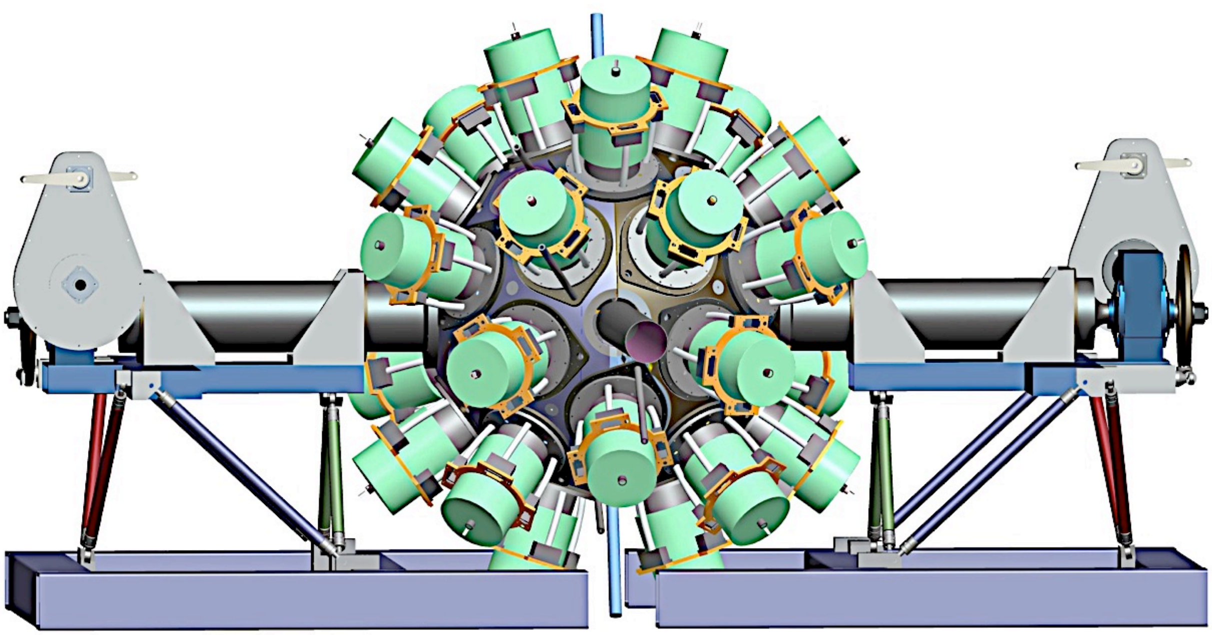
THE GAMMA-RAY ENERGY TRACKING ARRAY

GRETA



Whitepaper submitted to the Nuclear Astrophysics and Low Energy Nuclear Physics Town Meeting August 2014

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This document was prepared by the GRETINA Users Executive Committee, the GRETINA Advisory Committee, and Physics Working Group as input to the 2014 Nuclear Astrophysics and Low Energy Nuclear Physics Town Meeting (Texas A&M University, August 21-23, 2014)

A workshop held at Argonne National Laboratory (June 10-11, 2014) provided input to the science case and technical performance described in this whitepaper.

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CONTENTS

1. Introduction and Executive Summary

First discussed in the 1996 NSAC Long Range Plan (LRP) and then recommended as a major new initiative in both the 2002 and 2007 LRPs, the 4π γ-ray tracking array GRETA (Gamma-Ray Energy Tracking Array) will be a powerful new instrument needed to accomplish a broad range of experiments that will play an essential role in addressing the intellectual challenges of our field of low-energy nuclear science. GRETA marks a major advance in the development of γ-ray detector systems and can provide order-of-magnitude gains in sensitivity compared to existing arrays. It uses highly segmented hyper-pure germanium crystals together with advanced signal processing techniques to determine the location and energy of individual γ-ray interactions, which are then combined to reconstruct the incident γ-ray in a process called tracking.

> *"The detection of γ-ray emissions from excited nuclei plays a vital and ubiquitous role in nuclear science. The physics justification for a 4π tracking array is extremely compelling, spanning a wide range of fundamental questions in nuclear structure, nuclear astrophysics, and weak interactions."* - 2002 NSAC Long Range Plan

The 2012 National Research Council (NRC) decadal survey on nuclear physics posed four overarching questions that frame the intellectual challenges of the field.

- How does subatomic matter organize itself and what phenomena emerge?
- How did visible matter come into being and how does it evolve?
- Are the fundamental interactions that are basic to the structure of matter fully understood?
- How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

The Facility for Rare Isotope Beams, FRIB, will provide access to thousands of nuclei and the data necessary to meet these intellectual challenges. Experiments on rare isotopes will guide theoretical developments and provide the basis for a comprehensive and predictive theory of nuclei. GRETA will provide the unique combination of high efficiency, good peak-to-background ratio, and excellent energy and position resolution needed to fully utilize and maximize the physics opportunities at FRIB, using both fast-fragmentation and reaccelerated beams. It will also add significant new capabilities to existing facilities, such as the premier stable-beam and unique CARIBU facilities at ATLAS (ANL).

> "*Construction of GRETA should begin immediately upon the successful completion of the GRETINA array*" - 2007 NSAC Long Range Plan

The NRC overarching questions can also be stated in the form of "benchmark scientific programs". In 2007, the NSAC Rare-Isotope Task Force introduced 17 such benchmark programs to help establish and evaluate capabilities for a future rare-isotope beam facility. These benchmarks characterize on a more detailed level the physics that can be pursued at FRIB and, more generally, the goals of our field. They are listed in Figure 1 and are mapped to the challenges and opportunities identified in the 2007 NSAC LRP and the NRC's Rare Isotope Science Assessment Committee (RISAC) report from 2007, as well as the recent NRC decadal survey. The majority of them, and hence a large fraction of the FRIB scientific program, will rely on high-resolution, high-efficiency, in-flight γ–ray detection. GRETA will provide this capability and is essential to meet the scientific goals at FRIB. The FRIB Science Advisory Committee (SAC) has consistently identified and endorsed GRETA as a top priority for instrumentation crucial to the success of FRIB.

> *"The SAC viewed the science addressed in your submission as having the highest scientific priority and this was communicated to the FRIB Laboratory Director. […] The SAC reiterates the support for GRETA in the LRP and looks forward to the initiation of GRETA construction following the successful campaign of GRETINA at the NSCL.*." - 2011 FRIB SAC Report

The technology and the scientific impact of a γ–ray tracking array has already been demonstrated. Between 2003 and 2011, the US low-energy nuclear physics community constructed GRETINA, a γ–ray tracking array covering approximately ¼ of 4π and employing the same segmented detector and signal decomposition

Intellectual challenges from NRC Decadal Study

How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interactions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?

Overarching questions from NSAC Long Range Plan

What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the universe?	What are new applications of isotopes to meet the needs of society?

Science drivers (thrusts) from NRC RISAC

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes

Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research

1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 13. Limits of stability 14. Weakly bound nuclei 15. Mass surface	6. Equation of State (EOS) 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment 15. Mass surface 17. Weak interactions	10. Medical 11. Stewardship

Figure 1: The 17 benchmark programs introduced by the NSAC Rare-Isotope beam Task Force (2007) listed together with the challenges and questions identified in the 2007 NSAC Long Range Plan and NRC 2012 decadal study. (Adapted from the FRIB Users Organization document submitted to the 2012 NSAC LRP Implementation Subcommittee.)

technology as GRETA. In the first science campaign carried out at NSCL (Summer 2012 – Summer 2013), GRETINA was used to address a broad range of physics including studies of shell evolution and weak nucleon binding, determining excitation energies and spectroscopic factors of astrophysical relevance, and benchmarking the treatment of weak interactions in modern shell-model Hamiltonians. These experiments are beginning to address many of the FRIB benchmarks mentioned above and the challenges posed in the recent NRC study. GRETINA is currently operating at ATLAS/ANL and first experiments using reaccelerated radioactive ions from CARIBU are underway.

GRETINA's first physics campaign at NSCL confirms the unique capabilities of a γ-ray tracking array to increase the sensitivity of experiments at a rare-isotope facility (see Appendix II). GRETA will provide order-of-magnitude gains in sensitivity and will play a central role in addressing the intellectual challenges of our field. The GRETA science program described in the following sections is organized around the NRC challenges and questions (Figure 1), and the selected examples were chosen to illustrate GRETA's broad impact in many of the benchmark experimental programs.

The 2007 NSAC LRP recommended: "*Construction of GRETA should begin immediately upon the successful completion of the GRETINA array*". This milestone has been met and a plan has been developed to complete GRETA for "day one" experiments at FRIB. ***We therefore urge that the 2007 NSAC LRP recommendation be fulfilled and that the 4π GRETA be completed in a timely manner.***

2.1 How does subatomic matter organize itself and what phenomena emerge?

Evolution of shell structure far from stability [Benchmarks 1, 15]

The shell structure of the atomic nucleus near stability is well established. The average nuclear potential is well parameterized and phenomenological frameworks describe many experimental facts. As one moves away from stability, however, decreasing nucleon binding energy and the large proton-to-neutron asymmetry lead to modifications in the nuclear potential and the spin-isospin component of the nucleon-nucleon interaction drives changes to the single-particle energies. Together with the increased role of many-body correlations, these changes to the single-particle structure lead to the disappearance of established shell closures and the appearance of new ones. Such evolution has been experimentally verified already at current facilities with present-day detectors, for example the disappearance of the $N=20$ shell gap leading to the island-of-inversion near ^{32}Mg [War90], or the new shell gaps at $N=32$ and $N=34$ in the Ca isotopes [Huc85, Gad06, Ste13].

Beyond these changes to shell structure, which can be at least partially captured within phenomenological models, theoretical descriptions of the atomic nucleus are pushing towards more microscopic and even ab-initio approaches. Already in light systems, such as the C and O isotopes where such calculations have been tractable for several years, microscopic calculations have shown the need to include forces beyond two-body interactions, with an accurate description of basic nuclear properties such as binding energies or masses requiring inclusion of three-nucleon (3N) interactions [Ham13]. Such descriptions are now available up to the Ca isotopic chain [Hol12]. Future experimental work in nuclear structure will have the critical task of not only tracking modifications to single-particle structure but also providing the spectroscopic data required to validate the predictions of such microscopic calculations to fully understand and quantify the role of higher-order interactions. Not only is such exploration of structural evolution critical for the development of a predictive model of atomic nuclei, but the driving forces and many-body correlations at play can have a profound impact on the number of bound isotopes that exist for a given element.

Sensitive in-beam measurements and the extension of scientific reach to the most exotic nuclei will depend directly on the resolving power of the γ-ray spectrometer used. GRETA will have superior resolving power for fast-beam experiments compared to any other γ-ray detector. The resolution and spectral quality of a tracking detector has been shown with the outstanding performance of GRETINA at NSCL; the completion of GRETINA to GRETA at FRIB will provide unparalleled sensitivity to answer the most pressing questions in nuclear structure physics in terms of the evolution of single-particle structure and nuclear forces with far reaching consequences for the limits of existence on the nuclear chart.

Rare isotopes not quite as far toward the driplines will be available for the first time at intensities that allow for unprecedented detailed spectroscopic studies. This will include, for example, spin determination from γ-ray angular distributions, a powerful and model-independent approach that is applicable for a variety of reactions and in different energy regimes. GRETA's 4π angular coverage paired with its position resolution will significantly extend the reach of this technique. The sensitivity of GRETA as a polarimeter will provide complementary information on the multipolarity of observed transitions. The precise knowledge of spin values is critical in tracking the evolution of nuclear structure across the nuclear chart.

A unique observable that quantifies the interplay of collective and single-particle degrees of freedom is the gyromagnetic ratio or g-factor. Different approaches to determine g-factors in exotic nuclei have been used for rare-isotope beams: HVTF (High-Velocity Transient Field) [Stu06] and RIV (Recoil in Vacuum) [Stu13], both involve the precise measurement of angular distributions, which will benefit tremendously from the angular coverage and position sensitivity of GRETA. Other important observables are excited-state lifetimes. As demonstrated by precision measurements with GRETINA at NSCL [Iwa14], the mm-scale position resolution and high detection efficiency greatly extends the reach of the approach, which relies on the clean separation of 2 or more peaks in a γ-ray spectrum.

The combination of pioneering in-beam γ-ray spectroscopy with fast beams from FRIB, and the detailed spectroscopy possible closer to stability with GRETA at FRIB and ATLAS/ANL will be important steps towards realizing a predictive model of the atomic nucleus, valid also in the exotic regime.

Calcium isotopes – a prototypical example of structural evolution [Benchmark 1]

The proton-closed-shell Ca isotopes with $Z=20$ present a unique laboratory to study the evolution of structure as a function of proton-to-neutron ratio. Within this single isotopic chain are some of the clearest examples to date of changing single-particle energies as a result of the spin-isospin component of the nucleon-nucleon interaction, namely the appearance of new sub-shell gaps at $N=32$ and 34. Recent microscopic calculations [Hag12, Hol12, Hol14] have highlighted the Ca isotopes as a region in which to test the role of three-nucleon (3N) forces in providing a more complete microscopic description of the atomic nucleus.

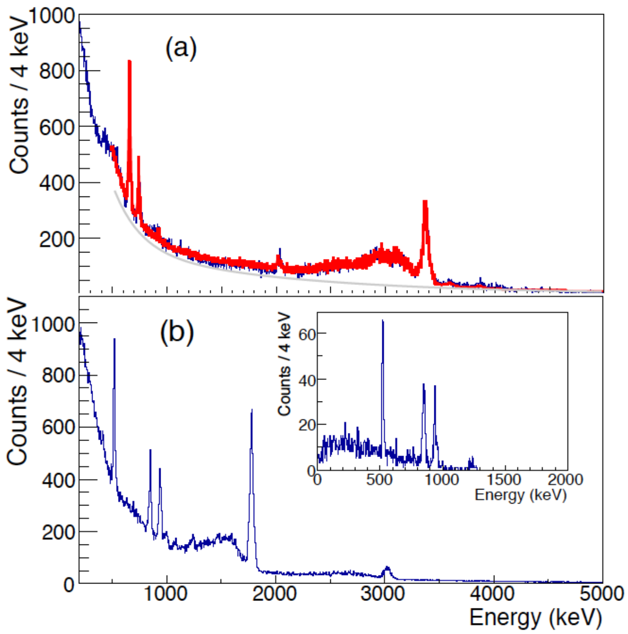

Figure 2.1.1: (a) Experimental GRETINA spectrum for neutron knockout from ^{50}Ca into ^{49}Ca (blue line), fit with GEANT4 simulation (red line) and a smooth background (gray line). (b) Simulated GRETA spectrum for neutron knockout from ^{57}Ca into ^{56}Ca at FRIB, based on a theoretical level scheme [Hol14]. Inset shows simulated γγ coincidence spectrum for 2^+ to 0^+ transition at 1.8 MeV. The efficiency for γγ coincidences will allow determination of unknown level schemes for such detailed spectroscopic studies.

Calculations including 3N forces, the only microscopic calculations to properly reproduce the $N=28$ shell closure in the Ca isotopes, have been validated by recent mass measurements extending to ^{54}Ca [Wie13], but make more subtle predictions regarding the structure of the Ca isotopes in terms of single-particle occupancies. A recent experiment performed with GRETINA at NSCL has made a first measurement to stringently test these predictions, using γ-ray decays following neutron knockout to study the occupancy of the neutron single-particle states. The demands of the complex level schemes and closely spaced γ-ray transitions required the resolution of GRETINA, but with the limitations of NSCL's beam intensity and GRETINA's γ-ray detection efficiency, the measurement was limited in reach to ^{50}Ca. GRETA at FRIB will allow detailed spectroscopy at least as far as ^{57}Ca. The resolving power in both γ singles and γγ coincidence data (Figure 2.1.1) with fast beams will allow confirmation of excitation level schemes, and quantification of neutron single-particle occupancies, well into the region where alterations to structure as a result of 3N forces are expected to become significant [Hol14] and where such data can provide a stringent test of nuclear forces, and constrain predictions for the location of the neutron dripline.

The structure of the neutron-rich Ca isotopes in this region also determines the location of the neutron dripline, one of the most fundamental benchmarks for energy density functional theories. The key nuclei ^{60,61}Ca have not yet been observed. The position of the neutron dripline in Ca is thought to depend sensitively on both the location of the neutron $1g_{9/2}$ orbital, which nominally starts to be filled at $N=40$ in ^{60}Ca, and a va riety of correlations and many-body effects [Men02, Len10]. Calculations with realistic two- and three-body forces [Hag12, Hol12] predict the neutron dripline to be located around ^{60}Ca, while many mean-field and density-functional calculations have the Ca isotopes (at least those with even A) bound out to $A=68–76$ [Erl12], often with a fine interplay of single-particle and many-body considerations deciding the fate of the most neutron-rich calcium isotopes that can exist [For13]. Undoubtedly, information on the structure of neutron-rich nuclei around ^{60}Ca [Gad14] is critical to benchmark modern calculations, which differ in their prediction of the location of the Ca dripline by more than 10 nucleons. Just as the chain of oxygen isotopes, this situation will repeat for other neutron-rich regions of the nuclear chart, accessible at the right level of detail with the luminosity and sensitivity afforded by fast beams, thick reaction targets, and in-beam spectroscopy with GRETA at FRIB. The pioneering spectroscopy of the key nucleus ^{60}Ca will be possible with GRETA at FRIB with a one-proton knockout reaction from ^{61}Sc projectiles. Figure 2.1.2 shows the simulation of the γ-ray spectrum of ^{60}Ca, first 2^+ energy taken from the

predictions by [Len10], with GRETINA (b) and GRETA (c) for γ-ray detection.

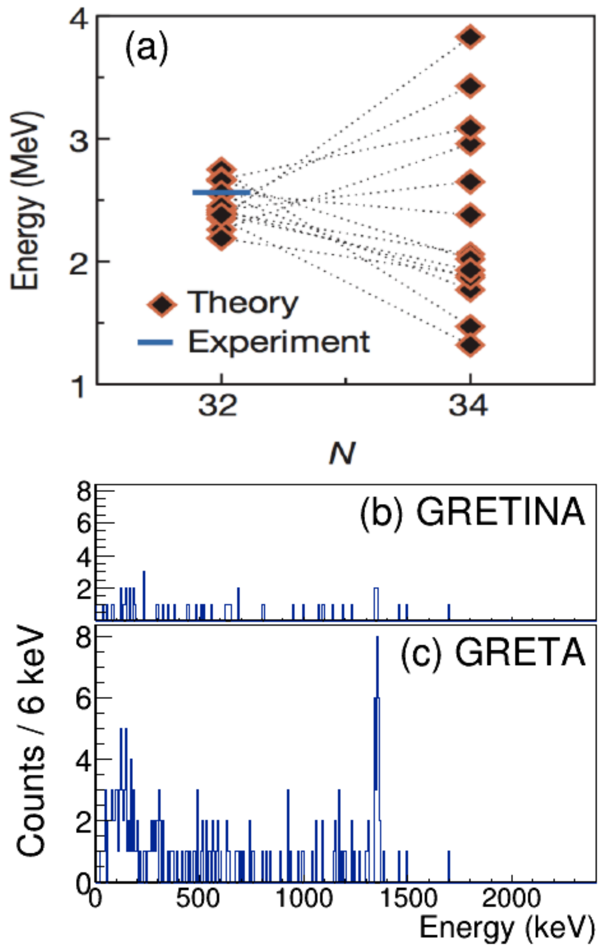

Figure 2.1.2: (a) Calculations for the ^{52,54}Ca 2^+ energy prior to the measurements for ^{54}Ca by [Ste13], illustrating the present difficulty of extrapolating out into the unknown by just 2 neutrons in exotic nuclei (figure adapted from [Ste13]). (b) Simulation for ^{9}Be(^{61}Sc,^{60}Ca+γ) with GRETINA at the proposed high rigidity spectrometer (HRS) at FRIB. (c) Same with GRETA instead of GRETINA, enabling first spectroscopy of ^{60}Ca.

FRIB will provide unparalleled access along the Ca isotopic chain and with GRETA we will be in a position to take full advantage of this access. Answers to the questions of changing single-particle energies out to ^{60}Ca will lie within experimental reach, as will a more direct quantification of the significance of 3N forces to describe nuclei. GRETA will be critical to provide the detection efficiency and energy resolution to study these systems using the techniques of fast-beam physics.

Shape and configuration coexistence across the nuclear chart [Benchmarks 1, 5]

Across the nuclear chart, nuclear shell structure and nuclear shapes are inextricably linked. Near closed shells, where gaps between single-particle orbitals are large, the low-energy structures of nuclei are dominated by single-particle excitations. However, toward mid-shell, where energy gaps between single-particle orbitals are small, collective excitations dominate, and nuclei develop deformation with excitations characteristic of rotational or vibrational systems. One region of recent theoretical and experimental interest in terms of the interplay between shells and shapes are the *N*=28 isotones below Ca. In this region, decreased occupancy of the proton $d_{3/2}$ single-particle orbital results in both a quenching of the *N*=28 shell gap and a narrowing of the spacing between proton orbitals, which leads to the development of quadrupole excitations for both protons and neutrons, and well-developed deformation along *N*=28 [Now09].

Recent spectroscopic work has shown that, at least in the Mg isotopes, deformation in fact extends all the way from the island of inversion near *N*=20 to ^{40}Mg [Doo13, Cra14], which sits at or near to the dripline. Calculations [Now09] that predict ^{40}Mg to be a well-deformed prolate rotor also indicate the last bound neutron orbital to be the low-l $p_{3/2}$ state, leading to the possibility that weak binding effects could play a role. How collective modes develop near the dripline is an open and challenging question. Quantifying the extent of deformation and the underlying single-particle states requires beam intensities that will only be reached at FRIB. Proton and neutron knockout experiments will provide the detailed information to fully map out the changing proton and neutron single-particle energies and occupancies in this region, while relativistic Coulomb excitation and lifetime measurements will provide a quantification of the degree of collectivity. As for the Ca isotopes, and indeed, many other regions of the nuclear chart, these measurements will be feasible only with the resolving power of GRETA. Complex level schemes will need to be understood, requiring the efficiency in γγ coincidence detection afforded by GRETA, while the possibility for spin assignments based on polarization and angular-distribution data supplements the available information.

Closer to stability, near *N=20*, FRIB will provide reaccelerated beams of neutron-rich Si, Mg, Ne and Na isotopes with rates sufficient to perform experiments

aimed at identifying signatures of collective modes, such as rotational bands. Light- and heavy-ion induced transfer, and Coulomb excitation reactions will allow detailed studies of such nuclei, including the odd-mass systems characterized by higher level densities (and thus higher γ-ray multiplicity) than their even-A neighbors. GRETA will be crucial for these measurements, with the resolution to disentangle complex level schemes, the angular coverage to allow for angular correlation measurements, and the polarization sensitivity to allow for multipolarity and spin assignments.

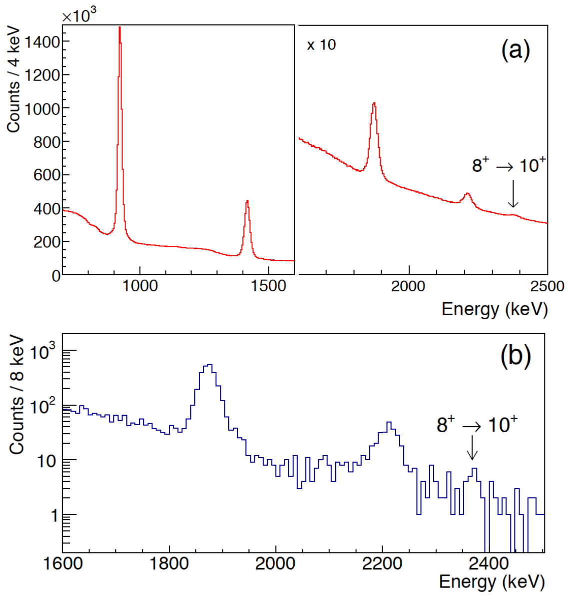

Figure 2.1.3: (a) Simulated ground-state rotational band in ^{32}Mg, based on calculated energy levels [Pov13] and populated in multi-nucleon removal from ^{46}Ar at 197 MeV/u at FRIB using GRETA and the proposed high rigidity spectrometer (HRS). (b) Simulated spectrum gated on the transitions from the 2^+ and 4^+ states in ^{32}Mg, showing identification up to the 10^+ state in ^{32}Mg, a 0.05% branch.

GRETA's resolving power is illustrated Figure 2.1.3 for the simulated case of a rotational cascade in ^{32}Mg produced using a fast-beam multi-nucleon knockout reaction at FRIB. The increased efficiency and energy resolution will be essential to use γγ coincidences (perhaps higher fold in some cases) that are needed to establish that the sequence is indeed a rotational cascade. This powerful and crucial capability is also illustrated in section 2.3 for the case of reaccelerated beams at Coulomb-barrier energies available at CARIBU/ATLAS as well as at NSCL, and in the future at FRIB.

Spin-isospin response of nuclei [Benchmarks 3, 17]

The spin-isospin response of nuclei provides a unique window into single-particle degrees of freedom as well as into bulk properties of the nuclear medium. Measurements of the allowed (Gamow-Teller) spin-isospin response of nuclei uniquely assess the validity of - and suggest improvements to - nuclear structure models up to high excitation energy. In hydrodynamical models of the nucleus, isovector giant resonances are associated with out-of-phase density oscillations of the neutron and proton fluids and have provided information on macroscopic nuclear properties associated with isovector fields.

Charge-exchange reactions are a unique tool to study the spin-isospin response of nuclei. In contrast to β decay, in which only nuclear states in the limited Q-value window are accessible, charge-exchange reactions probe the entire response function, including the giant-resonance region. Gamma-ray tagging in charge-exchange reactions has become an important new experimental tool in recent years, complementing high-resolution particle spectroscopy. A variety of new reaction probes involving the detection of γ rays have been developed to isolate specific spin-isospin excitations in charge-exchange experiments with beams of about 100 MeV/u and above. With rare-isotope beam intensities and γ-ray detection capabilities currently available, the scientific reach of these experiments has been limited: the nuclei studied were light (A<35) and relatively close to stability. With GRETA, the efficiency and quality of these new types of experiments can be vastly improved, and in combination with the availability of intense rare-isotope beams at FRIB, provide exciting opportunities to improve our understanding of the spin-isospin response of nuclei far away from stability.

The (^{7}Li,^{7}Be+γ) reaction in inverse kinematics was used to measure the Gamow-Teller strength distribution in the (n,p) or β^+ direction in unstable isotopes [Zeg10,Meh12] with the goal to probe configuration mixing and shell evolution in neutron-rich nuclei. In these experiments, a 429-keV γ line emitted at rest when ^{7}Be is produced in its $1/2^-$ excited state at 429 keV from the $3/2^-$ ^{7}Li ground state, serves as a clean tag for a spin-transfer (ΔS=1) charge-exchange reaction. The excitation energy of the probed rare isotope is determined by tracing the path of the recoiling excited rare isotope in a magnetic spectrometer, while addi-

tional information is deduced from detecting in-flight decay γ rays emitted from this recoiled nucleus. Although significant successes were achieved, the technique was limited in part by the ability to detect photons with high efficiency and with sufficient angular resolution to perform Doppler reconstruction of the in-flight γ-rays. GRETA will revolutionize these measurements, as both of these issues will be resolved. By placing GRETA around the target station of the planned High-Rigidity Spectrometer (HRS), further improvements can be made by including the detection of neutrons emitted in-flight from the excited rare-isotopes, in particular to reconstruct the Gamow-Teller strength beyond the neutron-decay threshold. Such a development would not only benefit nuclear structure studies, but also be of great importance for testing theoretical models used for estimating electron-capture rates in astrophysical phenomena (see section 2.2).

Equally promising is the use of light rare-isotope beams as novel probes to extract detailed information about specific spin-isospin excitations and giant resonances. For example, the (^{10}C,^{10}B+γ) [Sas12] and (^{10}Be,^{10}B+γ) [Sco14] reactions have been employed to seek unambiguous evidence for the elusive isovector giant monopole resonance [Har01,Yos10,Nik13] (IVGMR). The IVGMR is the isovector partner of the isoscalar giant monopole resonance and can be described macroscopically as an out-of-phase breathing mode of the neutron and proton fluids. A detailed knowledge of its properties will complement information about the equation of state of nuclear matter obtained from the properties of the ISGMR [Har01] and further constrain theoretical models used in, for example, the modeling of neutron skins and neutron stars. Because the IVGMR is not associated with spin transfer (ΔS=0), it is usually impossible to isolate its signature in charge-exchange experiments, since spin-transfer transitions (ΔS=1) strongly dominate. By impinging unstable ^{10}C or ^{10}Be (both have $J^{\pi}=0^+$) beams on stable targets, and gating on γ rays from the 0^+ excited state in ^{10}B (1.022 MeV γ ray from the decay of the 1.74 MeV 0^+ state) that are emitted in flight, a clean ΔS=0 filter can be created. The (^{10}C,^{10}B+γ) experiment [Sas12] suffered from a limited Doppler-reconstructed γ-ray energy resolution, which made it difficult to unambiguously characterize background under the 1.022 MeV γ ray and resulted in relative poor signal-to-noise ratios. The (^{10}Be,^{10}B+γ) experiment [Sco14] resolved these issues by using GRETINA. However, given the limited solid-angle coverage of GRETINA, and the relatively low ^{10}Be beam intensities currently available, the heaviest target that could be studied at NSCL was ^{28}Si.

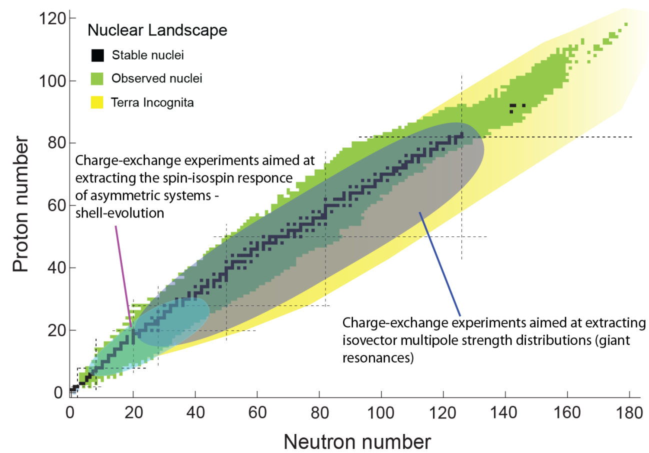

Figure 2.1.4: Charge-exchange experiments in the marked regions will be aimed at extracting the spin-isospin response from rare isotopes with focus on the study of shell evolution and the determination of macroscopic properties of nuclear matter. GRETA's high efficiency and resolution and angular coverage will revolutionize these measurements.

The use of GRETA, in combination with intense rare-isotope beams at FRIB, will provide unprecedented access to details of the IVGMR, for which the only significant information comes from studies that suffered from very significant and poorly-understood backgrounds [Ere86, Iro86, Nak99]. GRETA provides additional opportunities: due to its near 4π solid-angle coverage, high-energy γ rays can be reconstructed by using add-back techniques, which will enable the detection of direct, high-energy decay branches from giant resonances. Moreover, due to the large solid angle coverage, the angular distribution of the emitted γ rays from specific excitations/resonances can be studied to constrain their multipolarities.

At the dripline – physics in the regime of weak binding [Benchmarks 3, 13, 14]

The limits of nuclear existence are defined by the nucleon driplines. They outline the combinations of neutrons and protons that can be made into bound systems. The exotic combinations of neutrons and protons encountered far from the region of β stability can significantly affect nuclear structure. Two effects receiving a great deal of theoretical and experimental interest are

the changes in shell structure, discussed in the previous section, and the physics of weakly-bound nuclei, where valence neutrons may move outside the core for a sizable fraction of the time leading to spatially extended "core-decoupled" wave functions (e.g. halo nuclei). While changes in the shell structure due to the valence nucleon interactions can be described within a shell-model framework based on well-bound states and harmonic-oscillator wave functions, the effects of weak binding and extended radial distributions go beyond such approaches. At some point, in the proximity of the particle continuum, these familiar models and their assumptions will no longer be valid [Dob07].

Halo nuclei serve as a benchmark to study and understand nuclear structure and correlations at the limit of stability [Tan85, Han85, Esb92], providing a sensitive test to validate and guide theories aimed to provide a predictive description of nuclei. The spatial extent of the valence-neutron wave functions can lead to a number of distinct and often unique observables such as large interaction cross sections [Tan85], narrow momentum distribution of fragments produced in neutron knockout reactions [Baz95], and an enhancement in the low-energy (soft) dipole transition strength [Aum13]. The emergence of low-energy ("soft" *E1* and *M1*) collective excitation modes in weakly-bound nuclei arising from the relative motion of the well-bound core and the more loosely bound valence neutrons [Ike88, Sag95, War97] are of specific interest to studies of many-body quantum systems and understanding the role of nuclei in astrophysical environments.

Experimental data characterizing the excitation properties of halo nuclei is, however, limited and available mainly for *E1* modes (i.e. soft-dipole excitations in light nuclei and low-lying *E1* modes in medium and heavy nuclei). Excited-state lifetime or Coulomb excitation measurements provide a sensitive method to characterize the properties of halo systems with respect to both electric and magnetic multipole modes. Coulomb excitation is primarily sensitive to *E1* and *E2* transitions, while excited-state lifetime measurements can be applied to both electric and magnetic transitions. These measurements invariably rely on the detection of γ rays.

Excited-state lifetime measurements performed with GRETINA on the neutron-rich C isotopes $^{17,19}C$ [Whi14] were crucial to confirm the presence of low-lying spin $1/2^+$ halo states close to the neutron threshold, where the *M1* decay mode (a spin-flip between the 0^+ core and the $s_{1/2}$ valence neutron) was found to be strongly hindered. In addition, a deformed halo structure was recently proposed for ^{31}Ne [Nak10] and ^{37}Mg [Kob14]. It is suggested that configuration mixing across the vanishing N=20 shell gap, resulting in nuclear deformation, increases the number of single-particle levels with low-l components. These deformation effects close to threshold may induce the formation of a p-wave (l=1) halo state, which could be accompanied by sizable *M1* and *E2* transition strengths

GRETA at FRIB in the future will enable, for example, sensitive spectroscopic studies of predicted halo nuclei in the Ne-Mg region near the neutron dripline. The large ground-state deformations occurring in neutron-rich Ne and Mg nuclei provide an opportunity to study the interplay between deformation and halo effects [Mis97]. However, the spins and parities of low-lying excited states are unknown in this region, leading to large uncertainties when comparing to theory and interpreting the underlying many-body effects. They can be experimentally constrained or determined by studying the transition strengths connecting the states.

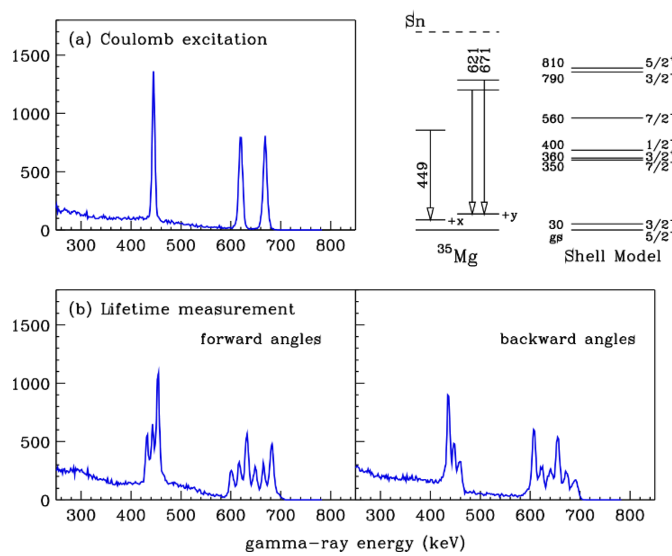

Figure 2.1.5: Simulated spectra of γ-ray transitions in ^{35}Mg obtained with GRETA for (a) Coulomb excitation and (b) lifetime measurements. In (b), three different velocity components are evident for each state. The upper right panel shows the level scheme of ^{35}Mg used in the simulation and a comparison to shell-model calculations.

GRETA will be critical for this program of measurements. The excellent energy resolution (which can only be achieved with a γ-ray tracking detector such as

GRETA) is necessary to carry out Doppler-shift lifetime measurements and resolve the multiple components that occur for each transition (Figure 2.1.5). The high detection efficiency will enable γγ coincidence measurements, needed to control or remove the effects from feeding transitions, which distort the measured level lifetime and lead to large uncertainties.

FRIB will produce dripline nuclei up to *Z=40* and perhaps higher, and provide intensities of rare isotopes sufficient to explore the properties of halos and skins, and to discover new modes of excitation associated with weak binding and the particle continuum. Indeed, FRIB will nearly double the number of such nuclei that can be studied with sufficient detail and extend the reach from *A*=40 to *A*=90. GRETA's unique combination of high efficiency and high resolution will be unmatched and essential to utilize FRIB's capability to study the most exotic nuclei found at or near to the neutron dripline. The sensitivity of GRETA for such studies is illustrated in Figure 2.1.6 for the relativistic Coulomb excitation of ^{40}Mg. Only observed for the first time in 2007 at the NSCL [Bau07], ^{40}Mg is located at the intersection of the *N=28* spherical magic number and the neutron dripline [Cra14].

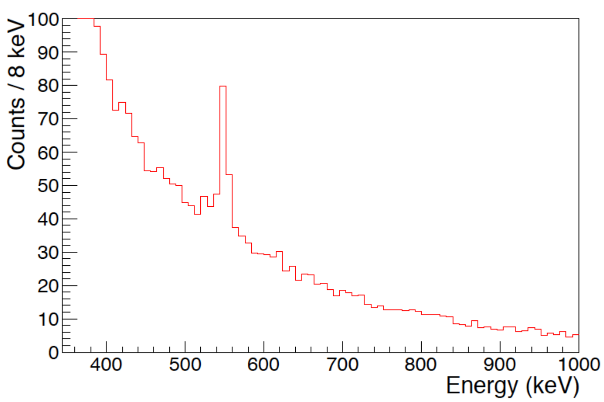

Figure 2.1.6: A simulation of the spectrum measured using GRETA and the proposed HRS from relativistic Coulomb excitation at 200 MeV/u of the near dripline nucleus ^{40}Mg produced at FRIB and impinging on a 492 mg/cm^2 ^{207}Bi target. The peak at 550 keV corresponds to the predicted 2^+ state ($E(2^+)$) and B(E2) in ^{40}Mg, from [Now09]).

At the limits of mass, charge, and spin [Benchmarks 2 and 5]

What is the heaviest neutron-proton combination that holds together as an entity long enough for us to investigate its properties? This question frames one of the frontiers of nuclear-structure research, and tests the limits of our current experimental technologies as well as our theoretical understanding of nuclear matter.

Experiments that focus on synthesizing the heaviest elements (*Z=112-118*), e.g. [Oga12], use reactions with pico barn cross sections, where the primary data is from ground-state alpha decays and with little or no information on possible excited states*. A complementary approach is to explore and expand the limits of nuclear spectroscopy to higher angular momenta where excitations and de-excitations of the heaviest nuclei can be studied. These detailed studies of higher spins in the heaviest nuclei are currently limited at *Z*~104 [Gre12], where the accessible nuclei are well deformed in their ground states. As such, they provide critical information on both collective correlations of the core, as parameterized by the shapes and moments of inertia, as well as single-particle phenomena that manifest themselves through deformation-aligned K-isomers or rotation-aligned quasiparticles. These two degrees of freedom and the rich interplay between them can be quantified through detailed measurements of level structures and transition matrix elements, which ultimately provide the most stringent tests for theoretical models that aim to understand the superheavy frontier.

The spectroscopy of these shell-stabilized nuclei that resist fission competition up to high angular momenta utilize both fusion-evaporation as well as inelastic and transfer reactions. While fusion reactions push inexorably towards the highest proton orbitals, inelastic and transfer reactions with heavy beams and radioactive targets enable studies of deformed neutron orbitals around *N*=154, relevant for superheavy nuclei. These measurements currently stretch the capabilities of the most advanced multi-detector arrays in the world. The unprecedented granularity, resolving power, and detection efficiency of GRETA will be essential for measurements aimed at understanding the limits of nuclear existence.

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* Recently γ-ray decays have been reported from excited states in elements *Z=109* and *Z=107*, produced in the ^{243}Am(^{48}Ca,xn)115 reaction, [Rud13, Gat14].

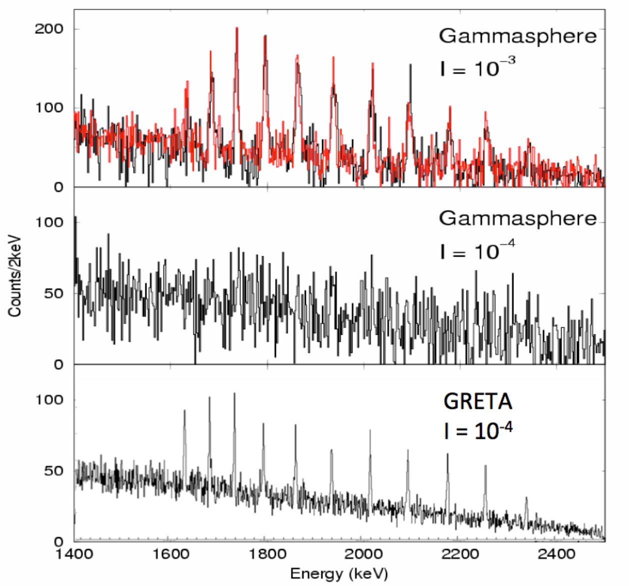


Figure 2.1.7: Simulations compared to data for the example of the highly-deformed rotational band in ^{108}Cd illustrating GRETA's gain in resolving power to observe weakly-populated, high angular-momentum rotational states The top panel shows the measured Gammasphere spectrum [Cla01] (black) together with the corresponding simulated spectrum (red). This is the observational limit for current detector arrays - a band with intensity of 10^{-4} would not be seen today (middle panel). GRETA, shown in the bottom panel, would clearly resolve such a structure.

The response of atomic nuclei to increasing angular momentum (or spin) and excitation energy is one of the most fundamental topics of nuclear structure research. Studies at the extremes of angular momentum and excitation energy probe the competing modes of nuclear excitation and the rich variety of shapes that occur. Rotational motion provides a striking example of emergent phenomena in many-body quantum systems and is a sensitive tool to study the underlying microscopic structure. GRETA will be essential to push these measurements beyond what can be done today. The sensitivity gained from using GRETA for a high-angular-momentum experiment is illustrated in Figure 2.1.7 for the case of ^{108}Cd, where a weakly populated rotational structure, with an intensity of ~10^{-3} of the total fusion cross section has been seen [Cla01] at high angular momentum in an experiment with Gammasphere. This structure corresponds to a strongly deformed prolate shape, possibly exceeding a 2:1 major-to-minor axis ratio. This rotational band is at the limit of observation for present arrays. GRETA will allow the study of structures that are 10 times weaker. (Similar gains are expected for many of the cases discussed above for studies of very heavy nuclei.) The order of magnitude gains in sensitivity will be essential, for example, to enable measurements of predicted high-spin hyperdeformed (HD) nuclei, e.g. [Cha01], which are associated with a third minimum in the potential energy surface of rapidly rotating nuclei. This extreme deformation (approaching a 3:1 major-to-minor axis ratio) is predicted to occur at the very limits of sustainable angular momentum before the nucleus undergoes fission. In ^{108}Cd, this corresponds to a spin of ~70ħ [Cha01], and a band beyond the reach of today's experimental sensitivity, but within the reach of GRETA. Reaccelerated radioactive beams at FRIB, e.g. ^{94}Kr, will give access to neutron-rich Cd isotopes up to ^{114}Cd, where hyperdeformed structures are predicted to be favored at even lower spins.

2.2 How did visible matter come into being and how does it evolve?

Explosive scenarios and the rp-process [Benchmark 16]

X-ray bursts are frequently observed thermonuclear flashes ignited on the surface of accreting neutron stars with periods of hours to days. Type I X-ray bursts are powered by the rapid proton-capture process (rp-process), a sequence of rapid proton captures and β^+ decays near the proton dripline. Once the underlying nuclear physics is understood, comparisons of burst observations with models offer a unique pathway to constrain neutron-star properties such as accretion rate, accreted composition, or radii.

Direct proton capture rates have been difficult to measure because of the limited intensities of low-energy rare-isotope beams (see review in [Sch06]). Most rates in the rp-process are still based exclusively on theory, but those are rather unreliable. Shell-model calculations, which can be used up to *A*~60, can estimate the excitation energies of resonant states. However, reaction rates are so sensitive to resonance energies that the rather small uncertainties in the shell-model predictions of around 100-200 keV still can translate into reaction-rate uncertainties of many orders of magnitude.

The vast majority of the reaction rates can also be constrained with powerful indirect techniques. Among them are direct reactions with fast beams and γ-ray tagging that allow measuring the low-lying resonance structure of the unstable nuclei relevant for proton capture rates [Cle04, Che12, Lan14]. The important resonances most often decay via sizable γ-ray branches that can reveal resonance energies with a precision at the keV level. In addition, the use of direct reactions provides access to spectroscopic factors or asymptotic normalization coefficients which also enter the calculations of capture reactions rates to some extent.

The role of in-beam γ-ray spectroscopy with large arrays was first pioneered with Gammasphere using fusion-evaporation reactions with light ions, where as many levels as possible are populated, especially those of low spin near the particle evaporation threshold which play a role in capture reactions. For example, the complete level structure of ^{20}Na below the proton threshold was determined [Sew04], a nucleus central to the reaction sequence ^{15}O(α,γ)^{19}Ne(p,γ)^{20}Na dominating the early breakout of the hot CNO cycle into the rp-process in X-ray burster scenarios. Later, the rate of the ^{21}Na(p,γ)^{22}Mg reaction of importance for oxygen-neon nova outbursts was evaluated [Sew05] based on the determination of the full structure of ^{22}Mg in the region relevant for astrophysical burning. In this instance, γ-ray spectroscopy proved essential to derive the precise energies of the most important astrophysical resonances. More recent measurements have focused, for example, on the ^{26g}Al(p,γ) and ^{26m}Al(p,γ) reactions [Lot09, Lota09], motivated in part by the observation of ^{26}Al decay by the COMPTEL all-sky map project, which reported irregular emission along the plane of the Galaxy. These studies and several others of the same type contribute significantly to the understanding of the rp-process by determining, with high precision, the energies of the states of interest for proton capture and by establishing their spins and parity through angular-correlation measurements. In this context, measurements with GRETA provide powerful new capabilities: not only does GRETA provide higher efficiency at the γ-ray energies most commonly involved (E_γ> 1 MeV), but the ability to measure polarization enables spin and parity determination in instances where angular correlations are impossible (1-step decays) and angular distributions provide no useful information (lack of spin alignment of low-spin states).

Exploiting the high luminosity afforded by fast-beam, thick-target measurements, Figure 2.2.1 displays spectra taken with GRETINA during the pioneering γ-ray spectroscopy of the neutron-deficient nucleus ^{58}Zn populated via a proton pickup reaction onto ^{57}Cu projectiles at 30% of the speed of light [Lan14]. GRETINA's γγ coincidence efficiency and peak-to-total together with the excellent resolution after Doppler reconstruction allowed a level scheme of ^{58}Zn to be reconstruct for the first time, including the precise identification of 2^+ states just above the proton separation energy that are critical for the ^{57}Cu(p,γ)^{58}Zn reaction rate. As a result, the uncertainty of this important reaction rate, that sets the effective lifetime of ^{56}Ni in Type I X-ray bursts, could be reduced by several orders of magnitude [Lan14].

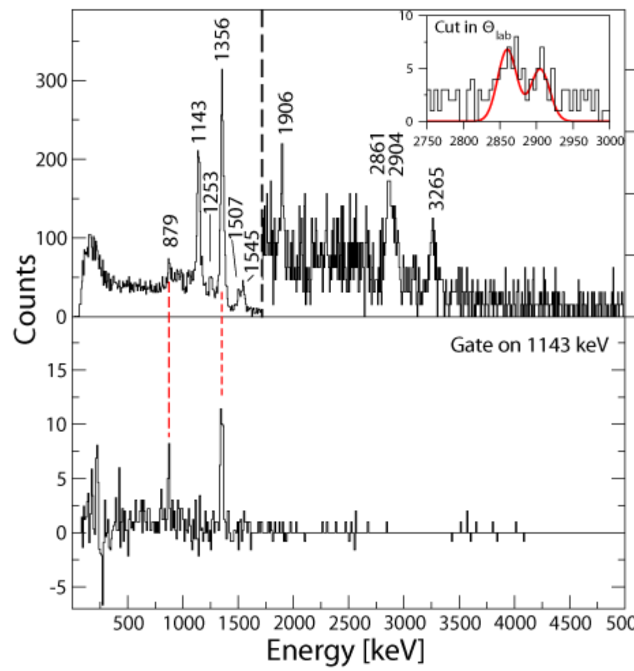


Figure 2.2.1: Event-by-event Doppler reconstructed spectrum of ^{58}Zn, using the interaction points from GRETINA's online signal decomposition. This first spectroscopic data of ^{58}Zn was taken with GRETINA at NSCL using the d(^{57}Cu,^{58}Zn+γ)X reaction at 70MeV/u [Lan14]. Upper panel: Total γ-ray spectrum with the higher-energy region expanded. The inset shows the resolution of a doublet structure when restricting the polar detection angle θ to ~70°. Lower panel: γγ coincidence spectrum. Figure adapted from [Lan14].

For slightly heavier nuclei away from magic numbers, in the important *A*~60 region, for example, many resonances of astrophysical importance [Par08a, Par08b, Cyb14] are not accessible to date as the level density of states in the critical region is too high and the γγ effi-

ciency of present arrays is not sufficient to reconstruct the complicated decay schemes. Among the important reactions are, for example, ^{67}As(p,γ)^{68}Se, ^{63}Ga(p,γ)^{64}Ge and ^{59}Cu(p,γ)^{60}Zn, where precise excitation energies of important capture states just above the proton separation energy of the *N*=*Z* nuclei ^{68}Se, ^{64}Ge and ^{60}Zn are needed. GRETA used in conjunction with direct fast-beam reactions will open up this mass region for the required, selective in-beam γ-ray spectroscopy studies for the first time. Also, firm spin assignments are needed. For lighter nuclei, spins are often assigned in comparison to theory, but in the regime of high level density, as present in this region of the nuclear chart, this approach fails as the level spacing in the region of interest is comparable or smaller than the uncertainty on the calculated excitation energies. Here, GRETA's angular coverage and position sensitivity, together with the energy resolution, will allow firm spin determinations from γ-ray angular distributions.

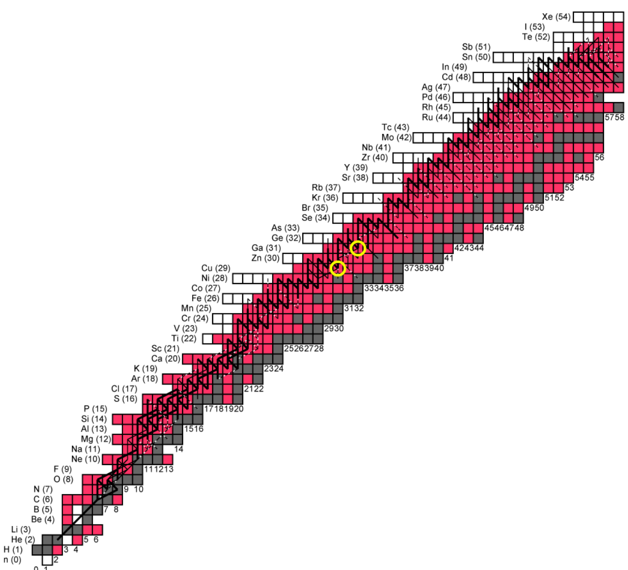


Figure 2.2.2: Opportunities to identify and characterize resonances important for the rp-process with GRETA at the S800 at FRIB, using (d,n) reactions performed in the scheme pioneered in [Lan14]. Isotopes marked in red will be accessible at FRIB at rates exceeding 10^5 pps and will be available for the very detailed γ-ray spectroscopy needed to conquer the high level density in the energy region of interest. ^{59}Cu and ^{63}Ga projectiles, needed for the critical ^{59}Cu(p,γ) and ^{63}Ga(p,γ) reaction rates, are circled. Almost all nuclei along the rp-process path will be available at sufficient intensity for the needed measurements.

The origin of the elements heavier than Iron – the r-process [Benchmark 7]

The rapid neutron-capture process (r-process) is believed to account for roughly half the abundance of elements above $Z \sim 30$. The r-process occurs in high-entropy environments (core-collapse supernovae and neutron-star mergers are leading candidates for the sites) in which extremely high neutron fluxes result in extremely rapid, successive neutron captures, driving the populated isotopic distribution toward very large neutron numbers. These isotopes subsequently β decay back toward stability, contributing to the observable abundance pattern of stable (and very long-lived) nuclei.

Recent precision measurements of elemental distributions of the envelopes of individual low-metallicity halo stars are placing unprecedented constraints on r-process abundance patterns [Sne08]. However, understanding r-process abundances requires a variety of physics input, including neutron densities and temperatures. Additionally, considerable sensitivity has been demonstrated to the properties of neutron-rich nuclei, such as nuclear masses, β-decay lifetimes, neutron-capture rates and fission properties. Presently, due to the unavailablity of experimental neutron-capture cross sections on these very short-lived nuclei, constraints come from a variety of nuclear structure models, which need to be calibrated in the neutron-rich region by a systematic program of spectroscopic measurements of states with single-neutron character. Furthermore, network calculations of late-stage r-process nucleosynthesis indicate that the final abundance pattern is significantly sensitive to neutron-capture cross sections on a particular subset of nuclei around shell closures, such as ^{81}Ni, ^{76}Cu, ^{78}Zn, ^{80}Ga, ^{86,88}As, ^{131,133,135}Cd, ^{133,135,137}Sn, ^{137}Te [Sur09, Sur14], making them prime targets for study. Spectroscopic measurements on such individual nuclei with particular r-process sensitivity are required to more directly constrain calculations of their neutron-capture cross sections.

Single-neutron transfer reactions that selectively populate states of importance for neutron capture can be used to constrain neutron-capture cross sections, and are critical in validating nuclear structure models. Beam intensities at FRIB will allow such reactions to be measured in inverse kinematics with radioactive beams of r-process nuclei to yield excitation energies and spin-parity assignments, along with spectroscopic

factors required for calculations of neutron-capture cross sections. However, the nature of such measurements with finite target thicknesses dictate that, in nuclei just a few nucleons away from shell closures, many levels are not resolvable via charged particle detection alone [Pai08]. The γ rays emitted in such reactions can vastly improve sensitivity and information yielded by the measurement, and are critical to surrogate measurements for statisitical neutron capture [Hat10], but experiments in inverse-kinematics require a precise Doppler correction of the measured γ-ray energies. For beams of ~12 MeV/u, it is necessary to know the interaction point of the γ-ray to 1-2 degrees in order to maintain close to intrinsic Ge-detector resolution. The capabilities of GRETA, when coupled to a high-resolution charged-particle array such as ORRUBA, will be key to enabling such measurements to be performed on r-process nuclei at FRIB.

The ^{137}Te(d,p+γ)^{138}Te reaction is a representative measurement required to constrain the ^{137}Te(n,γ)^{138}Te reaction rate. To date, none of the states likely to contribute significantly to the neutron capture rate have been observed. The projected FRIB beam intensities for ^{137}Te is 3.5x10^{5} ions per second, allowing a high-precision, thin-target measurement at ~12 MeV/u to be performed.

Benchmarking electron-capture rates – Towards understanding supernovae and processes in neutron stars [Benchmark 17]

Supernovae are critical to our understanding of the Universe. They are the major sources of nucleosynthesis and their shockwaves are considered major drivers of galactic chemical evolution. These energetic and bright explosions are characterized by some of the most extreme conditions encountered anywhere in the Universe and leave behind black holes and neutron stars. For both main types of supernovae, core-collapse (Type II) and thermonuclear (Type Ia), the driving mechanisms are not yet fully understood and nuclear-physics input, such as weak-interaction rates, play a crucial role [Lan03]. Neutron stars are among the elusive remnants resulting from gravitational collapse during supernovae. These objects of unrivaled high density are thought to have a very complex, layered structure, with electron-capture (EC) rates being important for the heating of the neutron-star crust [Gup07] and cooling processes [Sch13].

The estimation of EC rates requires detailed knowledge of Gamow-Teller strength transitions in the β^{+} direction. EC on a large number of nuclei (stable and unstable), primarily with $40 \leq A \leq 120$, play a role. Moreover, due to the high temperatures in stellar environments, transitions from ground states and excited states are significant. It is impossible to measure even a sizable fraction of all relevant strengths. Therefore, it is important to perform targeted experiments to validate and improve theoretical calculations. Transitions to low-lying excited states are especially critical for electron captures at low stellar temperatures and densities in pre-supernovae stars [Heg01] and for the neutron-star crustal processes, and their exact location must be known with high precision. A variety of charge-exchange probes have been used for extracting Gamow-Teller strength distributions from stable nuclei, but the development of high-precision charge-exchange probes for experiments with unstable nuclei proved a challenge. The use of high-resolution γ-ray spectroscopy has emerged as a powerful tool to address this problem, for example, in the use of the (^{7}Li,^{7}Be+γ) reaction in inverse kinematics (see section on "The spin-isospin response of nuclei" above). More recently, GRETINA was used in a ^{46}Ti(t,^{3}He+γ) experiment to extract the Gamow-Teller strength to a very weak low-lying transition which dominates the electron-capture rate under most stellar conditions, but which would have been unobservable without the use of GRETINA [Noj14]. Although the experiment was performed in forward kinematics (but with a secondary triton beam), the γ-coincidence technique will be very useful in future charge-exchange experiments performed in inverse kinematics with rare-isotope beams. Achieving high resolution in such experiments; e.g. (p,n) or (^{7}Li,^{7}Be) in inverse kinematics, relies on high-precision Doppler reconstruction since the relevant γ rays are emitted in flight. By combining high-efficiency detection with high-precision γ-ray tracking, GRETA will be a tremendous asset for such experiments. In addition, by placing GRETA at the target station of the planned High-Rigidity Spectrometer (HRS) at FRIB, Gamow-Teller transitions for nuclei with large neutron-to-proton asymmetries can be reached.

2.3 Are the fundamental interactions that are basic to the structure of matter fully understood?

Studies of octupole collectivity to guide searches for physics beyond the Standard Model [Benchmark 12]

Despite its spectacular phenomenological success, it is recognized that the Standard Model is incomplete and may eventually be incorporated into a more fundamental framework. For example, the excess of matter over antimatter in the Universe indicates the presence of baryon-number-violating interactions and most likely of new sources of CP violation. At present, the Standard Model does not violate the CP symmetry sufficiently strongly to account for this excess. The observation of a permanent electric dipole moment (EDM) would indicate time-reversal (T) or charge-parity (CP) violation, most likely due to physics beyond the Standard Model [Eng13, Pos05].

As shown by the most sensitive EDM search to date, performed on ^{199}Hg [Gri09], the present upper limits already constrain various extensions of the Standard Model. In the past few decades, it has been realized that nuclear structure can strongly amplify the sensitivity of nuclear EDM measurements to the underlying physics [Eng13]. The occurrence of octupole deformation and enhanced octupole vibrations in nuclei lead to closely-spaced parity doublets and considerably larger Schiff moments (proportional to the difference between the mean-square radius of the nuclear dipole moment distribution and the nuclear charge distribution). Because a CP-violating Schiff moment induces a contribution to the atomic EDM, a large enhancement due to octupole effects translates into an improved sensitivity to an atomic EDM when compared to atomic systems without this deformation (such as ^{199}Hg). Enhancement factors of 10^2-10^3 have been calculated [Eng13, Dob05, Spe97].

A signature of the rotation of an octupole-deformed, even-even nucleus is the presence of rotational bands with levels of alternating parity, connected by strong electric-dipole transitions (i.e., both $(I^+ \rightarrow (I-1)^-$ and $I^- \rightarrow (I-1)^+$ transitions) where the large B(E1) values of the connecting transitions are interpreted as resulting from the presence of an intrinsic electric dipole moment [But96]. Bands with these properties have been reported in both ^{224}Ra and ^{226}Ra [Wol93, Coc97]. Furthermore, a pioneering Coulomb excitation measurement was performed at REX-ISOLDE with ^{220}Rn and ^{224}Ra radioactive beams [Gaf13], which provided the *E2* and *E3* intrinsic moments for the two nuclei. The data provide evidence for stronger octupole deformation in ^{224}Ra and the results enable discrimination between some of the available calculations. Inverse-kinematics, barrier-energy Coulomb excitation, with GRETA for γ-ray detection, is best suited to search for the regular band structures that serve as a fingerprint for static octupole deformation. With multiple Coulomb excitation at beam energies near the Coulomb barrier, the nucleus can be excited to states of relatively high spins: spins as high as 36 have been observed in ^{232}Th and ^{238}U, for example. In the near-term, with GRETINA at ATLAS/ANL, pioneering exploratory measurements with long-lived, radioactive Ra isotopes will be performed. Specifically, the ^{225}Ra nucleus will be investigated first, in order to provide input for the EDM measurement currently being prepared at ANL using atom-trapping technology. The focus of the GRETINA experiment is on the identification of the collective octupole band sequences that would be built on the so-called parity-doublet states; i.e., pairs of bands with the same K quantum number, but opposite parity where states of the same spin are rather close in excitation energy so that they can be described as the projections from a single intrinsic state of mixed parity.

At FRIB, using reaccelerated beams, high-statistics multi-step Coulomb excitation with GRETA will be possible for the ^{225}Ra and ^{223}Rn nuclei; e.g, for both nuclei where efforts to measure the EDM are currently underway. With the available beam intensities, detailed, quantitative studies of octupole collectivity will become possible, including the precise determination of static moments and transition strengths. Furthermore, new candidate nuclei will be probed for the presence or absence of octupole deformation as inferred from properties of the excited levels, including spin-parity assignments and electromagnetic transition rates. One such possible candidate, which is out of reach for the required detailed studies at present generation facilities, is ^{229}Pa. In this nucleus, the EDM contribution induced by the Schiff moment is predicted to be 3 x 10^4 times larger than the one for (spherical) ^{199}Hg and 40 times larger than the contribution to one of the most promising candidates today, ^{225}Ra [Fla08]. Little is known about the structure of ^{229}Pa to date: most spin-parity assignments are uncertain and no information exists on transition strengths or moments. At FRIB, ^{229}Pa will be available at reaccelerated-beam

rates of the order of 10^6/s allowing for first-rate, inverse-kinematics Coulomb excitation measurements. In addition to the high detection efficiency, the angular coverage and tracking ability of GRETA will be invaluable to exploit linear polarization and angular distributions in the characterization of possible new, game-changing EDM candidate nuclei like ^{229}Pa and, perhaps, entirely new candidates not envisioned today.

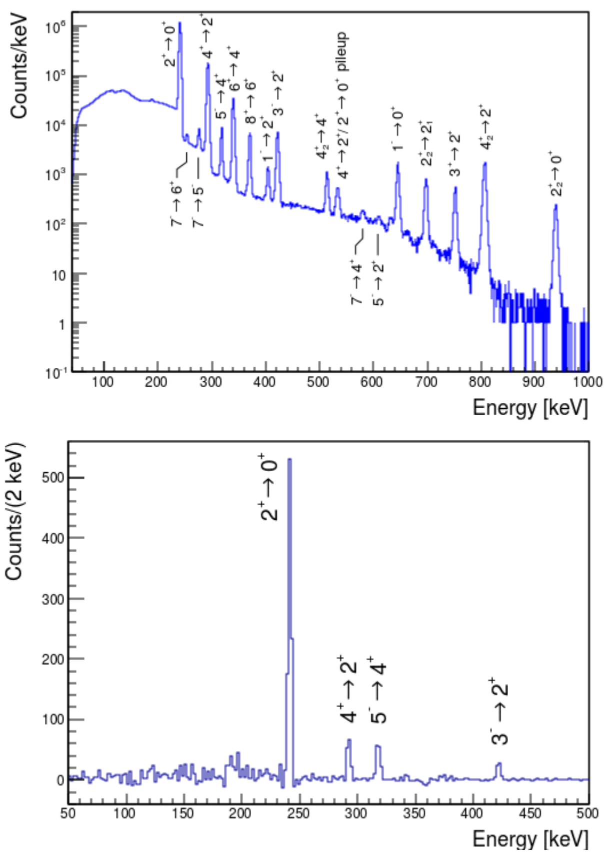


Figure 2.3.1 Upper panel: Simulated spectrum for ^{220}Rn Coulomb excitation carried out at FRIB using GRETA at 4.5 MeV/u. Lower panel: Simulated spectrum of ^{220}Rn from GRETA at FRIB gated on the 7^- → 5^- 276 keV transition (see [Gaf13] for the best possible measurement to date).

The gains in sensitivity for multiple Coulomb excitation measurements with GRETA at FRIB's reaccelerator are illustrated in Figure 2.3.1 for the case of ^{220}Rn that was studied at REX-ISOLDE [Gaf13]. The efficiency and position resolution of GRETA combined with the FRIB reaccelerated beam intensity and energy provide a 100-fold or higher increase in the intensity of transitions characterizing higher-spin states, sufficient for the detailed and quantitative coincidence spectroscopy of collective structures at high-spin values. With this, GRETA at FRIB's reaccelerator will afford unprecedented discovery potential on the quest for the identification and characterization of octupole-collective candidate nuclei for key EDM searches.

2.4 How can the knowledge and technological progress provided by nuclear physics best be used to benefit society? [Benchmark 11]

A national priority being addressed by the nuclear science community relates to stockpile stewardship and nuclear safeguards. Here, specific nuclear reaction and structure data is crucial and high-resolution γ–ray spectroscopy is often used to both tag the final states and map the relevant nuclear decay paths. Neutron-induced reactions on unstable nuclei are not only important for understanding the synthesis of heavy elements in stellar environments, but also for applied-science topics in nuclear energy, nuclear forensics, and stockpile stewardship. For these topics, neutron-capture reactions play a prominent role and the resulting complex reaction networks are difficult to calculate using modern reaction theory.

For over 10 years [Esc12] there has been considerable effort spent in using surrogate reactions to determine neutron-induced reactions on short-lived nuclei. For nuclei close to stability a variety of light-ion induced reactions, such as (p,p'), (p,d), (p,t), and (α,α'), have been utilized in the actinide region and for selected lighter-mass nuclei such as Gd and Y/Zr. For (n,f) reactions the agreement with directly measured cross sections is within ~5-10%. For (n,γ) reactions the surrogate approach is more challenging due to angular-momentum differences between the neutron-capture and surrogate reactions as well as the challenge of quantifying the γ-ray exit channel using the observed discrete transitions. The existing surrogate data is often limited by the γ-ray sensitivity – the high efficiency and excellent sensitivity of GRETA will have a significant impact.

For isotopes more than two nucleons removed from stability the use of the surrogate approach requires rare-isotope beams and inverse-kinematics measurements. This requires beams with energies of 8-12 MeV/u to populate the compound nucleus with excitation energies greater than the neutron separation energy. Experiments require efficient arrays of charged-

particle and γ-ray detectors to identify the nuclear reaction of interest. In conjunction, a recoil separator would enable the identification of the heavy recoils emitted at small angles with velocities and masses close to those of the beam. The fragment separator would need to analyze 12-MeV/u beam-like recoils with a mass resolution of ±1 for a given *Z*. The γ rays emitted by the projectile-like nuclei in flight will be significantly broadened by Doppler shifts. The Doppler broadened γ-ray energy can be corrected by using the excellent tracking capabilities of GRETA. High-efficiency particle-γ-ray coincidence spectroscopy will be needed to disentangle such complex spectra. With GRETA coupled to an efficient silicon-based charged-particle array, surrogate experiments on fission fragments such as ^{95}Sr and other key nuclei in reaction networks can be performed for the first time. An example reaction network is illustrated in Figure 2.4.1.

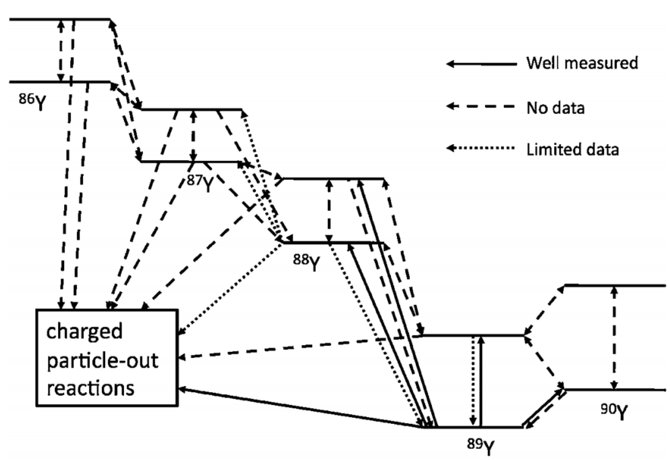


Figure 2.4.1: Yttrium reaction network showing isomeric states and partial level schemes of ^{86}Y, ^{87}Y, ^{88}Y, ^{89}Y, and ^{90}Y and associated reaction channels. Most cross sections are unknown or poorly constrained [Esc12].

3. The GRETA Project

GRETA is a shell of 120 hexagonal germanium crystals, tapered and shaped to enable close packing into a 4π geometry. Each crystal has an inner electrical contact (the core) and 36 electrical contacts on the outer surface (segments). Four crystals are combined into one detector quad module. GRETA will have 30 modules. Signals from all 37 contacts are digitized and passed through advanced signal-processing algorithms to extract in real time the position and energy of individual γ-ray interaction points within a detector crystal. The individual interactions are then combined to reconstruct all interaction of the incident γ ray in a process called tracking.

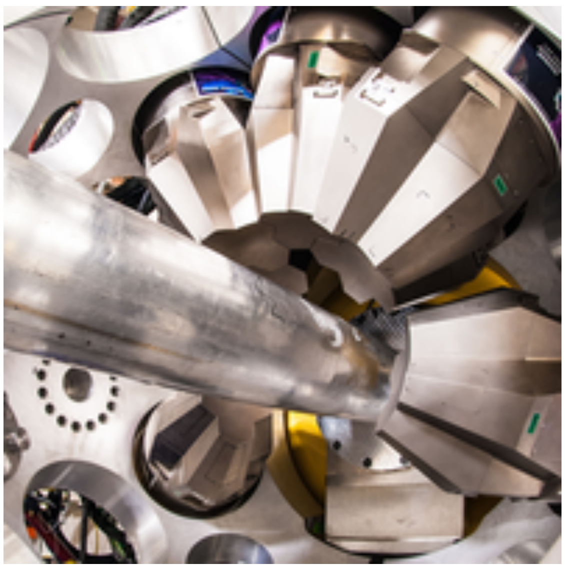
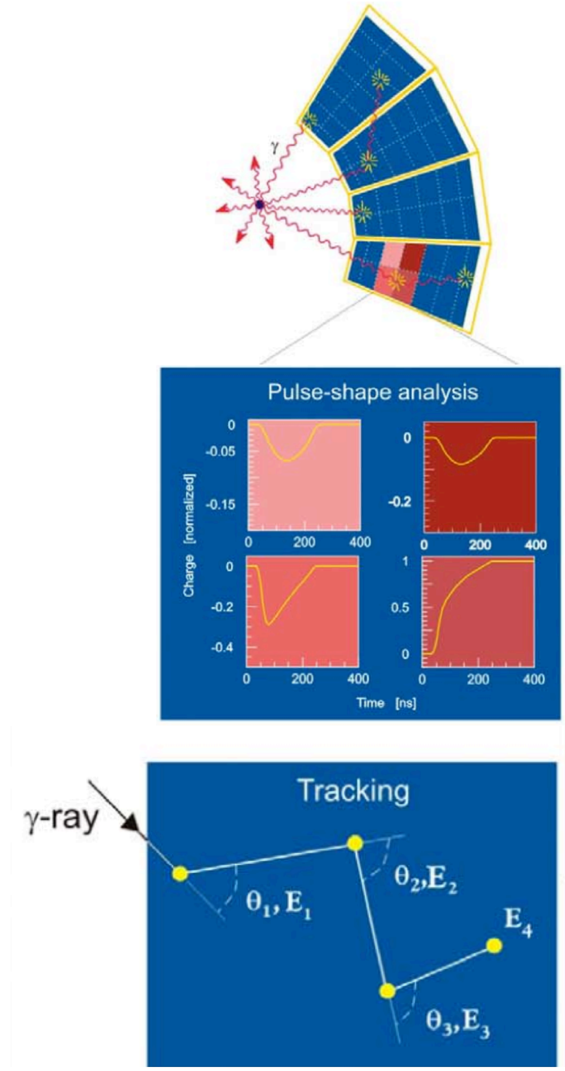


Figure 3.1: Seven quad-modules of GRETINA located at the target position of the S800 spectrometer at NSCL.



Figures illustrating the basic principles of γ-ray tracking. Instead of individually shielded Ge detectors, as in Gammasphere, a tracking array will consist of a closed shell of segmented Ge detectors (upper panel). Pulse-shape analysis of signals from segments containing the interaction(s), as well as analysis of transient signals in adjacent segments, allows the determination of the three-dimensional locations of the interactions, and their energies (middle panel). Tracking algorithms, which are based on the underlying physical processes such as Compton scattering or pair production, are able to identify and separate γ rays and to determine the scattering sequence (lower panel)

GRETA detector modules will be based on the existing quad-module design successfully used in the GRETINA array. GRETINA is a γ-ray tracking array covering ¼ of 4π. It was constructed between 2004 and 2011 and is now operating in science campaigns using fast and reaccelerated rare-isotope beams and stable beams. It has demonstrated the technology and the science reach of a highly-segmented germanium tracking array. The GRETA project builds on this proven success and involves the addition of 18 quad modules to be combined with GRETINA detectors. A plan based on current technology has been developed to complete GRETA for "day one" experiments at FRIB, and the goal is

to receive CD0 for GRETA in 2015. The project is estimated to cost $45M with the proposed funding profile given below.

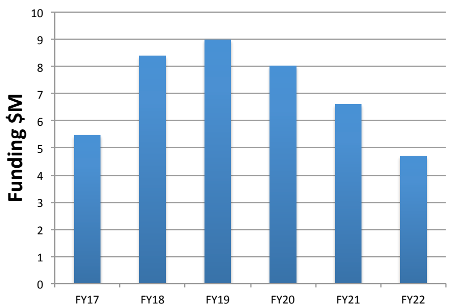


Figure 3.2 Proposed GRETA funding profile, with the completion of GRETA aligned with the anticipated completion of FRIB in 2022.

GRETA will be used in conjunction with a wide variety of state-of-the-art instruments. Indeed, for much of the physics cases presented in section 2, these instruments are essential to enable the measurements. High-resolution fragment separators and spectrometers, such as the FMA (ANL), S800 (NSCL), and the proposed HRS and the S800 (FRIB), will uniquely identify residual nuclei over a wide range of energies. Gas-filled separators, such as AGFA (ANL) and the BGS (LBNL), are key to studies of heavy nuclei. Compact charged-particle and heavy-ion detectors, such as CHICO2, ORRUBA, Nanoball, to name a few, will measure the energy and direction of emitted and scattered particles/nuclei needed for accurate Doppler energy reconstruction and reaction-channel selection.

Appendix I: The Management Structure of GRETINA/GRETA

Operations and Technical Manager for GRETINA: At the end of 2012, Augusto Macchiavelli (LBNL) became the Operations and Technical Manager for GRETINA, taking over from I-Yang Lee (LBNL) who had been the original Contractor Project Manager since 1994.

The GRETINA/GRETA Advisory Committee:
This committee has worked closely with the Manager from the very beginning in the mid-90's and continues to help steer the project forward towards GRETA. Its members are:

Con Beausang (Univ. of Richmond)
Mike Carpenter (ANL)
Mario Cromaz (LBNL)
David Radford, Chair (ORNL)
Mark Riley (FSU)
Demetrios Sarantites (Wash. Univ.)
Partha Chowdhury (U.Mass Lowell)
Dirk Weisshaar (MSU)

Previous members include: Kim Lister (formally ANL now U.Mass Lowell), Doug Cline (Rochester), Augusto Macchiavelli (LBNL) and Thomas Glasmacher (MSU), and Kai Vetter (formally LLNL now LBNL/UCB).

The chairpersons of the working groups are:

Electronics: David Radford (ORNL)
Software: Mario Cromaz (LBNL)
Detector Development: Dirk Weisshaar, (MSU)
Physics Case: Mark Riley (FSU)
Auxiliary Detectors: Demetrios Sarantites (Wash. Univ.)

The GRETINA Users Community and GRETINA Users Executive Committee:
The user community group was formed in 2012 prior to the start of operation of GRETINA at the NSCL and is an organization of scientists interested in the development, and use of GRETINA. Following an election in 2012, the GRETINA Users Executive Committee was formed. Its members are:

Partha Chowdhury (U.Mass Lowell)
Paul Fallon, Chair (LBNL)
Alexandra Gade (MSU)
Ingo Wiedenhoever (FSU)
Shaofei Zhu (ANL)

Appendix II: Early GRETINA Science Results

news & views

NUCLEAR PHYSICS

Track it to the limit

Powerful γ-ray detectors are revealing fresh details about the interior of the nucleus, focusing initially on cases where there is a large excess of neutrons and edging towards the neutron drip-line limit.

Philip Walker

NATURE PHYSICS | VOL 10 | MAY 2014 | www.nature.com/naturephysics

In its first "fast-beam" science campaign carried at NSCL (Summer 2012 - Summer 2013) GRETINA was used in 24 experiments, using approximately 3300 hours of beam time and involving more than 200 users from over 20 institutions worldwide, to address a broad range of physics. The high demand for GRETINA beam time in the first NSCL campaign illustrates the key position that a γ-ray tracking array holds at a rare-isotope beam facility. A list of the physics publications so far from this NSCL campaign is given below. GRETINA is currently operating at ATLAS/ANL and first experiments using reaccelerated radioactive ions from CARIBU have begun.

- "Configuration mixing and relative transition rates between low-spin states in ^{68}Ni", F. Recchia, C. J. Chiara *et al.,* Phys. Rev. C 88, 041302(R) (2013).
- "Nuclear Structure Towards N=40 ^{60}Ca: In-Beam γ-Ray Spectroscopy of $^{58;60}$Ti" A. Gade, R. V.F. Janssens *et al.*, Phys. Rev. Lett. 112, 112503 (2014).
- "Evolution of Collectivity in ^{72}Kr: Evidence for Rapid Shape Transition", H. Iwasaki, A. Lemasson *et al.*, Phys. Rev. Lett. 112, 142502, (2014).
- "Determining the rp-process flow through ^{56}Ni: Resonances in ^{57}Cu(p,γ)^{58}Zn identified with GRETINA", C. Langer, F. Montes *et al.,* Phys. Rev. Lett. 113, 032502 (2014).
- "β^+ Gamow-Teller transition strengths from ^{46}Ti and stellar electron-capture rates", S. Noji, R.G.T. Zegers *et al.*, Phys. Rev. Lett. 112, 252501 (2014).
- "Inverse-kinematics proton scattering on ^{50}Ca: Determining effective charges using complementary probes", L. A. Riley, M. L. Agiorgousis, T. R. Baugher *et al.,* Phys. Rev. C 90, 011305(R) (2014).
- "Single-particle structure of silicon isotopes approaching ^{42}Si", S.R. Stroberg, A. Gade, J.A. Tostevin, *et al*., Phys. Rev. C 90, 034301 (2014)
- "Neutron single-particle strength in silicon isotopes: constraining the driving forces of shell evolution", S.R. Stroberg, *et al*., submitted
- "Magnetic response of the halo nucleus ^{19}C studied via lifetime measurement", K. Whitmore *et al*., submitted
- "Identification of deformed intruder states in semi-magic ^{70}Ni", C. J. Chiara *et al.,* submitted

GRETINA result on ^{60}Ti featured in *Nature Physics*:

- "Track it to the limit", P. Walker, Nature Physics Vol 10, 338 (2014).

GRETINA result featured as an "Editors Suggestion" in Phys. Rev. Letters

Editors' Suggestion

Determining the *rp*-Process Flow through ^{56}Ni: Resonances in ^{57}Cu$(p,\gamma)^{58}$Zn Identified with GRETINA
C. Langer et al.
Phys. Rev. Lett. **113**, 032502 (2014) – Published 14 July 2014

Updated measurements of the ^{57}Cu$(p,\gamma)^{58}$Zn reaction rate provide a crucial input to x-ray burst modeling reducing the uncertainty in Nickel production by a factor of ten. This reduction in uncertainty will allow for an improved modeling of x-ray burst observables, such as light curves and x-ray spectra of nearby interstellar medium.

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Nuclear Physics: Exploring the Heart of Matter, The Committee on the Assessment of and Outlook for Nuclear Physics, Board on Physics and Astronomy, National Research Council of The National Academies (The National Academies Press: Washington, D.C., 2012).
http://www.nap.edu/catalog.php?record_id=13438

NSAC Rare-Isotope Beam (RIB) Task Force Report 2007, Nuclear Science Advisory Subcommittee, James Symons Chair.
http://science.energy.gov/~/media/np/nsac/pdf/docs/nsacrib_finalreport082007_dj.pdf

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