Final Progress Report: Research activities at the University of Washington relating to the SciDAC project titled NUCLEI.

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Project Title: Nuclear Computational Low Energy Initiative (NUCLEI)

Additional Personnel:

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I. Introduction and Overview

I.a. Abstract: This is the final report for University of Washington for the NUCLEI SciDAC-3. The NUCLEI -project, as defined by the scope of work, will develop, implement and run codes for large-scale computations of many topics in low-energy nuclear physics. Physics to be studied include the properties of nuclei and nuclear decays, nuclear structure and reactions, and the properties of nuclear matter. The computational techniques to be used include Quantum Monte Carlo, Configuration Interaction, Coupled Cluster, and Density Functional methods. The research program will emphasize areas of high interest to current and possible future DOE nuclear physics facilities, including ATLAS and FRIB (nuclear structure and reactions, and nuclear astrophysics), TJNAF (neutron distributions in nuclei, few body systems, and electroweak processes), NIF (thermonuclear reactions), MAJORANA and FNPB (neutrino-less double-beta decay and physics beyond the Standard Model), and LANSCE (fission studies).

I.b. Group Overview: Research at the UW was focused on nuclear physics aspects of neutron stars and supernova. Through collaborations and computing enabled by this SciDAC project, work at the UW improved the description of: (i) thermodynamic and transport of the neutron star crust; and (ii) hot and density matter at sub-nuclear density encountered in supernova. These improvements are crucial to our understanding of core-collapse supernova explosions and associated neutrino emission, and to interpret thermal, transient and explosive phenomena observed in x-rays from accreting and magnetized neutron stars.

I.c. Personnel: Sanjay Reddy (PI), Ermal Rrapaj (Graduate Student), Alessandro Roggero (Postdoc)

I.d. Personnel changes:Ermal Rrapaj graduated in August 2016 and a postdoc Alessandro Roggero joined the collaboration during the final year from August 2016-August 2017

II. Research Program

II.a Research Highlights:

Nuclear pasta in hot dense matter and its implications for neutrino scattering: Alessandro Roggero, Sanjay Reddy and collaborators developed a simple framework to calculate the abundance of large clusters of nucleons in neutron-rich matter at sub-nuclear density at finite temperature effects when matter is close to beta-equilibrium. Matter at these densities and temperatures plays an important role in supernova and neutron star mergers because neutrinos transport in this environment can influence the supernova explosion mechanism and nucleosynthesis of heavy elements through the rapid neutron capture process called the r-process. We found that large nuclei and exotic non-spherical nuclear configurations called pasta, favored in the vicinity of the transition to uniform matter at T = 0, dissolve at relatively low temperature.

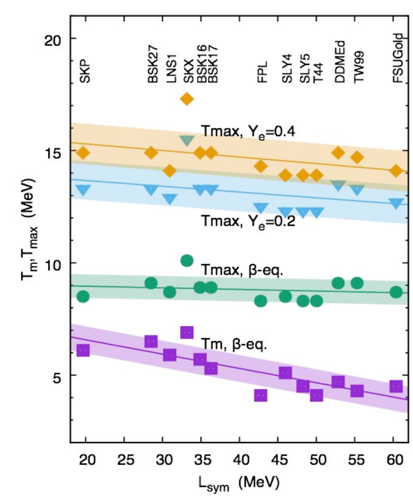

Figure 1 Pasta melting temperature in beta-equilibrium and at constant electron fraction.

For matter close to beta-equilibrium we found that the pasta melting temperature is T_β ⍰ 4 ± 1 MeV for realistic equations of state. The mechanism for pasta dissolution as understood, and in general T_β is shown to be sensitive to the proton fraction. We also studied the implications for neutrino transport and found that coherent neutrino scattering from nuclei and pasta makes a modest contribution to the opacity under the conditions encountered in supernovae and neutron star mergers. At low temperature and high proton fraction when large nuclei favored, coherent neutrino scattering off them was found to be strongly suppressed due to correlation in the strongly couple Coulomb plasma. One our main finding was that heterogeneous phase containing nuclei at low temperature acts as a low-pass filter for low energy thermal neutrinos with implications for supernova dynamics and nucleosynthesis.

Microscopically constrained mean field models from chiral thermodynamics: Efforts are underway to combine astrophysical observations of neutron star properties, terrestrial laboratory experiments of finite nuclei and hot/compressed nuclear matter, and microscopic many-body theory to construct a more complete picture of the nuclear equation of state (EOS) across the range of conditions probed in supernovae and neutron star merger simulations. Traditionally mean field models, based on either Skyrme or relativistic mean field (RMF) interactions, have been used to construct nuclear equations of state for use in astrophysics simulations. Rrapaj, Roggero and Holt (arXiv:1510.00444) have explored the use of mean field models to approximate microscopic nuclear equations of state derived from chiral effective field theory across the densities and temperatures relevant for astrophysical phenomena such as core-collapse supernovae and binary neutron star mergers. They considered both relativistic mean field theory with scalar and vector meson exchange as well as energy density functionals based on Skyrme phenomenology and compare to thermodynamic equations of state derived from chiral two- and three-nucleon forces in many-body perturbation theory. Quantum Monte Carlo simulations of symmetric nuclear matter and pure neutron matter are used to determine the density regimes in which perturbation theory with chiral nuclear forces is valid. Within the theoretical uncertainties associated with the many-body methods, we found that select mean field models describe well microscopic nuclear thermodynamics. As an additional consistency requirement, we study as well the single-particle properties of nucleons in a hot/dense environment, which affect e.g., charged-current weak reactions in neutron-rich matter. The identified mean field models can be used across a larger range of densities and temperatures in astrophysical simulations than more computationally expensive microscopic models.

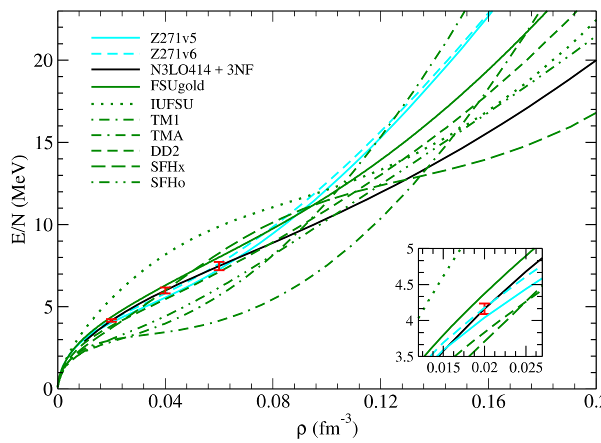

Figure 2: Energy per particle at T=0 obtained using Quantum Monte Carlo calculations of neutron matter (shown in red with error bars) are used to select a class of mean field models suitable for applications in neutron stars and supernovae.

Nucleon-nucleon bremsstrahlung of dark gauge bosons and revised supernova constraints: We (Rrapaj and Reddy, arXiv:1511.09136) calculated the rate of production of hypothetical light vector bosons (LVBs) from nucleon-nucleon bremsstrahlung reactions in the soft radiation limit directly in terms of the measured nucleon-nucleon elastic cross sections. Using these results and the observation of neutrinos from supernova SN1987a we deduced constraints on the couplings of vector bosons with masses □200 MeV to either electric charge (dark photons) or to baryon number. Our study established for the first time strong constraints on LVB that couple only to baryon

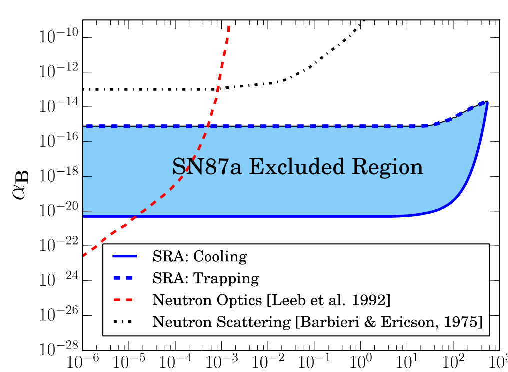

Figure 3: Supernova constraints on the coupling of dark gauge bosons to standard model baryons

number. Results in Fig. 1 show that for couplings for the range the shaded region are excluded because it leads to too much energy loss to dark gauge bosons and would be incompatible with the neutrino signal observed from supernova SN1987a. Our study also found that earlier constraints on the dark photon needed revision and the excluded region of parameter space is diminished by about a factor of 10. This has important implications for terrestrial experiments and for other astrophysical searches for light hidden sector particles

II.b. Research Progress:

The NUCLEI SciDAC project aims to develop computational tools to calculate the ground state properties of the neutron star crust – where nuclear structure, band structure of neutrons and electrons induced by the solid state and superfluid properties that arise due to strong attractive interactions between neutrons are all accounted for in a microscopic approach. However, this computational intensive microscopic approach is too unwieldy to describe the low energy dynamics of the crust necessary to calculate thermal and transport properties of the crust needed to interpret neutron star observations. During the past years work at UW helped develop an effective theory of collective excitations (phonons) to describe thermal and transport properties [2]. More recently we have studied induced interactions and dense matter and we are now working with the other members of the NUCLEI SciDAC collaboration to extract the induced interactions and the low-energy coefficients of the effective theory from the large-scale computations of the microscopic theory.

IV. References

1. Low-energy collective excitations in the neutron star inner crust, N. Chamel, D. Page and S. Reddy, Phys. Rev. C 87, 035803, (2013).
2. Thermal conductivity and impurity scattering in accreting neutron stars, A. Roggero and S. Reddy, arXiv:1602.01831, submitted to Phys. Rev.

V. Research Metrics

PI / Investigator	**publ.**	**prept./sub.**	**Talks**
Reddy	5	1	20
Total	5	1	20

Publications:

1. *Thermal conductivity and impurity scattering in the accreting neutron star crust, ,* A. Roggero and S. Reddy, Phys. Rev. C **94**, 015803 (2016).
2. *Nucleon-nucleon bremsstrahlung of dark gauge bosons and revised supernova constraints,* E. Rrapaj and S. Reddy, Phys. Rev. C**94** 045805 (2016).
3. *Microscopically constrained mean field models from chiral nuclear thermodynamics*, accepted for publication Phys. Rev. C. (2016).
4. *Quantum Monte Carlo calculations of the thermal conductivity of neutron star crusts*, E. Rrapaj, A. Roggero, J. W. Holt, Phys. Rev. C **92**, 045809 (2015).
5. *Electron-neutron scattering and transport properties of neutron stars,* Bridget Bertoni, Sanjay Reddy, Ermal Rrapaj, Phys.Rev. C **91** 025806 (2015

Preprints submitted:

1. *Nuclear pasta in hot dense matter and its implications for neutrino scattering,* Alessandro Roggero, Jérôme Margueron, Luke F. Roberts, Sanjay Reddy. arXiv:1710.10206. Submitted to Phys. Rev. C (2017)

Talks:

1. Nuclear Astrophysics in the Gravitational Wave Era, Summary Talk, ECT*, Trento, Italy, June 16, (2017)
2. Interaction of low energy neutrinos at high baryon density, ECT*, June 9, (2017)
3. Dark matter in neutron stars and supernovae, CENPA seminar, May 8, (2017).
4. Neutron star tomography with supernova neutrinos invited talk at the SLAC workshop on "Precision Investigations of the Neutrino Sector", Stanford, CA, March 13-17, (2017).
5. Neutron star in the multi-messenger era, Laboratory Colloquium, TRIUMF, Vancouver, Canada, Feb 23, (2017).
6. Neutron star in the multi-messenger era, Physics and Astronomy colloquium, University of Victoria, Victoria, Canada, Feb 22, (2017).
7. Low energy excitations in cold dense matter, contributed talk at the APS April meeting, Washington DC, Jan 28-31, (2017).
8. Nuclear and particle physics aspects of neutron star mergers, invited talk at the International workshop on gross properties of nuclei and nuclear excitations, Hirschegg, Austria, January 15-21, (2017)
9. Thermal and transport properties of neutron stars, invited talk presented at 626. WE-Heraeus-Seminar on "Neutron Stars: A Cosmic Laboratory for Matter under Extreme Conditions", Bad Honnef, Germany, October 27, (2016).
10. Cold dense matter: New insights and near-term prospects, Nuclear Physics Colloquium, Goethe University (Institute for Theoretical Physics), Frankfurt, October 24, (2016).
11. *Neutron stars in the multi-messenger era*, Invited talk, APS April Meeting, Salt Lake City, UT, April 18, (2016).
12. *Cold quantum matter in neutron stars*, CTQM Seminar, Department of Physics, University of Colorado, Boulder, CO, April 8, (2016).
13. *Neutron stars in the multi-messenger era*, Physics Department Colloquium, Penn State University, March 3, (2016).
14. *Nuclear physics aspects of binary neutron star mergers*, High Energy Physics and Astrophysics Seminar, Penn State University, March 2, (2016).
15. *Nuclear astrophysics in the multi-messenger era*, Colloquium, Cyclotron Institute, Texas A&M University, College Station, TX, February 23, (2016).

16. *Nuclear astrophysics in the multi-messenger era*, Physics Colloquium, University of Washington, Seattle, WA, November 30, (2015).
17. *Role of correlations in neutrino interactions in nuclear matter and nuclei*, Invited talk, DNP meeting, Santa Fe, NM, October 28-31, (2015).
18. *Neutron stars as laboratories for nuclear and particle physics*, Physics Colloquium, Technical University, Darmstadt, Germany, October 16, (2015).
19. *Dense matter in neutron stars: New insights from theory and observations*, EMMI workshop on "Cold dense matter: From short-range correlations to neutron stars", GSI, Darmstadt, Germany, October 15, (2015).
20. *Recent advances and open questions in neutron star physics*, Invited talk at Extreme Gravity Workshop, Bozeman, MT, August 20-22, (2015).