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Constraining the Equation of State of Dense Neutron-rich Matter

Final Technical Report

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Final Report for DE-SC0014350

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Abstract

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), we performed two experiments with the SAMURAI spectrometer at RIKEN, Japan to study the equation of state of neutron rich matter. As a result of the project, the SpiRIT collaboration, an international collaboration consisting of groups from US, Japan, Korea, Poland, China and Germany, has been formed to pursue the science opportunities provided by the SpiRIT TPC. After the experiments, we developed the software to analyze the SpiRIT experiments and extract constraints of symmetry energy at supra-saturation densities. As a result 270 TB of data have been obtained. Over 10 technical papers on the TPC and 4 science papers on the nuclear equation of state have been published. A total of six (2 US, 1 Japanese and 1 Korean) PhD students have graduated based on their research on the EOS research using the SpiRIT data. In addition, the data also stimulated theorists on transport models to form the "Transport Model Evaluation Project" collaboration to improve the transport model to compare calculations with the data.

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.

II. 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 publications resulting from this project are listed in Section C.

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. We have published over 10 technical papers on the TPC and 4 science papers on the nuclear equation of state have been published. A total of six (3 US, 1 Japanese and 2 Korean) PhD students have graduated based on their research on the EOS research using the SpiRIT data.
c. We have also constructed a web site to educate the public about the TPC, the science of our experiments using the cosmic data taken with the TPC. https://groups.nscl.msu.edu/hira/cosmic

B. New Technology or Techniques

We have successfully constructed the SpiRIT TPC and use it in two experiments. The analysis software can be found in https://github.com/SpiRIT-Collaboration/SpiRITROOT.

The analysis software 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. See publication products under e-LINKS.

C. Publications

Also submitted to DOE E-Link:

[1] C. Y. Tsang, M. B. Tsang, Pawel Danielewicz, W. G. Lynch, and F. J. Fattoyev. "Impact of the neutronstar deformability on equation of state parameters". *Physical Review C* 102.4 (2020), p. 045808. doi: 10.1103/physrevc.102.045808.

[2] C. Y. Tsang, J. Estee, R. Wang, J. Barney, G. Jhang, W. G. Lynch, Z. Q. Zhang, G. Cerizza, T. Isobe, M. Kaneko, M. Kurata-Nishimura, J. W. Lee, T. Murakami, and M. B. Tsang. "Space charge effects in the SpiRIT time projection chamber". *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 959 (2020), p. 163477. doi: 10.1016/j.nima.2020.163477.

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[8] C. Y. Tsang, B. A. Brown, F. J. Fattoyev, W. G. Lynch, and M. B. Tsang. "Constraints on Skyrme equations of state from doubly magic nuclei, ab initio calculations of low-density neutron matter, and neutron stars". *Physical Review C* 100.6 (2019), p. 062801. doi: 10.1103/physrevc.100.062801.

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III. Participants and Personnel

The major US participants are listed in Table 4. Betty Tsang, the PI and William Lynch, coPI from Michigan State University are the main persons responsible for the project. Three MSU students, Jonathan Barney, Justin Estee and Chun Yuen Tsang, joined the project and their theses were based on the TPC data. Dr. Jonathan Barney (2019) is now a staff member at the Los Alamos National Lab. Dr. Justin Estee (2020) is a postdoc at MIT.

The following postdocs were supported by the grant and has moved on with their career. Dr. Giordano Cerizza (currently head of Data Acquisition group at FRIB), Dr. Geni Jhang (Staff member at FRIB), Dr. Clementine Santamaria, (currently a faculty member at Morgan State University).

Finally, nearly 10 US and foreign undergraduate students, including Corinne Anderson (Technology Industry) and Hananiel Setiawan (Medical Physics at Duke University) contributed significantly to the project and the experience affect their career paths.

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
Jonathan Barney	MSU	Graduate Student	Design, construct, test, thesis	0
Justin Estee	MSU	Graduate Student	Design, construct, test, thesis	0

Chun Yuen Tsang	MSU	Graduate Student	Analysis and thesis	24
Giordano Cerizza	MSU	Postdoc	Software Design, Experiment, analysis	24
Clementine Santamaria	MSU	Postdoc	Experiment, analysis	18
Genie Jhang	MSU	Postdoc	construct, test, simulation, Experiment, analysis	36
Rohit Kumar	MSU	Postdoc	Neutron star analysis	10
Corinne Anderson	MSU	Undergraduate	construct, test, simulation	2
Hananiel Setiawan	MSU	Undergraduate	construct, test, simulation	2

The project provided invaluable and abundant opportunities for training and professional developments to graduate students, postdocs and undergraduate students. Some specific examples are discussed below. Travel supports from the award, sometimes with local expense from our Japanese hosts, provided opportunities for participation of postdocs and students to work in prominent non-US institutes such as RIKEN working with a diverse group of scientists.

a. Graduate Students

The project provided training in thesis topics for 3 MSU students in addition to Suwat Tangwancharon who graduated in June, 2016 based on his work on constructing the TPC and the gating grid which we received a patent. The other 3 MSU Students are Jonathan Barney and Justin Estee who graduated in 2019, and 2020 respectively.

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

One Polish student (Pawel Lasko, Katana array) and one visiting Chinese student (Yan Zhang, veto collimator & gating grid) joined the project to work on the auxiliary detectors.

The award also provided local support for short visits to international students who came to MSU to work on the TPC analysis project including Rensheng Wang (12 months) working as visiting professor at MSU.

Undergraduate students

The award, especially provided opportunities to many undergraduate students to participate in research during the school years as well as summer interns. Two of the students (Corinne Anderson and Hananiel Setiawan) have been working consistently through the projects.

b. Postdoctoral

The award supported postdocs working in US institutions as shown in the table; Clementine Santamaria (MSU,18 months); Giordano Cerizza, (MSU, 24 months), Genie Jhang, (MSU, 36 months), and Rohit Kumar, (MSU, 10 months).

IV. 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 published in Ref.

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.

c. Impact on the development of human resources

The project provided thesis topics for 3 MSU students.

1. Jon Barney graduated in 2019 and is currently a staff member at the Los Alamos National Laboratory.
2. Justin Estee graduated in 2020 and is currently a postdoc at MIT.
3. Chun Yuen Tsang expected to graduate in 2022.

The award has provided opportunities for 9 postdocs most of whom receive none or short term support to participate in experiments at GSI and RIKEN as well as involving in the construction and running TPC experiments.

1. Clementine Santamaria (18 months, 2016-2019).
2. Giordano Cerizza (24 months, 2014-2020).

In addition, the award supported many undergraduate students: Corrine Anderson and Hananiel Setiawan.

The undergraduate students, 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.

The award supported the travels of graduate students and postdocs to RIKEN, Japan for collaboration meetings, and working on TPC experiments thus providing these junior scientists opportunities to work in world-premiere facilities, interacting with scientists worldwide, preparing our future science leaders for tomorrow's global work place.

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. The experiments required high speed data acquisition speed, up to 10 Gb/s from the combined 12 CoBo boards, and a high speed data transfer rate (up to 350 Mb/s) from the DAQ machine to offsite preliminary storage. The 250 TB recorded data were then transferred for offline analysis to a local computer cluster at an average speed of 75 MB/s. All these currently taxed the systems in the University and steps were being taken to solve the problems and provide advance glimpse of what DAQ and analysis resources will be needed when FRIB came on line. Thus it is not surprising that both of our postdocs, Giordano Cerizza and Genie Jhang, who worked on the software and analysis of the data ended in the FRIB data acquisition group. Giordano Cerizza is currently the head of that group.

e. Impact on Technology transfer

We are one of the first groups to test the state of the art readout electronics, the Generic Electronics for TPC and devise software to overcome its limitations on the dynamic range.

We have received a patent for the gating grid driver of the TPC.

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.

References:

[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.