LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

LLNL-TR-793005

Fission In R-process Elements - FY19 Q4 Quarterly Report

N. Schunck

October 8, 2019

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Quarterly Progress Report Q2 FY19 Jul 2019-Oct 2019

Project: Fission in R-processes Elements

Project Number: Ll16-V-FIRE-PD3Za

Principal Investigator: Nicolas F. Schunck, LLNL, 925-422-1621

HQ Project Manager: Donald Hornback

Date submitted: 10 Oct 2019

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 fission work, 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 DOE Office of Science, while national laboratories receive funds directly from NA221.

Progress this quarter

Administrative

- As of Oct. 10, 2019, the carry-over into FY20 is $45k. Funds have been added to subcontracts with ND and NCSU to continue work in the project.
- Nearly all members of the FIRE collaboration attended and gave talks at the "International Workshop on Fission Product Yields" organized by LANL in Santa Fe, Sep. 30 – Oct. 4, 2019. The LANL existing pipeline for fission product yield evaluation is largely based on work performed within the FIRE collaboration.
- LANL postdoc Marc Verrière accepted a staff position at LLNL to work on fission theory, computational nuclear structure and nuclear data evaluations. After Matt Mumpower, who was hired at LANL in 2017, this is the second FIRE-supported postdoc hired by a national laboratory.

Science

- *ND-NCSU-LLNL-LANL*

  In a joint effort led by N. Vassh (Notre Dame) and involving R. Surman (Notre Dame), M. Mumpower and M. Verrière (LANL), R. Vogt (LLNL) and G. McLaughlin (NCSU), r-process network

calculations were performed with fission fragment yields calculated across the chart of nuclides from the macroscopic-microscopic theory of the Finite Range Liquid Drop Model (FRLDM). This is the first time that such nucleosynthesis simulations use FPY coming from the explicit simulation of fission (within a macroscopic-microscopic nuclear structure framework complemented by random walk dynamics) rather than semi-empirical fits to data. Being rooted in a genuine physics model of fission, these predictions should have significantly more predictive power than before. In addition, with the fission rates and yields derived within the same theoretical framework, the results are the most consistent r-process calculations to date. The model predicts very wide fission fragment distributions for extreme neutron excess. The team showed that these wide distributions of neutron-rich nuclei, particularly the asymmetric yields for key species which fission at late-times in the r-process, can contribute significantly to the abundances of the lighter heavy elements, specifically the light precious metals such as palladium and silver. Since such asymmetric yields also deposit into the lanthanide region, the team considered the possible evidence for co-production by comparing their nucleosynthesis results directly with the trends in the elemental ratios of metal-poor stars rich in r-process material. They found that silver over europium, and palladium over europium, display mostly flat trends suggestive of co-production and compare to the lanthanum over europium trend which is often used to justify robustness arguments in the lanthanide region, see figure 1. They also found that such robustness arguments may be extendable down to palladium and heavier and demonstrate that fission deposition is a mechanism by which such a universality or robustness can be achieved.

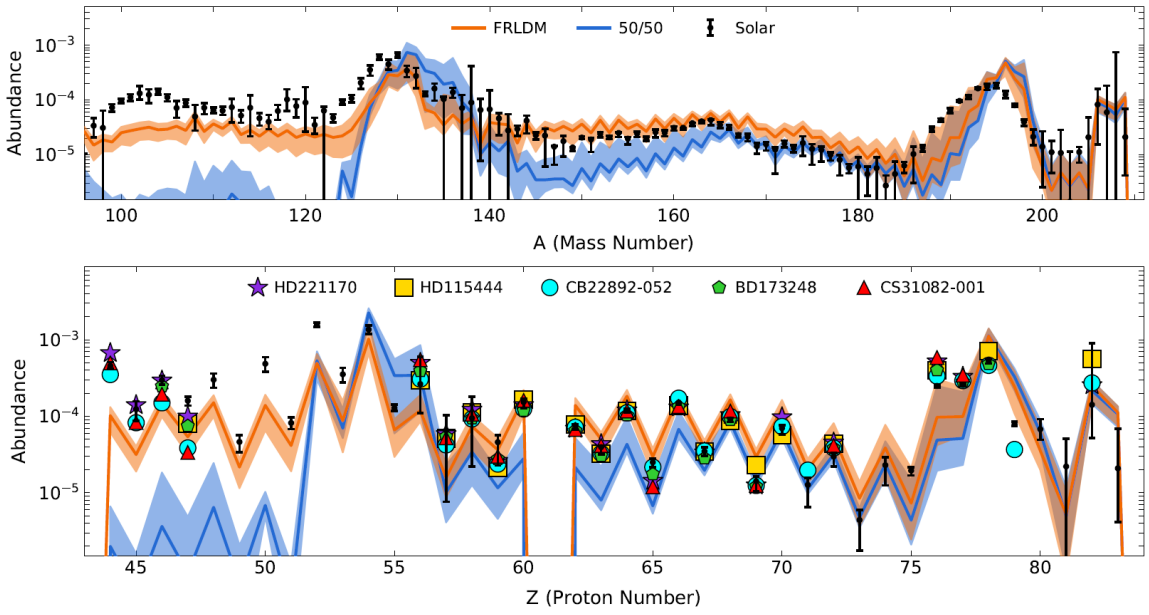

Figure 1 - *The range (bands) and mass weighted average (lines) of the r-process abundances for the dynamical ejecta simulation conditions of Rosswog et al. with input fission fragment distributions given 50/50 splits (blue) as compared to FRLDM predictions (orange). Solar abundances and uncertainties (Arnould et al. 2007) as well as the r-process rich stars considered in Sneden et al. are shown for comparison.*

- 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 2 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.

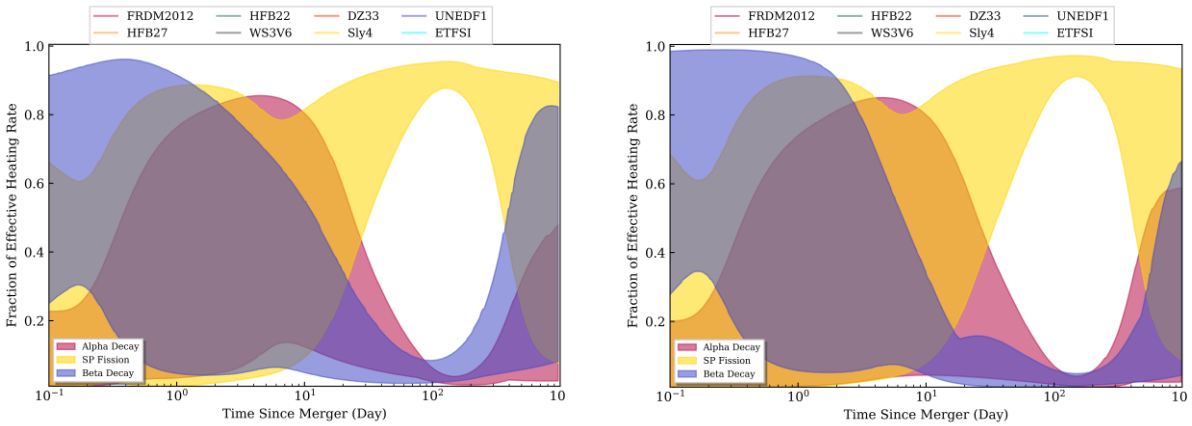

Figure 2 - *Fraction of effective heating rate (erg/s) vs time since the merger in days. In both figures, the shaded color regions show the spread of the fraction of effective heating rates from different reaction channels. The figures were generated with data from 8 calculations each using a different 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.*

Outlook

- The LLNL team is putting the finishing touches on a paper reporting the first systematic calculation of beta-decay rates across the entire mass table in a purely microscopic framework based on the charge-exchange QRPA theory. This work is performed by Evan Ney as part of this summer internships at LLNL and is a collaboration with UNC Chapel Hill and the NUCLEI SciDAC-4 project.
- A collaboration between LANL (T. Sprouse, M. Mumpower) and Notre Dame (R. Surman, N. Vassh) is finalizing work on a new capability to selectively follow the evolution of individual fission products during a full r-process network calculation. This will allow identifying isotopes of special interest in the process.
- In analogy with the existing LANL capability, LLNL has begun leveraging FIRE-related work to put together an integrated pipeline for fission product yield calculations. It is based on slightly

different physics models from the LANL codes: it relies on density functional theory (code: DFTNESS) and the time-dependent generator coordinate method (code: FELIX) for fission fragment distributions, a statistical Weisskopf-Ewing framework for particle evaporation (code: FREYA). As a result, it is aimed at providing cross-validation of theoretical predictions.

Cumulative List of Publications and Talks

Submitted

1. 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*", submitted to Phys. Rev. C (2019) [arXiv:1901.10337]
2. Xilu Wang, Brian D. Fields, Matthew Mumpower, Trevor Sprouse, Rebecca Surman, Nicole Vassh, *Sandblasting the r-Process: Spallation of Ejecta from Neutron Star Mergers*, submitted to ApJ [arXiv:1909.12889]

Publications (cumulative list)

1. Marc Verriere, Nicolas Schunck, Toshihiko Kawano, "*Number of Particles in Fission Fragments*", Phys. Rev. C **100**, 024612 (2019)
2. 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)
3. 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)
4. 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)
5. 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)
6. 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)
7. 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)
8. 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)
9. 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)
10. 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)

11. 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)
12. X. B. Wang and A. C. Hayes, *"Weak magnetism correction to allowed β-decay for reactor antineutrino spectra*", Phys. Rev. C **95**, 064313 (2017)
13. 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)
14. 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)
15. M. Mumpower, T. Kawano, P. Möller, "*Neutron-gamma competition for β-delayed neutron emission*", Phys. Rev. C **94**, 064317 (2016)

Talks

1. R. Vogt, "*Employing FREYA as a tool for fission product yield evaluations*", Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
2. T. Sprouse, "*Following fission products in explosive astrophysical environments*", Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
3. R. Surman, "*Fission and the origins of the heaviest element*", Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
4. N. Vassh, "*Fission and lanthanide production in r-process nucleosynthesis"*, Fission Product Yields (FPY) Workshop 2019, Sept. 30 - Oct. 3, 2019
5. N. Vassh*, "r-process nucleosynthesis in compact object merger"s*, Microphysics In Computational Relativistic Astrophysics (MICRA) Workshop, August 12-16, 2019
6. G. McLaughlin, "*Nuclear Physics of Neutron Star Mergers*", FRIB Low-Energy Community Meeting, August 8, 2019
7. N. Vassh, "*Fission and lanthanide production in r-process nucleosynthesis"*, Institute for Nuclear Theory, S@INT Seminar, June 6 06/06/2019
8. 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
9. N. Vassh, "*Fission and lanthanide production in r-process nucleosynthesis"*, SouthEast Laboratory Astrophysics Community (SELAC) Conference, May 13-16, 2019
10. N. Vassh*, "Fission and lanthanide production in r-process nucleosynthesis"*, R-process Sources in the Universe JINA-CEE conference, March 27-30, 2019
11. N. Vassh, *"Fission and lanthanide production in r-process nucleosynthesis"*, University of Maryland, Nuclear Physics Seminar, March 6, 2019
12. N. Vassh, *"Fission and lanthanide production in r-process nucleosynthesis"*, University of California - San Diego, Astrophysics Seminar, Feb. 6, 2019
13. G. McLaughlin, "*Neutrino and Nuclear Physics of the r-process*", Colloquium, APC Laboratory, Paris, France December 14, 2018
14. R. Surman, "*GW170817 and the origins of the heaviest elements*", Colloquium, Department of Physics, Rutgers University, November 7 2018

15. 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
16. 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
17. G. McLaughlin, "*Neutrino and Nuclear Physics of the r-process*", Colloquium, College of William and Mary, Williamsburg, VA, October 2018
18. R. Surman, "*The microphysics of the GW170817 kilonova*", Colloquium, Department of Physics, University of Massachusetts Lowell, September 26, 2018
19. R. Surman, "*Nuclear physics and the r process*", To 2020 and Beyond: Radionuclide Astronomy, Los Alamos National Laboratory, August 20-22, 2018
20. M. Mumpower, "*Recent progress on Los Alamos nuclear structure, reaction and fission models*", Nuclear Structure 2018, MSU, August 2018
21. N. Schunck, "*Theories of Nuclear Fission*", FRIB and the GW170817 kilonova, MSU, July 16-27, 2018
22. M. Mumpower, "*Fission in the r-process*", Ariel Science Week, Triumf, Vancouver, July, 2018
23. G. McLaughlin, "*Neutron Star Mergers*", Workshop on Quantum Kinetic Equations, Santa Fe, NM, July 1-7, 2018
24. 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
25. N. Vassh, "*Studying lanthanide production in r-process nucleosynthesis*", Conference on the Intersections of Particle and Nuclear Physics (CIPANP) June 2018
26. 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
27. 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
28. R. Surman, *"Understanding the r process through nuclear data*", 232nd Meeting of the American Astronomical Society, Denver, CO, June 3-7, 2018
29. R. Surman, "*The astrophysical origins of the heaviest elements*", Colloquia at Michigan State April 5, 2018 and LANL March 2018
30. 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
31. N. Vassh, "*The r-process in neutron star mergers*", Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS) Collaboration Meeting, UC San Diego, CA, January 2018
32. 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
33. 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,

34. 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
35. R. Surman, "*Astrophysical Alchemy*", colloquium, Ball State University, Muncie, IN, April 2017
36. R. Surman, "*Nuclear masses and the site of r-process nucleosynthesis*", invited talk, Nuclear Physics in Astrophysics VIII, Catania, Sicily, June 2017
37. 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
38. 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

Lab Program Manager Comments [optional]:

No comments from the Lab PM this quarter.