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The Structure of Nuclei Far From Stability

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1. Executive summary

The work performed under this grant has led to the development of a detection system that will be used to measure reaction rates for proton or neutron capture reactions at stellar energies on radioactive ions far from stability. The reaction rates are needed to better understand the physics of nucleosynthesis in explosive stellar processes such as supernovae and x-ray burst events. The radioactive ions will be produced at the Radioactive Ion Beam Facility (RIBF) at RIKEN near Tokyo, Japan. During the course of this work, the group involved in this project has expanded by several institutions in Europe and Japan and now involves collaborators from the U.S., Japan, Hungary, Romania, Germany, Spain, Italy, China, and South Korea.

As part of the project, a novel design based on large-area silicon detectors has been built and tested and the performance characterized in a series of tests using particle beams with a variety of atomic numbers at the Cyclotron Institute of Texas A&M University and the Heavy Ion Medical Accelerator in Chiba facility (HIMAC) in Chiba, Japan. The work has involved mechanical construction of a special purpose vacuum chamber, with a precision mounting system for the silicon detectors, development of a new ASICs readout system that has applications with a wide variety of silicon detector systems, and the development of a data acquisition system that is integrated into the computer system being used at RIBF. The parts noted above that are needed to carry out the research program are completed and ready for installation. Several approved experiments that will use this system will be carried out in the near future. The experimental work has been delayed due to a large increase in the cost and availability of electrical power for RIBF that occurred following the massive earthquake and tsunami that hit Japan in the spring of 2011.

Another component of the research carried out with this grant involved developing the theoretical tools that are required to extract the information from the experiments that is needed to determine the stellar reaction rates. The tools developed through this part of the work will be made freely available for general use.

2. Introduction

The scope of this project was to facilitate the development of a research program of reaction studies at the Radioactive Isotope Beam Factory (RIBF) at the RIKEN Nishina Center for Accelerator-Based Science in Wako, Japan (RIKEN) and to continue the effort to developing knowledge and tools for use in the rare isotope beam (RIB) research in the U.S.

The scientific focus of the program was to use one-proton removal (breakup) reactions at intermediate energies as an indirect method for nuclear astrophysics. The goal of such experiments is to obtain information of (p,γ) and (n,γ) reaction rates at stellar energies for nuclei far from stability through determination of Asymptotic Normalization Coefficients (ANC). The experimental program was based on the fragmentation beams from the BigRIPS projectile separator at RIBF utilizing the Zero-Degree Spectrometer and the SAMURAI spectrometer[1]. A major part of this project was dedicated to the development and construction of components for a silicon-detector array and corresponding instrumentation to be mounted just after the reaction target in front of SAMURAI. The activities under this award have been part of the wider international SAMURAI HI-p (Heavy Ion - proton) collaboration.

This project consisted of two tasks, as laid out in the project management plan:

Task 1. Carry out a physics program by performing a series of nuclear and Coulomb breakup experiments with rare isotope beams at RIBF. To develop, improve and test reaction theories and codes for breakup at intermediate energies.

Task 2. Develop a large silicon-detector array that will incorporate both existing state-of-the-art technology and generate extensions to this technology for silicon readout electronics employing Application Specific Integrated Circuits (ASICs).

3. Results

This section summarizes the major project activities during the grant period and provides a comparison of the actual project accomplishments with the goals and objectives laid out in the project management plan. In the following discussion, the deliverables of each task are presented, followed by comparison to the actual achievements.

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[1] http://www.nishina.riken.jp/RIBF/SAMURAI/overview.html

3.1. Task 1

Deliverables, as in the project management plan:
Experiments with RIBs successfully conducted at RIBF and the data analyzed. The theory effort will deliver not only new, improved models, but also codes for reaction calculations. The results will be published.

Actual accomplishments, experiments:
The major setback for the experimental part of task 1 occurred in the form of an earthquake and the following tsunami in Japan on March 11, 2011. These events caused major problems to power generation in Japan, as well as significant issues in funding of the operations of the RIBF facility RIKEN. After recovering from the actual event, the available time for running experiments at RIKEN has been limited to a few months per year. During this period, our original, accepted experimental proposals to the RIKEN scientific program advisory committee (PAC) expired and no experiments could be conducted during this grant period. The experiments were decoupled from this project after the no-cost extension at the end of FY2013 (the no-cost extensions were awarded to finalize the technical part, Task 2 of this project), as the situation in Japan didn't allow conducting experiments in the foreseeable future. The overall collaboration (referred to as HI-p, or SAMURAI-Si) that will utilize the detector system (Task 2) in RIKEN has grown to include more than 50 researchers from about 20 institutions from the U.S., Japan, Hungary, Romania, Germany, Spain, Italy, China, and South Korea. At the end of this grant period (end of FY2015), the collaboration has four physics proposals accepted, totaling about two weeks of beam on target and two more submitted to the RIKEN PAC. These experiments, utilizing the developed silicon-detector system at SAMURAI, are waiting to be scheduled in 2016-2017.

Actual accomplishments, theory:
In this project, the TAMU-Commerce participants in this project (Carlos Bertulani, Co-PI and Mesut Karakoc, Post-doc) have evaluated the contributions of the final-state interaction (FSI) and of the medium modifications of the nucleon-nucleon interactions and obtained the shapes and magnitudes of the momentum distributions in nucleon knockout reactions. Such effects have been often neglected in the literature. We find that the two effects are important and their relative contributions vary with the energy and with the atomic and mass number of the projectile involved.

We have also updated predictions of effective elastic nucleon-nucleon cross sections intended for use in nucleus-nucleus reactions. A novel characteristic of our approach combines all microscopic medium effects included in the Dirac-Brueckner-Hartree-Fock G-matrix with a Pauli blocking mechanism which is more appropriate for applications in ion-ion reaction models as compared to a previous approach. The effective in-medium cross section is found to be quite sensitive to the description of Pauli blocking in the final configurations.

We have published three articles related to this problem:
Mesut Karakoc, A. Banu, C. A. Bertulani, L. Trache, Phys. Rev. C **87**, 024607 (2013).
Mesut Karakoc and C. A. Bertulani, J. Phys. Conf. Ser. **420**, 012074 (2013).
B. Chen, F. Sammarruca and C.A. Bertulani, Phys. Rev. C **87**, 054616 (2013).

More calculations were made to determine the importance of medium and Coulomb effects on the results of calculations for breakup reactions. It was directly related to the scope of this grant: an increased reliability of calculations through a better treatment of Coulomb distortion and of final state interaction at projectile energies from 35 to 1000 MeV/nucleon and on targets with low and large atomic numbers Z.

We have continued working on the development of reaction theories and models for this project. We have performed tests of the theories and codes to be used in the analysis of the reactions proposed. After completing his tasks in this project Mesut Karakoc, the theory postdoc in TAMU-Commerce, became an assistant professor at the University of Akdeniz in Antalia, Turkey.

Mesut Karakoc and Carlos Bertulani are working on an extension of this research on momentum distributions in knockout reactions to include higher-order corrections due to continuum-continuum couplings. Carlos Bertulani is currently working on the theoretical calculation of 2 proton removal of ^{9}C for the experiment waiting to be scheduled at RIKEN.

3.2. Task 2

<u>Deliverables, as in the project management plan:</u>
(a) a system with 512 channels of high-density readout electronics will be setup at the TAMU Cyclotron Institute and will be used with exiting silicon detectors in experiments with beams from the K500 superconducting cyclotron;
(b) a system of multi-strip silicon detectors installed at the SAMURAI spectrometer at RIBF;
(c) a remote data acquisition, diagnosis and detector control system and associated electronics running at RIKEN with parts of the DAQ system provided by RIKEN funds.

<u>Actual accomplishments,(a):</u>
A data acquisition system with 512 channel high-density readout electronics was setup at the TAMU Cyclotron Institute in 2011. This system, based on the initial chip (HINP-c)[2], is a part of

[2] G. Engel et al., Nucl. Instrum. and Meth. in Phys. Res. A **652**, 462 (2011).

the ASICs pool to be used for experiments at RIKEN. Since the commissioning and initial testing, the system has been used for several test beam times for the silicon detector development at the TAMU Cyclotron Institute and at the Heavy Ion Medical Accelerator in Chiba (HIMAC) facility in Chiba, Japan. One of the early test experiments conducted at the TAMU Cyclotron Institute was a study of proton decay of excited states of ^{12}N and ^{13}O. The results of this experiment yielded: a) an improved mass for the proton-unbound nucleus ^{12}O, b) identification of its T=2 analog state in ^{12}N, completing the quintet and allowing for more extensive testing of the validity of the Isobaric Multiplet Mass Equation (IMME), c) a new measurement of the second excited state of ^{12}N, a state contributing to the resonance contribution of the $^{11}C(p,\gamma)^{12}N$ step of the rapid p/alpha (rap) process and d) finding of a few (unbound) states in ^{13}O at excitation energies significantly lower than the bound analogs in the mirror nucleus ^{13}B. These results were published in two articles in which the full discussion can be found[3].

In addition, the ASICs system at TAMU has become an integral part for the experiments conducted with the Forward Array Using Silicon Technology (FAUST), used on its own, or in combination with the Quadrupole Triplet Spectrometer (QTS) at the TAMU Cyclotron Institute.

Actual accomplishments, (b):

The whole SAMURAI collaboration consists of several smaller experimental collaborations utilizing the spectrometer. So far the priority at RIKEN has focused on running neutron-rich rare isotope beams, meaning that SAMURAI has been equipped and occupied for the experiments focused on these beams. This has limited the access and prevented physical assembly of any setup for the HI-p collaboration. However, our collaboration has all the necessary components available and appropriate preparation time allocated when the experimental campaign will be scheduled in the future. Below is an itemized listing of the main activities under this award related to completing this task.

1. We have tested properties of single-sided (SSD) and double-sided (DSSSD) Si microstrip detectors to determine the optimal detector type for the silicon array. Detailed simulations of the full SAMURAI setup, including the Si-array and the hodoscopes after the spectrometer, indicate the need for two layers of detectors forming two co-ordinate planes (X,Y and U,V) from which the trajectories of the breakup products can be reconstructed in coincidence with the final momentum measurement with the hodoscopes following the magnetic spectrometer. Depending on the physics case, the detector thickness can be either 300 or 500 μm. The required detector size will be about 10 cm across with strip pitch under 1 mm wide. An additional, thick (1 mm) annular Si-strip detector with a hole in the middle may be required to enhance proton detection

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[3] M. F. Jager et al., Phys. Rev. C **86**, 011304(R) (2012).
L.G. Sobotka et al., Phys. Rev. C **87**, 054329 (2013).

efficiency for some cases. However, this development will be beyond the scope of this award.

Two in-beam test experiments were conducted at the HIMAC facility in November 2012 and in February 2015. In these tests several beams ranging from 150 MeV/u protons to 400 MeV/u ^{84}Kr were used, simulating typical expected conditions in the experiments at RIKEN. Furthermore, we have studied TTT2 type detectors of different thicknesses with 50 MeV/u protons at the TAMU Cyclotron Institute. In these tests following beams were used:

- ^{12}C at 400 MeV/u for setting up and checking the system
- ^{56}Fe at 400 MeV/u to produce a cocktail of secondary beams with A/Z = 2 to check linearity and response of the system with wide range of energy deposits. This provided also the energy calibration (access to external sources was limited to a single ^{241}Am source)
- ^{1}H at 150 MeV/u and 230 MeV/u to see if system can detect protons with high energy
- ^{40}Ar at 290 MeV/u to determine effects from delta rays
- ^{84}Kr at 400 MeV/u to determine effects from delta rays and to see responses from ions closer to A = 100 region at this energy range.
- ^{132}Xe at 400 MeV/u to determine linearity up to 1 GeV total energy deposits.
- ^{1}H at 50 MeV/u to test energy deposits in different detector thicknesses and carefully study the electronics thresholds.

The SSD was a 300 μm thick GLAST type (Hamamatsu) detector having active area of 89.5 × 89.5 mm^2 consisting of 128 strips on one side with pitch of 684 μm. In the first test only a single layer of GLAST detectors was installed. For the second test Hamamatsu provided a detector where two SSDs were mounted on the same PCB in close proximity, in order to provide the functionality of a DSSSD detector. Due to a limited amount of external preamplifiers available, this functionality was not tested. The DSSSD was a TTT2 type (Micron Semiconductor Ltd., MSL) with active area of 100.42 × 100.42 mm^2 and 128 + 128 strips on opposite sides with pitch 760 μm. The TTT2 detectors were available with thickness of 300 and 500 μm though the latter has been tested only at TAMU. In all experiments, the detectors were instrumented with two full systems of HINP-c chips. The TTT2 detectors were instrumented with the internal preamplifiers on the HINP-c, while the GLAST detectors were using limited amount of prototypes (32 channels total) of a dual gain charge-sensitive preamplifier (DGCSP) developed by the group in RIKEN and read with the HINP-c. The first iteration of the DGCSP was used in 2012, and based on the results a new version was tested in 2015.

The energy response of a 300 μm TTT2 to the A/Z = 2 cocktail beam at 400 MeV/u is illustrated in Fig. 1. In this case the internal CSA of the HINP-c with 70 MeV full scale was used and thus the spectrum is cut at higher energy. The measured energies agree with expected energy deposits for each species and system to be linear throughout the whole range of observed particles from

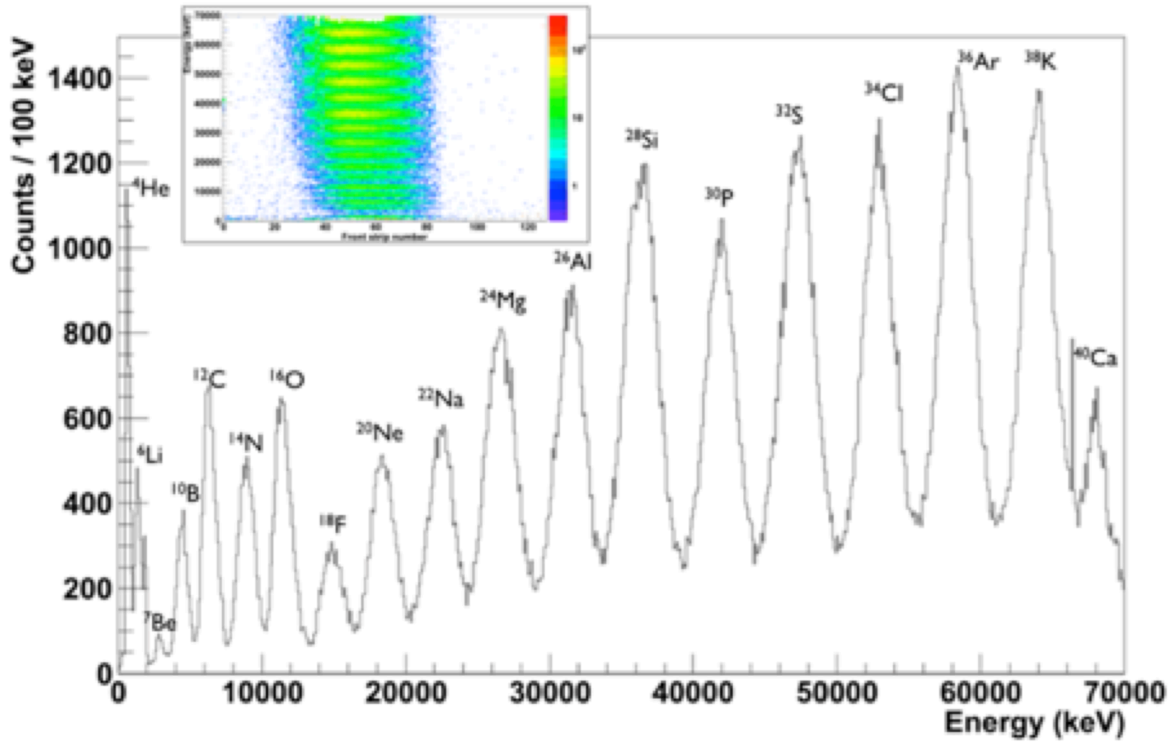

Figure 1. *TTT2 energy response with the A/Z = 2 cocktail beam at 400 MeV/u. The inset shows the energy deposit versus the strip number on front side of the detector.*

about 700 keV (^{4}He) to nearly 70 MeV (^{40}Ca). The external RIKEN DGCSP with two simultaneous gain stages yielded a linear response up to about 300 MeV deposits in the case of the ^{84}Kr cocktail beam.

A comparison of observed cross-talk effects in both TTT2 and GLAST with the same beam are shown in Fig. 2. In this case differences arise most likely from the difference in the detector electrode structure and the two different readout schemes used. It is worth noting that the TTT2 was located about 30 cm downstream from the GLAST thus possibly was exposed to δ-electrons. Unfortunately beam time constraints did not allow studying the opposite geometry for comparison.

In the 2012 experiment at HIMAC, the detection thresholds were mostly too high (primarily due to noise conditions) that reliable identification of the high-energy protons could not be achieved. Also, the DGCSP high gain part was found to have too small gain and this was modified for the second test run in 2015.

The panel on the left in Fig. 3 shows the best candidates as observed with TTT2. Notably these are only a very small fraction of the total beam exposure. In addition to lowering the detection thresholds, proton detection can be improved by increasing the detector thickness and thus the

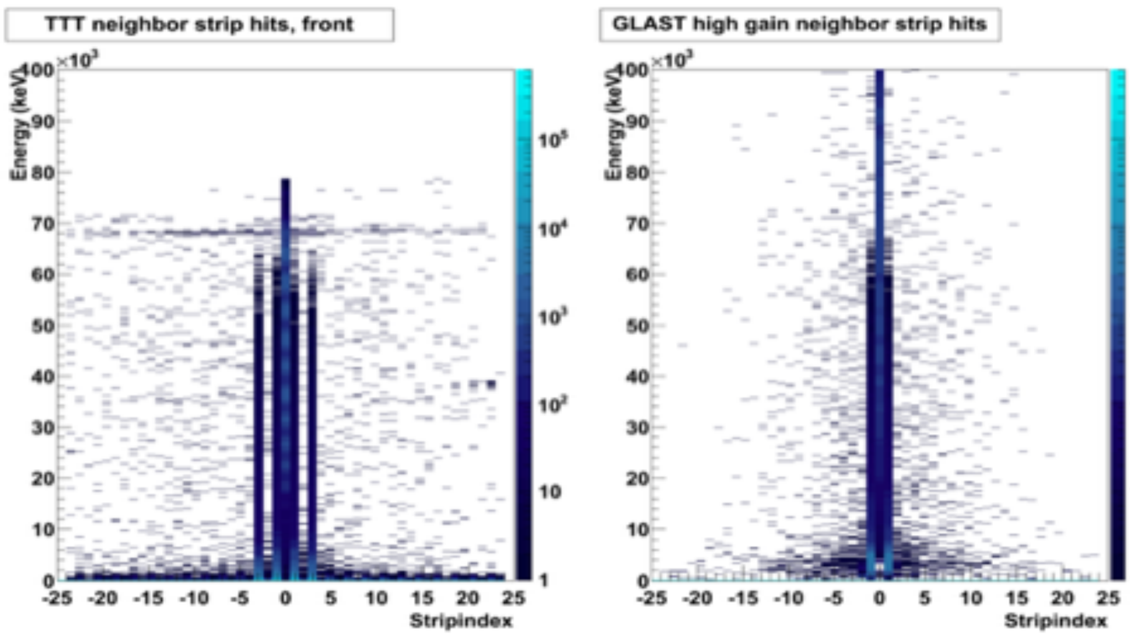

Figure 2. *Cross talk effects in TTT2 (left) and GLAST (right) from A/Z = 2 cocktail beam at 400 MeV/u. Strip index 0 indicates highest energy observed in an event with closest 25 strips on either side of such event displayed.*

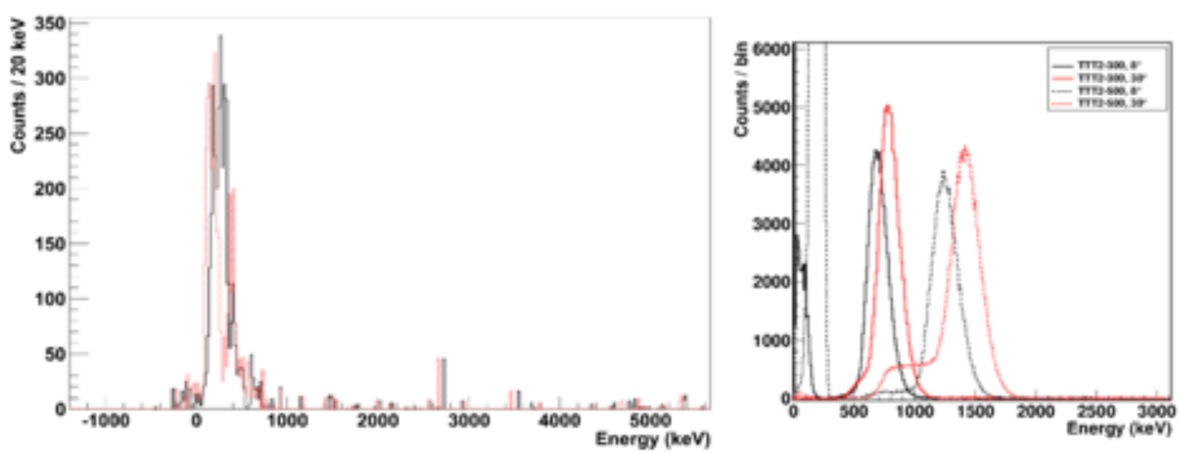

Figure 3. *On the left, TTT2 response to 150 MeV/u protons at HIMAC in 2012 (front strips in black and back in red). On the right, response to 50 MeV/u protons at TAMU with different detector thicknesses and angles.*

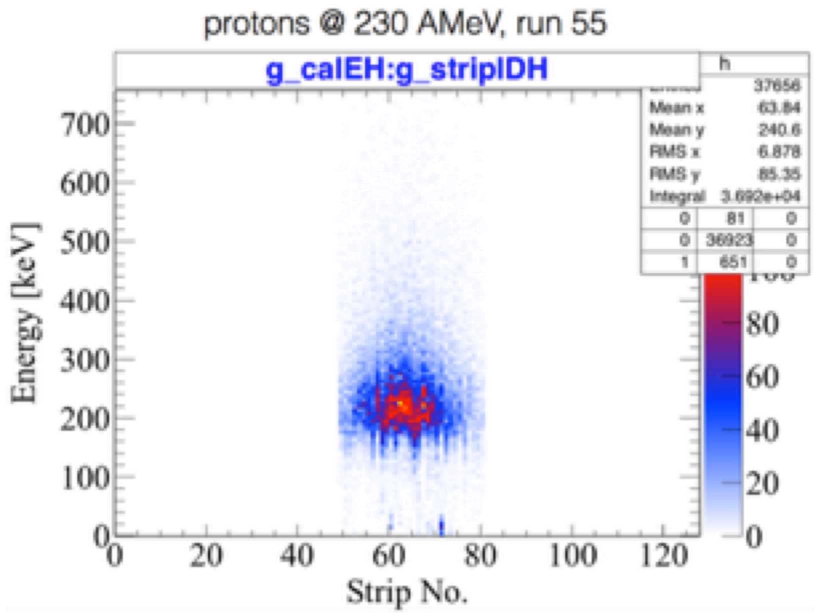

Figure 4. *GLAST response to 230 MeV/u protons at HIMAC in 2015 with the improved RIKEN DGCSP external preamplifier read with the HINP-c chips.*

energy deposit as illustrated with 50 MeV protons as shown on the right panel of Fig. 3. However the energy deposit of heavy ions increases in a similar fashion, which may end up limiting the heaviest case that can be studied due to saturation of the amplifiers. During the 50 MeV proton run, the noise conditions were carefully controlled and the thresholds were pushed at best to about 200 keV, as illustrated in the right panel of Fig. 3. The performance of the improved RIKEN DGCSP, tested in 2015 is shown in Fig. 4., illustrating the capability of detecting 230 MeV/u protons. The low gain branch of the DGCSP was shown to be able to measure events up to 1 GeV energy deposits in silicon.

2. A group from the ATOMKI institute in Debrecen, Hungary, part of the SAMURAI HI-p collaboration, has designed and manufactured a vacuum chamber and mechanical supports to house the silicon-detector array between the target and the SAMURAI spectrometer. This chamber was used in the test experiment at HIMAC in February 2015.

3. The actual configuration of the Si-array detectors (mainly distance from target) will be dictated by the scheduling of the upgrade of the gamma-detector array around the target: The present configuration is based on use of the DALI2 NaI array, but the improved CATANA array may be housed around the target by the time our experimental campaign will be scheduled.

4. We have a working data acquisition system with 512 channel high-density readout electronics

(based on the initial HINP-c chip) available at TAMU, WU, LSU, and RIKEN. These are available for experiments at SAMURAI, totaling up to 2048 channels, which is sufficient to instrument the experiments under consideration in case external preamplifiers are used.

5. The simplified (block diagram) schematics of the Silicon-Strip processing chip (HINP-d) produced by this grant is shown below. By this technology we sought to both extend the linear range and reduce the triggering threshold over existing technologies. Both of these principal objectives were met.

The range of the linear side was extended by using dual active shapers with a gain difference of a factor of 4, Fig. 5, top. Lower thresholds are achieved by the addition of a x10 amplifier before the leading-edge comparator, Fig. 5 bottom. We had 160 of these chips (each 16 ch) fabricated. We have tested about 60 chips in a test rig, made a prototype system of 192 channels and used this system in a test experiment at TAMU Cyclotron Institute. An itemized list of the results of the testing and initial deployment follows.

1. There is a logical error on the chip that requires a slower than planned download procedure to circumnavigate. The procedure took us a month to develop but there are no serious repercussions from this error.
2. About 75 % of the chips passed all tests in the test rig. At present we have not figured out what the failures are due to. We suspect some of the failures are due to operator error, likely chip misplacement in the rig. From past experience, we expect that about 15% of produced ASICs are unsuitable for ultimate use.
3. There is a pulser cross coupling from the pulser input to channel 7. This only affects pulser data as the pulser input is normally open when taking data.
4. The fully differential (chip to ADC) linear signals have a negative offset of about 500 keV (on the high-gain branch, i.e. out of 100 MeV) on negative polarity. This required a change in the chip board (CB) to bleed in a small charge. This change was made after the TAMU test. It has been tested and is now in the production chip boards.
5. The dual-gain operation works almost exactly as simulated. A pulser ramp is shown for a high-gain channel in Fig. 6. The one exception is that *some* channels have a slight non-linearity starting at about half of the scale. At present we do not understand this channel-to-channel variation. However, this variation is easily calibrated.
6. The chip (when attached to Si) can trigger down to between 200 and 250 keV on both polarities. (The linear range on negative polarity only recently recovered, down to the trigger point, with the redesigned CB mentioned above.)

A 512-channel system based on the new HINP-d chip is now in production. An experiment was done with HINP-d at the TAMU Cyclotron Institute in August 2015. From this experiment a science paper can be expected in 2016. Also, in 2016, the technical paper describing the HINP-d chip will be submitted for publication.

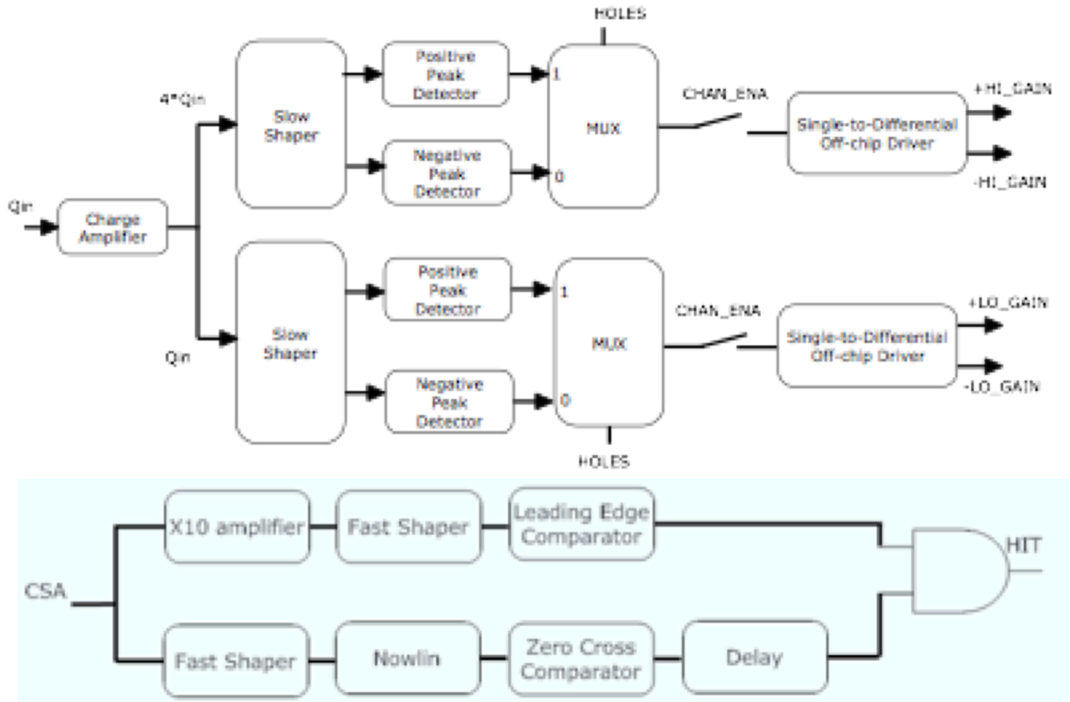

Figure 5*: Schematics of the dual-gain Si-strip signal processing chip. The nominal full ranges of the two active ranges are 100 and 400 MeV. The significant changes relative to our prior chip are a different design of the charge amplifier, the dual active shapers, and a 10x amplifier in the logic branch. This chip cannot process external charge amplifiers (CSA's)*

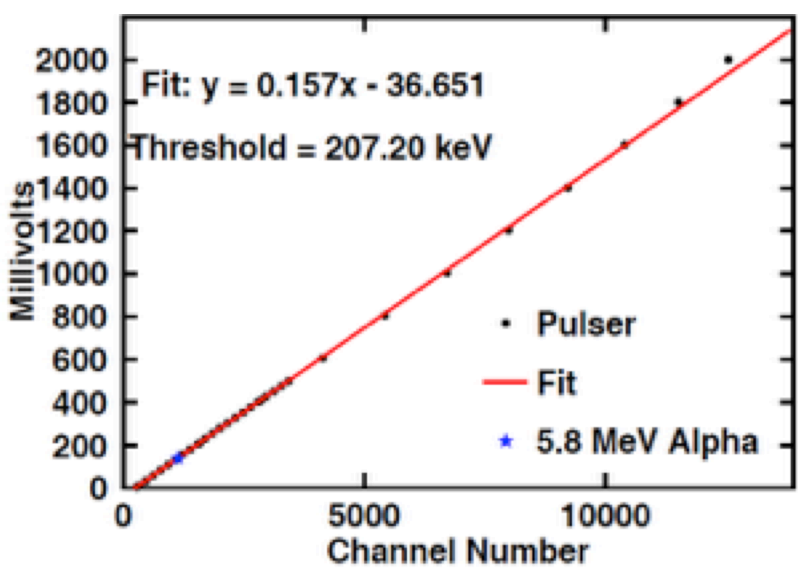

Figure 6*: Pulser and linearity test of the high-gain channel of the dual-range chip. Not all channels are this linear. The linear fit is on the dense data at low pulse height.*

Actual accomplishments, (c):
A full 512 channel system based on the initial chip design (HINP-c) was delivered to RIKEN in 2012. Since then it has been integrated into the RIBF data acquisition system (RIBFDAQ) for the data collection side. It is controlled through an installation of the NSCL DAQ which is in use in other facilities using the HINP chips. In the future also the control side will be integrated into the RIBFDAQ. This is done based on the experiences gained from the integration of the system into the TAMU data acquisition system (CycApps), which presently can handle both the control and the readout of the TAMU system. The RIKEN ASICs system has been tested in online conditions in combination with the pooled ASICs system from TAMU (experiments in item (b)). In addition to the actual chipboards and the associated motherboard, all necessary components to run and diagnose a multi-motherboard system were delivered. RIKEN has not acquired a full system with their own funding, but the collaboration has enough systems that can be pooled together for an experimental campaign.

4. Summary of products developed under the award

4.1. List of publications

M. F. Jager, R. J. Charity, J. M. Elson, J. Manfredi, M. H. Mahzoon, L. G. Sobotka, M. McCleskey, R. G. Pizzone, B. T. Roeder, A. Spiridon, E. Simmons, L. Trache, and M. Kurokawa, *"Two-proton decay of ^{12}O and its isobaric analog state in ^{12}N"*, Phys. Rev. C **86**, 011304(R) (2012), DOI:10.1103/PhysRevC.86.011304

L. G. Sobotka, W. W. Buhro, R. J. Charity, J. M. Elson, M. F. Jager, J. Manfredi, M. H. Mahzoon, A. M. Mukhamedzhanov, V. Eremenko, M. McCleskey, R. G. Pizzone, B. T. Roeder, A. Spiridon, E. Simmons, L. Trache, M. Kurokawa, and P. Navrátil, *"Proton decay of excited states in ^{12}N and ^{13}O and the astrophysical $^{11}C(p,\gamma)^{12}N$ reaction rate"*, Phys. Rev. C **87**, 054329 (2013), DOI:10.1103/PhysRevC.87.054329

M. Karakoc, A. Banu, C. A. Bertulani, L. Trache, *"Coulomb distortion and medium corrections in nucleon-removal reactions"*, Phys. Rev. C **87**, 024607 (2013), DOI:10.1103/PhysRevC.87.024607

M. Karakoc and C. A. Bertulani, J. Phys. Conf. Ser. **420**, 012074 (2013), DOI:10.1088/1742-6596/420/1/012074

B. Chen, F. Sammarruca and C.A. Bertulani, *"Microscopic in-medium nucleon-nucleon cross sections with improved Pauli blocking effects"*, Phys. Rev. C **87**, 054616 (2013), DOI:10.1103/PhysRevC.87.054616

A. Saastamoinen, H. Baba, J. C. Blackmon, J. Elson, M. Kurokawa, M. McCleskey, H. Otsu, B. C. Rasco, B. T. Roeder, L. G. Sobotka, L. Trache, R. E. Tribble, K. Yoneda, J. Zenihiro, *"Development of a Position Sensitive Microstrip Detector System and its Readout Electronics Using ASICs Technologies for SAMURAI"*, JPS Conf. Proc. **6**, 030131 (2015), DOI:10.7566/JPSCP.6.030131.

V. Panin, K. Yoneda, M. Kurokawa, J. Blackmon, Z. Elekes, D. Kim, T. Motobayashi, H. Otsu, B. C. Rasco, A. Saastamoinen, L. Sobotka, L. Trache, T. Uesaka, *"New generation of experiments for the investigation of stellar (p,γ) reaction rates using SAMURAI"*, submitted to Nucl. Phys. Rev.

D. Hoff et al.,*"Spin alignment of excited ^{7}Li projectiles facilitated by spin-flipping the molecular structure of ^{9}Be targets,"*, manuscript in preparation.

G. L.Engel, S.Thota, R. Singamaneneni, J. M. Elson, L. G. Sobotka, K. Brown, and R. J. Charity, *"HINP16Dual; A pulse processing Circuit with dual active shapers for use with Si-strip detectors"*, manuscript in preparation.

4.2. Collaborations fostered

The research and development work on both Si detectors and electronics under this grant has been crucial part of the SAMURAI HI-p collaboration. The full international collaboration consists of researchers from Japan, Hungary, Romania, Germany, Spain, Italy, China, South Korea, and our groups from TAMU, TAMU-Commerce, WU, and LSU.

4.3. Technologies and techniques

A new Silicon-Strip processing chip (HINP-d) was produced by this grant. By this technology we extend the linear range and reduce the triggering threshold over existing technologies (HINP-c).

This grant funded a repackaging (from Micron SemiConductor Ltd) of the preexisting TTT2 Si strip detector design into a PCB framing system that greatly simplifies its use as an in-beam tracking detector (mechanical mounting, cabling). We call this packaging the TTT-Diamond, see Fig. 7. for illustration of the detector and the mounting scheme.

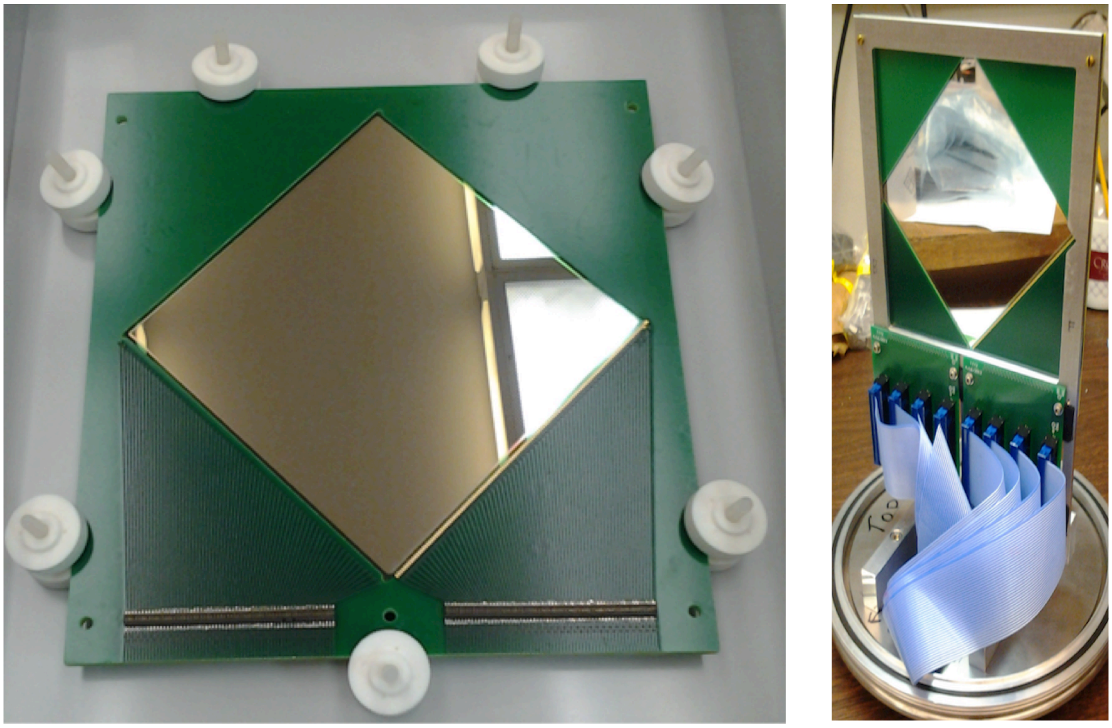

***Figure** 7: Left panel: A photo of the Micron Semiconductor Ltd. TTT2 type Si strip detector with the new PCB packaging funded by this award. Right panel: The detector on a mounting frame, attached to a standard vacuum flange. This configuration allows easy handling of detectors and minimizes the required cabling length. The box housing HINP motherboard and chips can be attached directly on the opposite side of the flange.*