar, Feb. 6, 2019
31. G. McLaughlin, "*Neutrino and Nuclear Physics of the r-process*", Colloquium, APC Laboratory, Paris, France December 14, 2018
32. R. Surman, "*GW170817 and the origins of the heaviest elements*", Colloquium, Department of Physics, Rutgers University, November 7, 2018
33. N. Vassh, "*The formation of the rare-earth peak in neutron star mergers*", 5th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan, October 23-27, 2018

34. N. Vassh, "*Examining the origin of the r-process rare earth peak with Markov Chain Monte Carlo*", Uncertainty Quantification at the Extremes (ISNET-6), TU Darmstadt, October 8-12, 2018
35. G. McLaughlin, "*Neutrino and Nuclear Physics of the r-process*", Colloquium, College of William and Mary, Williamsburg, VA, October 2018
36. R. Surman, "*The microphysics of the GW170817 kilonova*", Colloquium, Department of Physics, University of Massachusetts Lowell, September 26, 2018
37. R. Surman, "*Nuclear physics and the r process*", To 2020 and Beyond: Radionuclide Astronomy, Los Alamos National Laboratory, August 20-22, 2018
38. M. Mumpower, "*Recent progress on Los Alamos nuclear structure, reaction and fission models*", Nuclear Structure 2018, MSU, August 2018
39. N. Schunck, "*Theories of Nuclear Fission*", FRIB and the GW170817 kilonova, MSU, July 16-27, 2018
40. M. Mumpower, "*Fission in the r-process*", Ariel Science Week, Triumf, Vancouver, July, 2018
41. G. McLaughlin, "*Neutron Star Mergers*", Workshop on Quantum Kinetic Equations, Santa Fe, NM, July 1-7, 2018
42. G. McLaughlin, "*Theoretical aspects of nuclear astrophysics*", National Nuclear Physics Summer School, June 17-30, 2018P. Jaffke, "*Correlations between the fission fragment yields and the prompt fission gamma-ray spectrum*", 15th International Conference on Nuclear Reaction Mechanisms, Varenna, June 11-15, 2018
43. N. Vassh, "*Studying lanthanide production in r-process nucleosynthesis*", Conference on the Intersections of Particle and Nuclear Physics (CIPANP) June 2018
44. N. Vassh, "*Reverse engineering properties of neutron-rich lanthanides by examining the r-process rare earth abundance peak*", INT-JINA Symposium: "First multi-messenger observations of a neutron star merger and its implications for nuclear physics" March 2018
45. N. Vassh, "*Fission and the Formation of the r-process Rare-Earth Abundance Peak in Neutron Star Mergers*", MSU FRIB Theory Seminar March 1, 2018 and UW-Madison NPAC Seminar May 2018
46. R. Surman, *"Understanding the r process through nuclear data*", 232nd Meeting of the American Astronomical Society, Denver, CO, June 3-7, 2018
47. R. Surman, "*The astrophysical origins of the heaviest elements*", Colloquia at Michigan State April 5, 2018 and LANL March 2018
48. N. Vassh, "Fission and the formation of the r-process rare-earth abundance peak in neutron star mergers", LBNL Nuclear Science Division Seminar, February 2018
49. N. Vassh, "*The r-process in neutron star mergers*", Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS) Collaboration Meeting, UC San Diego, CA, January 2018
50. R. Surman, "*r-process nucleosynthesis and radioactivity in merger ejecta*", KITP Program GW170817: The First Double Neutron Star Merger, 2017, Kavli Institute, Santa Barbara, CA, December 2017
51. N. Vashh, "*Recent results of reverse engineering nuclear masses from solar r-process abundances and the challenges faced in the presence of fissioning nuclei*", DNP Fall Meeting, Pittsburgh,
52. 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 20-22, 2017
53. R. Surman, "*Astrophysical Alchemy*", colloquium, Ball State University, Muncie, IN, April 2017

54. R. Surman, “*Nuclear masses and the site of r-process nucleosynthesis*”, invited talk, Nuclear Physics in Astrophysics VIII, Catania, Sicily, June 2017
55. 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
56. G. C. McLaughlin, “*Theory Initiatives*”, NSAC Meeting, June 2017

Posters

1. N. Vassh, “*Examining the astrophysical site of r-process nucleosynthesis by reverse engineering nuclear properties from rare earth abundances*”, ARIS 2017, Keystone CO, May 2017

Scientific Engagement

Several members of the FIRE collaboration attended the “*Workshop for Applied Nuclear Data Activities*” (WANDA) that took place in Washington DC, Mar. 3-5, 2020. The goal of the workshop was to provide inputs to stakeholders and program managers about nuclear data needs. Participants often mentioned the FIRE collaboration as a poster child of a successful inter-agency collaboration. FIRE members Patrick Talou and Ramona Vogt, together with Fredrik Tovesson, are co-editors of a forthcoming book on fission product yields. FIRE PI Nicolas Schunck is a contributing author of this book. Two summer schools initially scheduled for summer 2020, the TALENT course #4 “*Density Functional Theory and Self-Consistent Methods*” organized by N. Schunck at UC Berkeley, and the N3AS Summer School on “*Multi-Messenger Astrophysics*” co-organized by R. Surman at UC Santa Cruz, were postponed due to the Covid-19 Pandemic.

Outlook for FY2021

Looking into 2021, the FIRE collaboration has at its disposal a couple of new, unique tools (i) a new macroscopic-microscopic solver developed by LANL (M. Verriere), which implements particle number projection for a better estimate of charge distributions as well as a new random walk solver (ii) a new tracer capability developed jointly by ND and LANL (T. Sprouse, M. Mumpower), which allows to follow the evolution of a single isotope through the series of nuclear reactions taking place in the r process. These tools are fully interfaced in PRISM, the flagship network reaction code developed by the collaboration. In 2021, we will continue to refine our calculations of primary fission yields (T. Sprouse, M. Mumpower) and use statistical reaction codes (T. Kawano, R. Vogt) to simulate the full decay of the fragments, including the number of neutrons emitted and the β-delayed fission probabilities and distributions. These simulations will continually be updated and compared against experimental measurements by the LANL (M. Mumpower), ND (N. Vassh, R. Surman), and NCSU (K. Lund, G. McLaughlin) team.

Project Management

Administrative Summary

Under the call for proposal for topical collaborations, DOE requires an unincorporated consortium business model for the distribution of funds. The subcontract with ND was signed on 02/07/2017 and with NCSU on 03/13/2017. As of July 10, 2020, all FY20 funds from DOE had been received by LLNL. As a reminder, FIRE supports a postdoc at the University of Notre Dame, a postdoc at LANL, a graduate student at NCSU and a summer student at LLNL. The remainder of the money is used to support staff in each of the participating institutions. Current FIRE-supported people are **Nicole Vassh** (postdoc, ND) **Trevor Sprouse** (postdoc, LANL), **Kelsey Lund** (graduate student, NCSU). **Marc Verriere, formerly a FIRE postdoc at LANL, was hired as full research staff at LLNL in March 2020**. Because of the Covid-19 pandemic, the annual meeting of the collaboration occurred online on July 1st, 2020 and was attended by 15 persons.

Financial Summary

Subcontracts were established in February 2017 (University of Notre Dame) and March 2017 (North Carolina State University), leading to delays of 6 months (ND) and 8 months (NCSU) between the time when funds were available at LLNL and the time the first invoices came in. For the first 4 fiscal years of the project, the total budget for ND is $453,792, and $292,000 for NCSU.

	Paid Amount	**Funded Amount**	**Cumulative Funding**	**Last Invoice**	**Paid as % of Cum.Funding**	**People supported**
Notre Dame	295,000.00	395,000	453,792	06/26/2020	65.0%	Nicole Vassh (PD)
NCSU	170,172.94	256,000	292,000	06/22/2020	58.3%	Kelsey Lund (GS)
Total	465,172.94	651,000	716,000			

Subcontracts are funded on a regular basis as money becomes available. Current *Funded Amounts* of each subcontract are listed in the table below. The *Cumulative Funding* is the total funding expected over FY17, FY18, FY19 and FY20. As of July 10, 2020, LLNL has $55 000 available, in addition to existing liens, to continue funding both subcontracts until the end of FY20.

Performance Summary

The milestones for FY2019 and FY2020 listed in the original FIRE proposal are recalled below, together with a comment about their status

Milestone FY19	**Comment**
Examine the sensitivity of the r-process abundance pattern on uncertain fission rates and daughter product distributions for astrophysical models that predict fission recycling	*Done*; see Vassh et al., J. Phys. G: Nucl. Part. Phys. **46**, 065202 (2019); Holmbeck et al. ApJ **870**, 23 (2019); Zhu et al., ApJL **23**, 863 (2018). Collaborative work between ND, NCSU and LANL
Complete database of potential energy surfaces, fission product yields, and spontaneous and neutron-induced fission rates for all nuclei with Z > 82	*Done*; see Mumpower et al., Phys. Rev. C **101**, 054607 (2020) **Note**: see also M. Verriere et al., Phys. Rev. C **100**, 024612 (2019) for an improved method to compute charge distributions
Calculate nuclear reaction rates, neutron-induced fission and capture, and perform model parameter sensitivity study	*Done*; see Vassh et al., J. Phys. G: Nucl. Part. Phys. **46**, 065202 (2019)
Milestone FY20	
Implement new β-delayed fission rates and fission	*Done*; see N. Vassh et al., ApJ **896**, 28 (2020), X.

daughter product distributions developed during Years 1-3 and study their astrophysical impact.	Wang, et al., ApJ **893**, 92 (2020)
Benchmark the fully microscopic calculation of β-delayed fission rates obtained by combining DFT+TDGCM fission rates produced in Years 1-3 and DFT-pnFAM β-decay rates computed in Year 2	***In-progress***; calculations will be limited to a single fissioning nucleus
Initiate the calculation of potential energy surfaces with other energy functionals.	***Postponed***; not enough manpower to perform microscopic calculations in this project
Calculate β-delayed neutron emission by coupling the DFT results with the Hauser-Feshbach code	*Done*; see N. Vassh et al., ApJ **896**, 28 (2020), X. Wang, et al., ApJ **893**, 92 (2020)
Upgrade the β-delayed fission rate database	*Done*; see N. Vassh et al., ApJ **896**, 28 (2020), X. Wang, et al., ApJ **893**, 92 (2020)
Calculate neutron multiplicities	***In-progress***; this is done by coupling primary fission yields with the fission event generator FREYA