Progress Report

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Project Title: "Theoretical Description of the Fission Process"
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Project period: 10/01/2018-06/30/2021

1. Accomplishments

The main goals of the project, can be summarized as follows:

i. Development of effective energy functionals that are appropriate for the description of heavy nuclei. Our goal is to improve the existing energy density (Skyrme) functionals to develop a force that will be used in calculations of fission dynamics. To this end, we use specialty Hartree-Fock (HF) and Hartree-Fock-Bogoliubov (HFB) codes.
ii. Systematic self-consistent calculations of binding energies and fission barriers of actinide, pre-actinide, and trans-actinide nuclei using modern density functionals. This is followed by calculations of spontaneous fission lifetimes and mass and charge splits using dynamic adiabatic approaches.
iii. Develop advanced methods of uncertainty quantification such as Bayesian machine learning and Bayesian model averaging and apply them to the problem of nuclear fission
iv. Develop codes and technology that can be freely used by NNSA researchers and, generally, by the low-energy nuclear physics community.
v. Train junior scientists and students to apply nuclear many-body techniques to describe low-energy nuclear phenomena.

We are pleased to report substantial progress in the all areas of the program. One measure of this progress is publications and invited material. During the reported period, our research resulted in 18 publications (Section 2.A). We carried our software developments (Section 2.B). We presented our research in over 30 talks at conferences and meetings (Section 2.C). The results obtained under this project have been crucial for identifying microscopic description of fission as the forefront scientific problem in the era of extreme computing.

Our group has been very active, in terms of presentations, publications, and organizational involvement, in publicizing the research covered by this grant. Specifically:

- We presented the status of microscopic fission theory at several meetings, including SSAA Annual Workshop and several conferences in the U.S., Europe, Asia, and Australia (see below).
- We established a fission project website, https://people.nscl.msu.edu/~witek/fission/fission.html, that popularizes our research.
- Our graduate student Zachary Matheson was selected as a fellow in the NNSA Graduate Fellowship Program (NGFP). For the NNSA highlight, see https://www.energy.gov/nnsa/articles/nnsa-s-missions-keep-young-scientists-coming-back-more

2. Products

A. Completed projects - Publications

1. *"The limits of nuclear mass and charge."* Four new elements with atomic numbers Z = 113, 115, 117, and 118 have recently been added to the periodic table. The questions pertaining to these superheavy systems are in the forefront of research in nuclear and atomic physics, and chemistry. In Nature Phys. 14, 537 (2018), we offered a high-level view of the field and outlined future

challenges. This article was broadly highlighted by numerous news outlets, see https://www.altmetric.com/details/43274279/news.

2. We published a Rev. Mod. Phys. Colloquium 91, 011001 (2019) on *Superheavy elements: Oganesson and beyond*, which offers a broad perspective on the field of superheavy nuclei and atoms.
3. *"Competing fission modes in ^{178}Pt"*. In Phys. Lett. B 790, 583 (2019), fragment mass distributions from fission of the excited compound nucleus ^{178}Pt have been deduced from the measured fragment velocities. The data are indicative of a mixture of the mass-asymmetric and mass-symmetric fission modes associated with higher and lower total kinetic energies of the fragments, respectively. Most probable experimental fragment-mass split of the asymmetric mode, A_L/A_H=79/99, is well reproduced by nuclear density functional theory using the UNEDF1-HFB and D1S density functionals. The symmetric mode is associated by theory with very elongated fission fragments, which is consistent with the observed total kinetic energy/fragment mass correlation.
4. *"Cluster radioactivity of ^{294}Og".* According to theory, cluster radioactivity becomes an important decay mode in superheavy nuclei. In a paper published in Phys. Rev. C 99, 041304(R) (2019), we predict that the strongly asymmetric fission, or cluster emission, is in fact the dominant fission channel for ^{194}Og, which is currently the heaviest synthetic isotope known. Our theoretical approach incorporates important features of fission dynamics, including quantum tunneling and stochastic dynamics up to scission. We show that despite appreciable differences in static fission properties such as fission barriers and spontaneous fission lifetimes, the prediction of cluster radioactivity in ^{194}Og is robust with respect to the details of calculations, including the choice of energy density functional, collective inertia, and strength of the dissipation term.
5. *"α-decay energies of superheavy nuclei: Systematic trends"*. Known superheavy nuclei primarily decay through alpha emission and spontaneous fission. In Phys. Rev. C 99, 014317 (2019), we evaluated the Q_α values for even-even nuclei from Fm to Z=120. For well-deformed nuclei between Fm and Ds, we find excellent consistency between different model predictions, and a good agreement with experimental results. For transitional nuclei beyond Ds, intermodel differences grow, resulting in an appreciable systematic error. The robustness of DFT predictions for well-deformed superheavy nuclei supports the idea of using experimental Q_α values, together with theoretical predictions, as reasonable (Z,A) indicators. Unfortunately, this identification method is not expected to work well in the region of deformed-to-spherical shape transition as one approaches N=184.
6. *"Bayesian approach to model-based extrapolation of nuclear observables".* In a Phys. Rev. C 98, 034318 (2018) paper, highlighted as Editors' Suggestion, we considered 10 global models based on nuclear density functional theory with realistic energy density functionals as well as two more phenomenological mass models. The emulators of two-neutron separation energy residuals and Bayesian confidence intervals defining theoretical error bars were constructed using Bayesian Gaussian processes and Bayesian neural networks. By establishing statistical methodology and parameters, we carried out extrapolations toward the two-neutron dripline. While both Gaussian processes (GP) and Bayesian neural networks reduce the root-mean-square (rms) deviation from experiment significantly, GP offers a better and much more stable performance. The increase in the predictive power of microscopic models aided by the statistical treatment is quite astonishing: The resulting rms deviations from experiment on the testing dataset are similar to those of more phenomenological models. The estimated credibility

intervals on predictions made it possible to evaluate predictive power of individual models and also make quantified predictions using groups of models. The proposed robust statistical approach to extrapolation of nuclear model results can be useful for assessing the impact of current and future experiments in the context of model developments. The new Bayesian capability to evaluate residuals is also expected to impact research in the domains where experiments are currently impossible, for instance, in simulations of the fission recycling in the astrophysical r process.

7. *"Neutron Drip Line in the Ca Region from Bayesian Model Averaging."* In a paper published in Phys. Rev. Lett. 122, 062502 (2019), we used a Bayesian model averaging analysis based on GP-based extrapolations we introduced the posterior probability for each nucleus to be bound to neutron emission. We found that extrapolations for drip-line locations, at which the nuclear binding ends, are consistent across the global mass models used, in spite of significant variations between their raw predictions. In particular, considering the current experimental information and current global mass models, we predicted that ^{68}Ca has an average posterior probability of 76% to be bound to two-neutron emission. This pilot study of the Bayesian Model Averaging will be extended to fission observables.
8. *"Non-perturbative collective inertias for fission: a comparative study",* S. A. Giuliani and L. M. Robledo, Phys. Lett. B 787, 134 (2018). The non-perturbative method to compute Adiabatic Time Dependent Hartree Fock Bogoliubov (ATDHFB) collective inertias is extended to the Generator Coordinate Method (GCM) including the case of density dependent forces. The two inertias schemes are computed along the fission path of the ^{234}U and compared with the perturbative results. We find that the non-perturbative schemes predict very similar collective inertias with a much richer structure than the one predicted by perturbative calculations. Moreover, the non-perturbative inertias show an extraordinary similitude with the exact GCM inertias computed numerically from the energy overlap. These results indicate that the non-perturbative inertias provide the right structure as a function of the collective variable and only a phenomenological factor is required to mock up the exact GCM inertia.
9. *Role of dynamic pairing correlations in fission dynamics*, R. Bernard, S.A. Giuliani, and L.M. Robledo, Phys. Rev. C 99, 064301 (2019). We studied the role of dynamic pairing correlations in fission dynamics by considering intrinsic HFB wave functions that are obtained by minimizing the particle number projected energy. For the restricted variational space, the set of self-consistent wave functions with different values of proton and neutron number particle fluctuations are considered. The particle number projected energy is used to define potential energy surface for fission whereas collective inertias are computed within the traditional formulas for the intrinsic states. The results show that the effect of the restricted variation after particle number projection in the potential energy surface is small while collective inertias substantially decrease. On the other hand, we showed that this quenching is strongly mitigated when Coulomb antipairing is considered.
10. *Spallation-altered Accreted Compositions for X-Ray Bursts: Impact on Ignition Conditions and Burst Ashes*, J. S. Randhawa, Z. Meisel, S. A. Giuliani, H. Schatz, B. S. Meyer, K. Ebinger, A. A. Hood, and R. Kanungo, Astrophys. J. 887, 100 (2019). Model predictions of X-ray burst ashes and light curves depend on the composition of the material accreted from the companion star, in particular the abundance of CNO elements. It has previously been pointed out that spallation in the atmosphere of the accreting neutron star can destroy heavy elements efficiently. In this work we studied this spallation using a realistic reaction network that follows the complete spallation cascade and takes into account not only destruction, but also production of

elements by the spallation of heavier species. We find an increased survival probability of heavier elements compared to previous studies, resulting in significantly higher CNO abundances. We provide resulting compositions as a function of accretion rate and explore their impact on 1D multi-zone X-ray burst models.

11. *Beyond the proton drip line: Bayesian analysis of proton-emitting nuclei*, L. Neufcourt, Y. Cao, S. Giuliani, W. Nazarewicz, E. Olsen, and O. B. Tarasov, Phys. Rev. C 101, 014319 (2020). Predicting properties of unstable nuclear states in the vast territory of proton emitters poses an appreciable challenge for nuclear theory as it often involves far extrapolations. With the help of Bayesian methodology, we mix a family of nuclear mass models corrected with statistical emulators trained on the experimental mass measurements. We studied the impact of such model mixing in the proton-rich region of the nuclear chart. Separation energies were computed within nuclear density functional theory using several Skyrme and Gogny energy density functionals. Quantified predictions were obtained for each model using Bayesian Gaussian processes trained on separation-energy residuals and combined via Bayesian model averaging. We obtained a good agreement between averaged predictions of statistically corrected models and experiment. In particular, we quantified model results for one- and two-proton separation energies and derived probabilities of proton emission. This information enabled us to produce a quantified landscape of proton-rich nuclei. The most promising candidates for two-proton decay studies have been identified.
12. *Quantified limits of the nuclear landscape*, L. Neufcourt, Y. Cao, S. A. Giuliani, W. Nazarewicz, E. Olsen, and O. B. Tarasov, Phys. Rev. C 101, 044307 (2020). Predicting the range of particle-bound isotopes poses an appreciable challenge for nuclear theory as it involves extreme extrapolations of nuclear masses beyond the regions where experimental information is available. Still, quantified extrapolations are crucial for a variety of applications, including the modeling of stellar nucleosynthesis. In this work, we used microscopic nuclear mass models and Bayesian methodology to provide quantified predictions of proton and neutron separation energies as well as Bayesian probabilities of existence throughout the nuclear landscape all the way to the particle drip lines. To account for uncertainties, Bayesian Gaussian processes were trained on the separation-energy residuals for each individual model, and the resulting predictions are combined via Bayesian model averaging. This framework allowed to account for systematic and statistical uncertainties and propagate them to extrapolative predictions. According to our Bayesian model averaging analysis, 7759 nuclei with $Z \leq 119$ have a probability of existence ≥ 0.5. The extrapolations obtained in this study will be put through stringent tests when new experimental information on exotic nuclei becomes available.
13. *Efficient method for estimation of fission fragment yields of r-process nuclei*, J. Sadhukhan, S. A. Giuliani, Z. Matheson, and W. Nazarewicz, Phys. Rev. C 101, 065803 (2020). The knowledge of fission fragment yields of hundreds of nuclei inhabiting very neutron-rich regions of the nuclear landscape is crucial for the modeling of heavy-element nucleosynthesis. In this study, we proposed a novel model for a fast calculation of fission fragment yields based on the concept of shell-stabilized prefragments calculated within realistic nuclear density functional theory. The new approach has been benchmarked against experimental data and advanced calculations reaffirming the dominant role of shell effects in the pre-scission region for forming fission yields.
14. *Fission and the r-process nucleosynthesis of translead nuclei*, S. A. Giuliani, G. Martínez-Pinedo, Meng-Ru Wu, and L. M. Robledo, Phys. Rev. C 102, 045804 (2020). We studied the impact of fission on the production and destruction of translead nuclei during the r-process

nucleosynthesis occurring in neutron star mergers. Abundance patterns and rates of nuclear energy production are obtained for different ejecta conditions using two sets of stellar reaction rates, one of which is based on microscopic and consistent calculations of nuclear masses, fission barriers and collective inertias. We show that the accumulation of fissioning material during the r process can strongly affect the free neutron abundance after the r-process freeze-out. This leads to a significant impact on the abundances of heavy nuclei that undergo α decay or spontaneous fission, affecting the radioactive energy production by the ejecta at timescales relevant for kilonova emission.

15. *Future of Nuclear Fission Theory*, M. Bender, R. Bernard, G. Bertsch, S. Chiba, J. Dobaczewski, N. Dubray, S. A. Giuliani, K. Hagino, D. Lacroix, Z. Li, P. Magierski, J. Maruhn, W. Nazarewicz, J. Pei, S. Péru, N. Pillet, J. Randrup, D. Regnier, P.-G. Reinhard, L. M. Robledo, W. Ryssens, J. Sadhukhan, G. Scamps, N. Schunck, C. Simenel, J. Skalski, I. Stetcu, P. Stevenson, S. Umar, M. Verrière, D. Vretenar, M. Warda, and S. Åberg, J. Phys. G 47, 113002 (2020). There has been much recent interest in nuclear fission, due in part to a new appreciation of its relevance to astrophysics, stability of superheavy elements, and fundamental theory of neutrino interactions. At the same time, there have been important developments on a conceptual and computational level for the theory. The promising new theoretical avenues were the subject of a workshop held at the University of York in October 2019; this report summarizes its findings and recommendations.
16. *Landscape of pear-shaped even-even nuclei*, Y. Cao, S. E. Agbemava, A.V. Afanasjev, W. Nazarewicz, and E. Olsen, Phys. Rev. C 102, 024311 (2020). We carried out global analysis of ground-state octupole deformations for particle-bound even-even nuclei with $Z \leq 110$ and $N \leq 210$ using nuclear density functional theory with several non-relativistic and covariant energy density functionals. We identified several regions of ground-state octupole deformation. In addition to the "traditional" regions of neutron-deficient actinide nuclei around ^{224}Ra and neutron-rich lanthanides around ^{146}Ba, we identified vast regions of reflecion-asymmetric shapes in very neutron-rich nuclei around ^{200}Gd and ^{288}Pu, as well as in several nuclei around ^{112}Ba. Our analysis suggests several promising candidates with stable ground-state octupole deformation, primarily in the neutron-deficient actinide region, that can be reached experimentally. Octupole shapes predicted in this study are consistent with the current experimental information. This work can serve as a starting point of a systematic search for parity doublets in odd-mass and odd-odd nuclei, which can be of interest in the context of new physics searches.
17. *r-Process Nucleosynthesis: Connecting Rare-Isotope Beam Facilities with the Cosmos (topical review),* C. J. Horowitz, A. Arcones, B. Cote, I. Dillmann, W. Nazarewicz, I. Roederer, H. Schatz, A. Aprahamian, D. Atanasov, A. Bauswein, J. Bliss, M. Brodeur, J. A. Clark, A. Frebel, F. Foucart, C. J. Hansen, O. Just, A. Kankainen, G. C. McLaughlin, J. M. Kelly, S. N. Liddick, D. M. Lee, J. Lippuner, D. Martin, J. Mendoza-Temis, B. D. Metzger, M. R. Mumpower, G. Perdikakis, J. Pereira, B. W. O'Shea, R. Reifarth, A. M. Rogers, D. M. Siegel, A.Spyrou, R. Surman, X. Tang, T. Uesaka, and M. Wang, J. Phys. G 46, 083001 (2019). This is an exciting time for the study of r-process nucleosynthesis. Recently, a neutron star merger GW170817 was observed in extraordinary detail with gravitational waves and electromagnetic radiation from radio to gamma rays. FRIB and other rare-isotope beam facilities will soon have dramatic new capabilities to synthesize many neutron-rich nuclei that are involved in the r-process. The new capabilities can significantly improve our understanding of the r-process and likely resolve one of the main outstanding problems in classical nuclear astrophysics. However, to make best use of the new experimental capabilities and to fully interpret the results, a great deal of infrastructure is

needed in many related areas of astrophysics, astronomy, and nuclear theory. In this review, we placed these experiments in context by discussing astrophysical simulations and observations of r-process sites, observations of stellar abundances, galactic chemical evolution, and nuclear theory for the structure and reactions of very neutron-rich nuclei.

18. *Microscopic description of the odd-even effect in fission yields*, J. Sadhukhan, S.A. Giuliani, and W. Nazarewicz, submitted to Phys. Rev. C (2021). Fission trajectories on two-dimensional potential energy surfaces were obtained within the density functional theory framework, allowing for a microscopic determination of the most probable fission fragment configurations. Mass and charge yield distributions were constructed by means of a statistical approach rooted in a microcanonical ensemble. We show that the proposed hybrid model can reproduce experimental mass and charge fragment yields for a wide range of fissioning nuclei as well as the observed odd-even staggering. Furthermore, experimental isotopic yields can be accurately described with a simple neutron evaporation scheme. Finally, we explored fission fragment distributions of exotic neutron-rich and superheavy systems, and compare our predictions with other state-of-the art global calculations. Our study suggests that microscopic rearrangements of nucleons into a fissioning nucleus occur well before the scission, and the subsequent dynamics is mainly driven by the thermal excitations and bulk features of the nuclear binding.

B. Computational tools

To help manage fission PES data, a Python module called PES Tools was co-developed by Z. Matheson for manipulating, extracting, interpolating, and plotting. Aside from the parser scripts, which collect data from the output of a particular DFT solver and store it in an XML data structure, PES Tools is not dependent on a specific DFT solver. In particular, a submodule was created to interface between PES Tools and Fission Tools, a set of codes used for fission calculations. Matheson also contributed to development to Fission Tools, a suite of codes which extend the functionality of HFODD, HFBTHO, and other DFT solvers to the problem of nuclear fission, and DFTNESS (Density Functional Theory for Nuclei at Extreme ScaleS), a computational DFT framework.

C. Presentations at Conferences and Meetings

1. *Role of fission during the r-process nucleosynthesis*, S. Giuliani, Nuclear Structure Conference, East Lansing, MI, August 2018.
2. *Applications of Nuclear Density Functional Theory*, W. Nazarewicz, International School of Nu-clear Physics, 40th Course, The Strong Interaction: From Quarks and Gluons to Nuclei and Stars, Erice, Italy, September 16-24, 2018.
3. *Role of fission in the r-process nucleosynthesis*, S. Giuliani, Joint Meeting of the APS DNP and the PSJ, October 2018, Waikoloa (Hawaii).
4. *Quantified Density Functional Theory*, W. Nazarewicz, International Conference on Nuclear Theory in the Supercomputing Era – 2018, IBS Headquarters, Daejeon, South Korea, October 30, 2018.
5. *Excitement and Challenges in Nuclear Structure*, W. Nazarewicz, CFNS Stony Brook, November 28, 2018
6. *Summary talk*, W. Nazarewicz, 13th International Conference on Nucleus-Nucleus Collisions (NN2018), Omiya, Saitama, Japan, December 4-8, 2018.
7. *Microscopic Description of the Fission Process*, W. Nazarewicz, 2019 Stewardship Science

Academic Programs Symposium, Albuquerque, NM, February 19-20, 2019.

8. *r-process nucleosynthesis: Fingerprints from fissioning nuclei*, S. Giuliani, 54th ASRC International Workshop Sakura-2019, Japan Atomic Energy Agency (JAEA), Tokai, Japan, March 2019.
9. *Cluster formation and emission in* ^{294}*Og*, Z. Matheson, 54th ASRC International Workshop Sakura-2019, Japan Atomic Energy Agency (JAEA), Tokai, Japan, March 2019.
10. *Nuclear physics and r process: a survey on fission*, S. Giuliani, International Molecule-type Workshop, Yukawa Institute for Theoretical Physics, Kyoto, Japan, March 2019.
11. *Quantified Density Functional Theory*, W. Nazarewicz, International Conference on Proton-Emitting Nuclei 2019 FRIB, MSU, June 3-7, 2019.
12. *Quantified Density Functional Theory*, International Workshop on Many-body System with Strong Interactions, W. Nazarewicz, Lanzhou, China, June 10-15, 2019.
13. *Survey of ground-state octupole deformations of atomic nuclei*, W. Nazarewicz, Workshop on the Nuclear Octupole Degree of Freedom, UWS, Paisley, UK, July 25-26, 2019.
14. *Survey of octupole deformations in nuclei*, W. Nazarewicz, Topical program: Hadronic Electric Dipole Moments in the FRIB Era: From the Proton to Protactinium, MSU, Aug. 19, 2019.
15. *Structure of superheavy nuclei*, W. Nazarewicz, 6th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN19), Wilhelmshaven, Germany, August 25-30, 2019.
16. *Nuclear Theory Challenges*, W. Nazarewicz, XXXVI Mazurian Lakes Conference on Physics, Piaski, Poland, September 17, 2019.
17. *Where are the limits of the periodic table?* W. Nazarewicz, 104th Meeting of the Argentine Physical Association (RAFA 2019), Santa Fe, Argentina, Sep. 3-Oct. 3, 2019.
18. *Quantified nuclear density functional theory through statistical machine learning*, W. Nazarewicz, 104th Meeting of the Argentine Physical Association (RAFA 2019), Santa Fe, Argentina, Sep. 3-Oct. 3, 2019.
19. *Quantified nuclear density functional theory*, W. Nazarewicz, 3rd Conference on Microscopic Approaches to Nuclear Structure and Reactions, LLNL, Livermore, CA, Nov. 15, 2019.
20. *Is there an end to the periodic table?* W. Nazarewicz, Solvay Workshop New Frontiers in Atomic, Nuclear, Plasma and Astrophysics', Brussels, Belgium, November 25 - 27, 2019.
21. *Superheavy elements: theoretical challenges*, W. Nazarewicz, SHE2019, International Symposium on Superheavy Elements, Hakone, Japan, December 1-5, 2019.
22. *Survey: Status of A.I. in Nuclear Structure Theory*, W. Nazarewicz, A.I. for Nuclear Physics workshop, CEBAF Center, Newport News, VA, 4-6 March 2020.
23. *Fission: emergence of cluster decay and imprinting in r-process nucleosynthesis,* S. Giuliani, NUCLEI meeting, May 2019, Santa Fe (New Mexico).
24. *Fission of translead nuclei: From cluster emission to r-process nucleosynthesis*, S. Giuliani, THEORY-5 Scientific Workshop, September 2019, Castelvecchio Pascoli (Italy).
25. *Realistic large-scale fission calculations*, S. Giuliani, Future of Fission Workshop, October 2019, York (UK).
26. *Fission fragments distributions of superheavy and r-process nuclei,* S. Giuliani, Microscopic Approaches to Nuclear Structure and Reactions, November 2019, Livermore (CA).
27. *Beyond the proton drip line with Bayesian analysis,* S. Giuliani, A.I. for Nuclear Physics workshop, March 2020, Thomas Jefferson National Accelerator Facility (Virginia).

28. *Fission fragments distributions of r-process nuclei using DFT*, S. Giuliani, NUCLEI meeting, June 2020, ANL (Illinois).
29. *Superheavy elements: theoretical challenges (an update)*, W. Nazarewicz, The Virtual Superheavy elements seminar (global virtual event), Oct. 13, 2020.
30. *Microscopic Description of the Fission Process*, W. Nazarewicz, 2021 Stewardship Science Academic Programs Symposium (virtual), Feb. 16-18, 2021.
31. *Machine Learning for Nuclear Fission*, D. Lay, April APS meeting, Apr. 17-21, 2021.

3. Participants

Research was carried out by the principal investigator, one research professor, two postdocs, one graduate student, and collaborators. A list of personnel involved in the research covered by this grant includes:

- E. Flynn (MSU, graduate student)
- S. Giuliani (MSU, postdoc)
- D. Lay (MSU, graduate student)
- Z. Matheson (MSU, graduate student; Ph.D. June 1019; currently at NNSA)
- W. Nazarewicz (MSU, Principal Investigator)
- E. Olsen (MSU, postdoc; left January 2019)
- J. Sadhukhan (Kolkata; visiting Research Professor)
- J. Wylie (MSU, graduate student)

Training of next-generation nuclear theorists is an important part of our undertaking. Two graduate students, **Eric Flynn, Daniel Lay** and **Josh Wylie**, are currently involved in this research. In 2019, our former graduate student **Zach Matheson** was selected as a fellow in the NNSA Graduate Fellowship Program (NGFP) beginning June 2019 and transitioned to a position of Physical Scientist at NNSA.

4. Changes/Problems

There are no changes from the DOE approved application.

5. Special reporting requirements

N/A

6. Budgetary Information

We estimate no unobligated balances remaining at the end of the budget period.