DE- SC0021235

# Expanding the frontiers of nuclear reactions with rare-isotope beams

# Final Technical Report

## Period covered: 09/01/2020 – 08/31/2022


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Final Report for DE- SC0021235

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# Abstract

The first year of this award provides funding for a postdoc and two students to analyze data obtained from experiments using a new Time Projection Chamber (TPC), called the SpiRIT (SAMURAI pion Reconstruction Ion Tracker) constructed and funded by DOE office of science (award # DE-SC0004835) to explore nuclear equation of state. The second year of the award funds the completion of analysis and theses for two MSU students.

# I. Major Goals/Objectives of the Project

The major goals of the project can be summarized as:

a. To study the equation of state (EoS) of asymmetric nuclear matter and the "nature of neutron stars and dense nuclear matter" via heavy ion collision experiments. Study of the nature of dilute and dense neutron-rich matter is one of the important research objectives listed in the 2015 Nuclear Physics Long Range Plan.
b. To maintain the US leadership in EoS research during the construction of FRIB by building detectors and doing experiments in facilities in Japan and GSI.
c. To carry out a science program with the TPC at RIKEN with radioactive beams.

# I. Project Results

The results of the project are reported in STI products under journal publication. Section A lists specific accomplishments that resulted from work supported by the award. Section B discusses the new technology and techniques developed to achieve these goals. The list of milestones and their accomplishment are discussed in Section C. Finally, publications resulting from this project are listed in Section D.

## A. Accomplishments

a. We successfully executed two approved TPC experiments in May, 2016
1. 108Sn+ 112Sn and 112Sn+ 124Sn reactions;
https://groups.nscl.msu.edu/hira/NP1306_SAMURAI15/1605Sn108/index.htm
2. 132Sn+ 124Sn and 124Sn+ 124Sn reactions;
https://groups.nscl.msu.edu/hira/NP1306_SAMURAI15/1605Sn132/index.htm
b. The two students and postdocs supported by this project have been analyzing the data and publish results. See Section C.

## B. New Technology or Techniques

We have successfully developed the analysis software to analyze 270 TB of data. The analysis can be separated into two distinct parts:

1. GETDecoder for general use in GET electronics
2. SpiRITROOT for analysis of SpiRIT TPC data

We developed the GETDecoder module that determines the data type of the files, unpacks in parallel the raw data from the CoBo modules, and merges them while converting the output file into a recognizable format by widely-used ROOT analysis package for later analysis. Creating multiple GETDecoders simultaneously for each file is advantageous because it not only saves computing time by a factor of 6 in our case with 12 CoBo files but also reduces the disk space usage by eliminating the pre-merging process. The GETDecoder has been adopted by the MSU Active-Target/TPC group to decode their TPC data.

The SpiRITROOT software has been developed to provide consistent analysis tools to the SpiRIT users for both simulation and data analysis. It is written on top of the FairRoot framework [6], which was developed for the FAIR experiments in Germany and later redesigned for any experimental setup. The analysis software has been use successfully in analyzing the TPC data for tracking and extraction of momentum and energy loss for low energy experiments. These are discussed extensively in the thesis of our students, Jon Barney, Justin Estee and Chun-Yuen Tsang and published in several articles in Nuclear Instrument and Methods A cumulated in the publication of The SpiRIT time projection chamber, by Barney et al in the Review of Scientific Instrument..

## C. Publications

Submitted to DOE E-Link:


[1] Hermann Wolter, Maria Colonna, Dan Cozma, Pawel Danielewicz, Che Ming Ko, Rohit Kumar, Akira Ono, ManYee Betty Tsang, Jun Xu, Ying-Xun Zhang, et al. "Transport Model Comparison Studies of Intermediate- Energy Heavy-Ion Collisions". *arXiv preprint arXiv:2202.06672* (2022). doi: 10.1016/j.ppnp.2022.103962.

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[5] M. D. Cozma and M. B. Tsang. "In-medium Δ(1232) potential, pion production in heavy-ion collisions and the symmetry energy". *The European Physical Journal A* 57.11 (2021), pp. 1–23. doi: 10.1140/epja/s10050-021-00616-3.

[6] J. Barney, J. Estee, W. G. Lynch, T. Isobe, G. Jhang, M. Kurata-Nishimura, A. B. McIntosh, T. Murakami, R. Shane, S. Tangwancharoen, et al. "The S _ RIT time projection chamber". *Review of Scientific Instruments* 92.6 (2021), p. 063302. doi: 10.1063/5.0041191.

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[10] S. Sweany, W. G. Lynch, K. Brown, A. Anthony, Z. Chajecki, D. Dell'Aquila, P. Morfouace, F. C. E. Teh, C. Y. Tsang, M. B. Tsang, R. S. Wang, and K. Zhu. *Reaction Losses of Charged Particles in CsI(Tl) crystals*. 2021. arXiv: 2107.13531 [physics.ins-det].

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G. Jhang, O. B. Khanal, S. Kodali, J. Manfredi, C. Y. Niu, and R. S. Wang. “Calibration of large neutron detection arrays using cosmic rays”. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 967 (2020), p. 163826. doi: 10.1016/j.nima.2020.163826.
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# II. Participants and Personnel

The major US participants are listed in Table 1. Betty Tsang, the PI and William Lynch, coPI from Michigan State University are the main persons responsible for the project. Dr. Chun Yuen Tsang (2022) is a postdoc at Kent State University. Dr. Wen Shang Wang is current a faculty member of the SooChow University.

**Table 1: Major participants and personnel**

| Name | Institution | Position | Contributions | Supported by grant (months) |
|---|---|---|---|---|
| Manyee Betty Tsang | MSU | Faculty | PI | 0 |
| William Lynch | MSU | Faculty | CoPI | 0 |
| Chun Yuen Tsang | MSU | Graduate Student | Analysis and thesis | 24 |
| Chi-En Teh | MSU | Graduate Student | Effective mass, analysis | 6 |
| Rohit Kumar | MSU | Postdoc | Neutron star analysis | 10 |
| Wen Sheng Wang | MSU | Postdoc | Software Design, Experiment, analysis | 3 |

The project provided invaluable and abundant opportunities for training and professional developments to graduate students, and postdocs.

### Graduate Students

The project provided training in thesis topics for 2 MSU students, Chun Yuen Tsang (2022) and Chi-En Teh (2023, 25% on this project), A total of 5 MSU students use the data of this project for their theses. The other 3 MSU Students are Suwat Tangwancharon (2016) , Jonathan Barney (2019), Justin Estee (2020).

In addition to US graduate students, two Korean students (Genie Jhang(2016), JungWoo Lee(2022)) and one Japanese student (Kaneko Masanori (2021)) have used the TPC data for their thesis work. Genie Jhang continued in the project as a postdoc in our group. He is now a staff member in the data acquisition group at FRIB.

### Postdoctoral

The award provided funding for short visits to international scholar who came to MSU to work on the TPC analysis project including Rensheng Wang (6 months) and Rohit Kumar (6 months) working as visiting research associate at MSU.

# III. Impacts

## a. Impact on the development of the principal disciplines of the project

The Equation of State (EoS) is a fundamental property of nuclear matter that describes relationships between energy, pressure, temperature, density and isospin asymmetry $\delta=(\rho_n-\rho_p)/\rho$ in a nuclear system. The EoS largely determines the stable phases of matter and the pressure as a function of density, key properties central to answering questions in the Long Range Plan (LRP) concerning *the nature of neutron stars and dense nuclear matter*. At low temperature, the EoS can be separated into a symmetric matter contribution that is independent of the isospin asymmetry and a poorly constrained symmetry energy term, proportional to the square of the asymmetry. Uncertainties in quantities such as the three-body neutron force contribute significantly to uncertainties in the density dependence of the symmetry energy. The experiments are designed to probe the density dependence of the symmetry energy and the nuclear Equation of State (EoS) at supra-normal density. Providing information on nucleon interactions by constraining the symmetry energy therefore helps address fundamental questions expressed in the LRP concerning *the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotope*s.

With the successful execution of the two TPC experiments using the radioactive beams of neutron rich 132Sn and neutron deficient 108Sn on 124Sn and 112Sn targets, the US group retains the leadership in the study of the nuclear Equation of State (EoS) of neutron-rich nuclear matter at supra-normal density and extracted a constraint for the symmetry energy at 1.5 times the saturation density – the main objective of the proposal. The work stimulated our desire to extract the symmetry energy at various densities from nuclear structure and heavy ion collision experiments resulting in the compilation of a list of constraints plotted in Ref [1].

Reference:

[1] W. G. Lynch and M. B. Tsang. “Decoding the density dependence of the nuclear symmetry energy”. *Physics Letters B* 830 (2022), p. 137098. doi: 10.1016/j.physletb.2022.137098.

## b. Impact on other disciplines

Macroscopic quantities of asymmetric nuclear matter exist in neutron stars and in type II supernovae over a wide range of densities.  Constraints on the EoS and the symmetry energy at sub-saturation and supra-saturation densities can improve our understanding of neutron star properties such as stellar radii and moments of inertia, crustal vibration frequencies, and neutron star cooling rates that have been investigated with ground-based and satellite observatories.  Consequently, the goal of determining the EoS has been a major motivation for recent analyses of X-ray observations aimed at extracting the correlation between neutron star masses and radii. Results of our experiments have provided significant constraints on the Equation of State of dense neutron-rich matter at 1.5 times the saturation density densities that are highly relevant to both the nuclear and neutron star equation of state. This result has been submitted to Nature-Astrophysics and is under peer review.

## c. Impact on the development of human resources

The project provided thesis topics for 3 MSU students.

1. Chun Yuen Tsang graduated in 2022 and is currently a postdoc at Kent State University.
2. Chi-En Teh, expected to graduate in July, 2023.

The graduate students and the postdocs form a workforce pipeline for areas which have a shortage of personnel trained in nuclear science, such as homeland security, the nuclear energy industry as well as the health industries that use nuclear-medicine technologies.

## d. Impact on Physical, institutional and information resources that form Infrastructure

Our simulations of the experiments with state of the art transport model simulations utilized the High Performance Computing Center (HPCC) at MSU. Both students are well-versed in computing using super-computer.

## e. Impact on Technology transfer

None.

## f. Impact on society beyond science and technology

Using the cosmic events accumulated between experiments, we have developed a website, https://groups.nscl.msu.edu/hira/cosmic/CosmicGallery.html, for the general public describing cosmic rates, our detectors and our experiments. This side project is an attempt to stimulate interest for K-12 students as well as the general public about nuclear science and nuclear detectors in a visually engaging fashion.