A Recoil Separator for ReA12

A whitepaper on the science case and proposed technical solution, ISLA

Produced by the ReA12 Recoil Separator Working Group
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Executive Summary

The FRIB and NSCL user communities have strongly endorsed the early implementation of reaccelerated beams with energy up to 12 MeV/u at FRIB [1] [2]. This capability would provide a world-unique set of beams from in-flight separation and gas stopping at energies compatible with many of the experimental and theoretical tools necessary for the FRIB scientific program. A recoil spectrometer coupled to ReA12 is needed to address large parts of the nuclear physics mission of FRIB—for aspects from nuclear structure and nuclear astrophysics to applications of rare isotopes—including the four overarching questions in the recent NRC decadal study of nuclear physics [3] and a majority of the Benchmarks from the 2007 NSAC RIB Taskforce report [4].

FRIB will provide unprecedented rare isotope beam intensities, particularly for very heavy ions, but also for lighter species. FRIB is expected to produce 80 % of all possible isotopes up to Z = 92 with rates sufficient to measure at least some basic structural properties [5]. ReA12 will reaccelerate stopped FRIB beams, providing high quality beams of rare isotopes at energies ideal for transfer reactions, multiple Coulomb excitation, massive transfer in deep inelastic scattering and fusion reactions. In the energy domain of ReA12 rare isotopes will be produced with many charge states after a reaction. The unambiguous identification of nuclei in this mass region and at low to medium energy will be a necessary and challenging task. Only a spectrometer specifically designed for this task can meet these needs. Besides excellent particle identification, the spectrometer is needed to reject unreacted beam. In many experiments it will be used in coincidence with detector arrays around the target, to clearly associate a particle or gamma detected at the target with a given reaction product. Focal plane detectors will facilitate decay studies of the reaction products themselves. A ReA12 recoil spectrometer will have the important ability to extend the reach of FRIB to study isotopes that cannot be reached by fragmentation, but that can be produced by multi-nucleon transfer in deep inelastic scattering, or by transfer or fusion. This includes studies of any elements beyond Z = 92, in addition to many other cases. Without a spectrometer, the lack of precise identification of residues will render most reaccelerated beam experiments infeasible due to the orders of magnitude higher statistics that would be necessary to disentangle different reaction channels. Consideration of the needs of the physics cases outlined in this document has led to the following essential properties of the spectrometer:

- large solid angle acceptance
- large momentum and charge state acceptance
- M/Q resolving power as high as possible, at least > 400
- magnetic rigidity $B\rho_{max}$ = 2.6 Tm
- atomic number resolution up to uranium
- variable incoming beam angle
- space around the target to accommodate large detector arrays (e.g. GRETA/Gretina)

A single spectrometer with these characteristics has emerged from the discussions of the community. The ISLA device has the above characteristics and will be world unique with its high M/Q resolving power of up to 10000 due to its isochronous properties. Its cost has been estimated to be about M$10.0 with a 20 % contingency included.

This spectrometer should be made available prior to FRIB start-up, in 2020 to 2022, to make the most of early research opportunities and to develop expertise to operate the spectrometer and its detectors efficiently. This suggests that it would be necessary for funding to become available before the end of 2016.

Introduction

With the use of fragmentation and fission of heavy-ion beams, and in-flight separation using the ARIS multi-stage fragment separator proposed for FRIB, a wide range of isotopes will be produced at unprecedented intensities. The fast isotopes will be stopped in either a linear gas cell—which was developed at ANL and is in operation at the CCF at NSCL—or in a cryogenic gas cell and a cyclotron stopper, currently under development at the NSCL.

By stopping the fragments in a He-gas cell, FRIB can provide a nearly chemically independent source of low energy ions. The facility will provide the full range of produced elements below mass 240. The low energy 1+ ions are then injected into an EBIT charge breeder for stripping of the electrons to obtain a high charge state for further acceleration in the ReA superconducting linac. Because the EBIT is a UHV device and by choosing an appropriate charge state the reaccelerated rare isotope beam will be nearly pure as shown in the current NSCL reaccelerated beam program in Figure 1. This is the unique feature of the reaccelerated beams compared to beams provided by the Isotope Separator On-Line (ISOL) technique. The availability of beams of elements difficult to extract from ISOL targets such as boron, zirconium, and tungsten provide the opportunity to investigate certain key nuclei not otherwise accessible. Figure 2 illustrates the variety of beams available from solid targets and hence ISOL facilities. The elements in white indicate those that will be unique to the FRIB concept. Additionally, a large gain will be possible at FRIB and NSCL for short-lived isotopes, or isotopes of elements that are not effectively released in ISOL techniques, such as Ni.

The scientific motivation for studies on reaccelerated rare isotope beams up to 12MeV/u is nearly identical to the general motivation for the FRIB project itself. Some of the intensity will be lost in the reacceleration process, however, the beams produced will have the same optical beam quality as primary beams, and the energy can be adapted to the reaction mechanism to be used for the studies of interest. The lower energy and

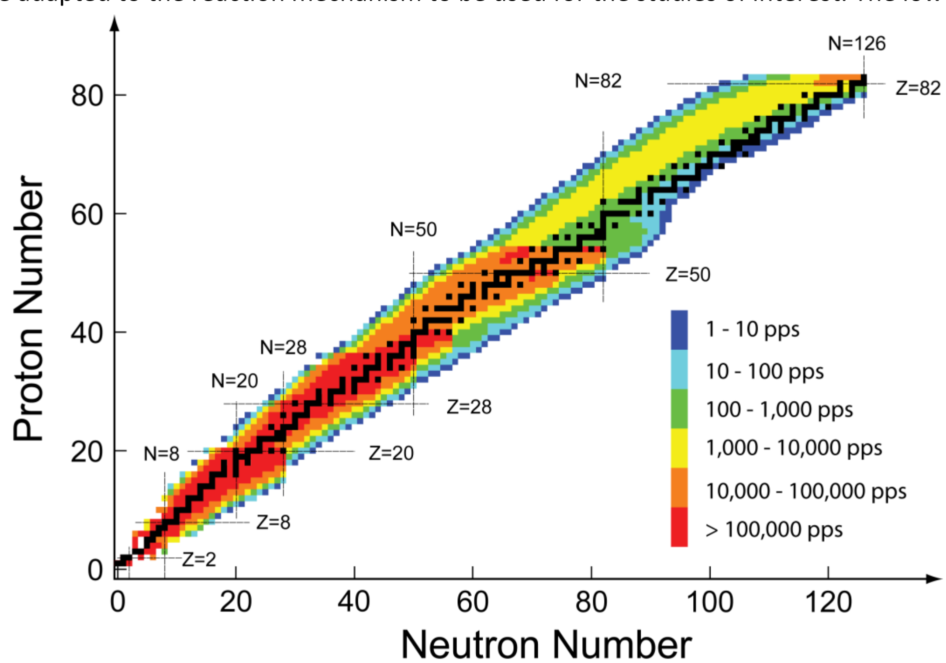

Figure 1: Reaccelerated beam rates based on the available fragment rates available at NSCL. The stopping and extraction efficiency for the gas cell was assumed to be 20 %, and charge breading and acceleration 50 %. The delay time in the cell was assumed to be 60 ms. For rates above 1x10^5/s the efficiency of extraction from the cell was assumed to drop to 10 % and to 2 % for rates above 1x10^6/s.

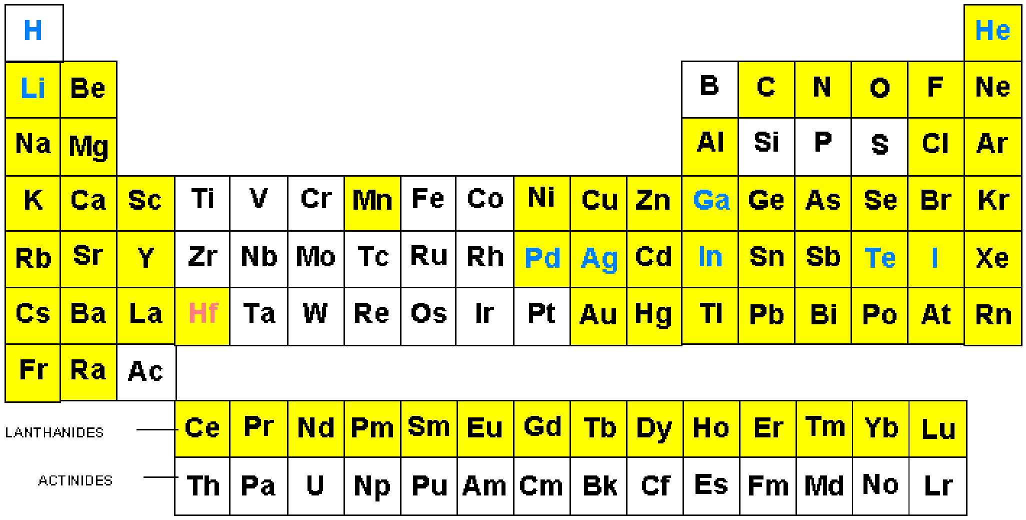

Figure 2: **Illustration of the beams typically available from ISOL facilities. The elements in yellow are available provided the half-lives are greater than 1 second. Some elements are available at shorter half-lives if the target release time is short. Blue indicates only neutron rich isotopes are available and red indicates only neutron deficient isotopes are available. Elements in white boxes are not available and represent the unique beams available at facilities using gas stopping, such as FRIB. Taken from [87]**

increased purity of the reaccelerated beams makes available a wide range of well-developed experimental techniques to studies with FRIB-produced rare isotopes. The FRIB scientific case has been described in detail in many documents including the RISAC report [6], the 2007 LRP [7], and the RIA Users Community document [8]. A high-resolution recoil separator will be necessary in many cases—discussed in the following sections—to identify the reaction products from studies with ReA12 beams and to separate the unreacted primary beam from the products of interest. The goal of the community is to have the important opportunities afforded by such a separator available to experiments on day one of FRIB operation.

As shown in Figure 3, the FRIB facility will provide an increase of more than 3 orders of magnitude above presently achievable intensities. In particular the intensity increase for medium to heavy nuclei will open this mass region for the study of nuclear properties much farther from stability. High quality experimental equipment will be needed to unambiguously identify nuclei for mass above 100 and Z above 50.

The FRIB community (previously the RIA user community) has consistently made the case that reaccelerated beam energies of up to at least 10 MeV/u are necessary to achieve the scientific goals of the FRIB project. The goal of reaching 10 MeV/u goes back to the initial discussion of an advance rare isotope beam facility in the early 1990s [9]. The argument was later made that access to energies above the Coulomb barrier for all beams, and in particular for beams used in inverse kinematics, is necessary. The RIA Users Document prepared in 2006 presents a number of example experiments that specifically require beams at about 10 MeV/u [8]. This document noted that higher than 10 MeV/u should be available for multi-nucleon transfer reactions, notably for (p,t) studies, and hence 12 MeV/u was generally accepted as the minimum energy for all ions. Multi-nucleon transfer studies feature prominently in the physics cases presented in the following sections.

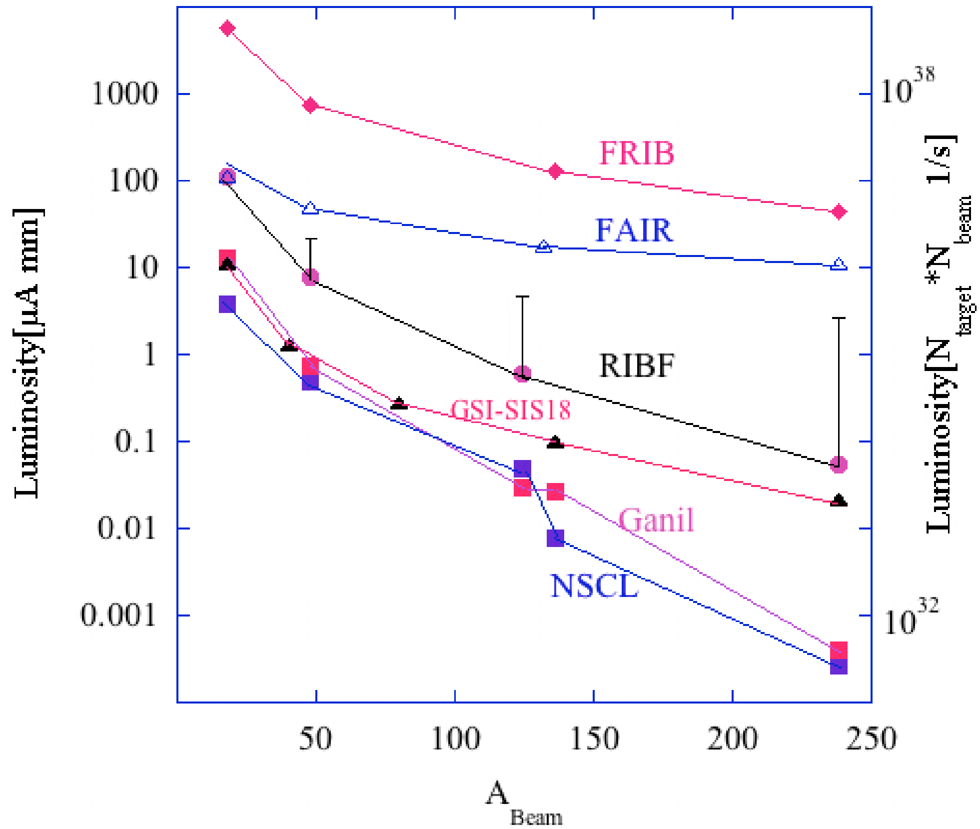

Figure 3: Secondary beam production capacities in units of µA·[8]*Be* -range, left scale, or luminosity for this range, right scale, of present inflight facilities, GANIL, NSCL, GSI-SIS18, (achieved intensities) and facilities under construction, FAIR and FRIB (planned intensities). For the RIBF the dots indicate the present intensities, the vertical bars indicate nominal intensities [84].

The 2007 NSAC Long Range Plan [7] highlights the scientific goals of the field. This includes understanding the forces of nuclei, the origin of their often-simple structure, the nature of neutron matter, and the reactions that drive the evolution of stars. As outlined in the following sections, to address many of these goals a large-acceptance, high-resolution recoil spectrometer following ReA12 at FRIB will be necessary. Beams of these energies open a range of nuclear reactions that can be used to create and study nuclei in unique ways: higher spin states, better l-value selectivity in transfer, more reliable spectroscopic information, more negative Q-value reactions (either to higher-energy nuclear excitations or capture or transfer reactions above the coulomb barrier with He input channels), multi-nucleon transfer and deep-inelastic reactions.

Multi-nucleon transfer reactions, for example, can be used to transfer many neutrons onto an already neutron-rich beam to probe the structure of exotic isotopes by observation of their γ-ray decay. A specific case is given in Figure 8 taken from [10]. It illustrates the cross section for transferring neutrons onto a beam by interaction with a neutron-rich target, in this example ^{208}Pb. With a beam intensity of 10^4 particles per second and a 4-neutron transfer cross section of only σ = 1 mb (see Figure 8) the use of a 20 mg/cm^2 target would yield 2 events per second. With the availability of a recoil tagging spectrometer at ReA12, in the course of a four-day experiment, the detailed level structure of some very exotic nuclei could be measured.

ReA12 beams will provide favorable kinematics for particle detection since the energy of the particles is sufficient for the use of segmented telescopes including ΔE and E particle identification. Focal plane detection, combined with M/Q resolving power provided by the recoil spectrometer, will allow for the unambiguous identification of recoils by mass (M), proton number (Z), and charge (Q).

In the past ten years, there has been significant progress in developing indirect methods to determine important nuclear reaction rates, either for nuclear astrophysics or for nuclear applications. This is necessary because measurement of the direct reaction is often impossible due to a very small cross section, or due to the lack of a suitable target. One example of this is the surrogate reaction program developed by the LLNL, LBL, Rutgers et al. collaboration [11]. Much of this work is done around 10 MeV/u in order to reach the equivalent neutron energy corresponding to neutron induced fission. The identification of the outgoing reaction channel is critical.

Another very successful and potentially widely applicable development has been the careful work to develop a method to extract Asymptotic Normalization Coefficients, ANCs, from transfer reactions at approximately 10 MeV/u. This work was initiated primarily at Texas A&M [12]. A critical aspect of the program is that in order to have reliable optical model parameters from the JLM formalism, approximately 10 MeV/u energy beams are needed [13].

ReA12 will allow a broad study of fission and fission barriers. For these studies a particle-by-particle identification of the recoil nuclei produced will be important. In general it will be important to make detailed reaction mechanism studies including study of fusion-evaporation, and incomplete fusion near and above the barrier in order to understand the role of the extra neutrons in exotic nuclei. This in turn can be used to determine if neutron-rich beams could provide a pathway to neutron-rich heavy elements.

Capabilities for FRIB from ReA12 with a recoil mass spectrometer – summary

ReA12 coupled to a recoil spectrometer adds unique capabilities to FRIB beyond those available in a purely in-flight and stopped beam facility. The ReA12 facility will provide high quality reaccelerated beams with energies around the Coulomb barrier giving access to reaction mechanisms specific to this energy domain:

- fusion-evaporation reactions
- high spin state population
- multi-nucleon transfer reactions to regions not accessible by fragmentation (neutron rich U isotopes, transuraniums, neutron rich nuclei below ^{208}Pb,…)
- direct reactions such as (d,p), (d,n), (p,t)
- direct heavy ion transfer reactions such as (^{7}Li,^{4}He), (^{12}C,^{14}C), ^{18}O,^{16}O)

Essentially all these reactions imply inverse kinematics. The recoil spectrometer will allow the efficient use of these reactions by:

- tagging reactions observed at the target by M and Z of the products to make a clear correspondence between the radiation (γ, light charged particles, neutrons, etc.) observed around the target in powerful detector arrays and the corresponding final nuclei of interest
- allowing for recoil-decay studies of reaction products in focal plane implantation stations.

The ISLA spectrometer will have a high acceptance and a high M/Q resolving power, unique in the world, to efficiently carry out these studies. Without this spectrometer, the lack of precise identification would render most such experiments impossible because of the many orders of magnitude higher statistics necessary to disentangle different reaction channels.

Physics Case

FRIB promises to dramatically expand the variety of nuclear systems available for direct experimental study by providing rates of many rare isotopes orders of magnitude higher than those currently available. Stopped and reaccelerated beam studies will be an important complement to in-flight techniques at FRIB, providing world-unique, high quality, intense rare isotope beams at low energies up to and beyond the Coulomb barrier—with the completion of ReA12—and serving many of the science goals of the broader facility, from nuclear structure and astrophysics to applications.

Two specialized recoil spectrometers are being developed for studies with reaccelerated beams at FRIB. SECAR, the Separator for Capture Reactions, is proposed by the FRIB nuclear astrophysics community to be built following ReA3, coupled to a windowless gas jet target, JENSA [14]. SECAR will focus on radiative capture reactions for astrophysics, particularly those needed to improve our understanding of novae and X-ray bursts. SECAR will have a lower maximum rigidity, 0.8Tm, appropriate to its location, and a limited angular and momentum acceptance, 2.5 msr and +/-1.6 % respectively, appropriate for radiative capture reactions, (p,γ) and (α,γ), in inverse kinematics. The most important feature of SECAR is its very high rejection efficiency for unreacted primary beam, which is necessary to allow direct astrophysical rate measurements with very low cross sections.

We propose a recoil separator following ReA12 to address a wide variety of physics cases based on fusion-evaporation, Coulomb excitation, transfer, and deep inelastic reactions by providing a large angular,

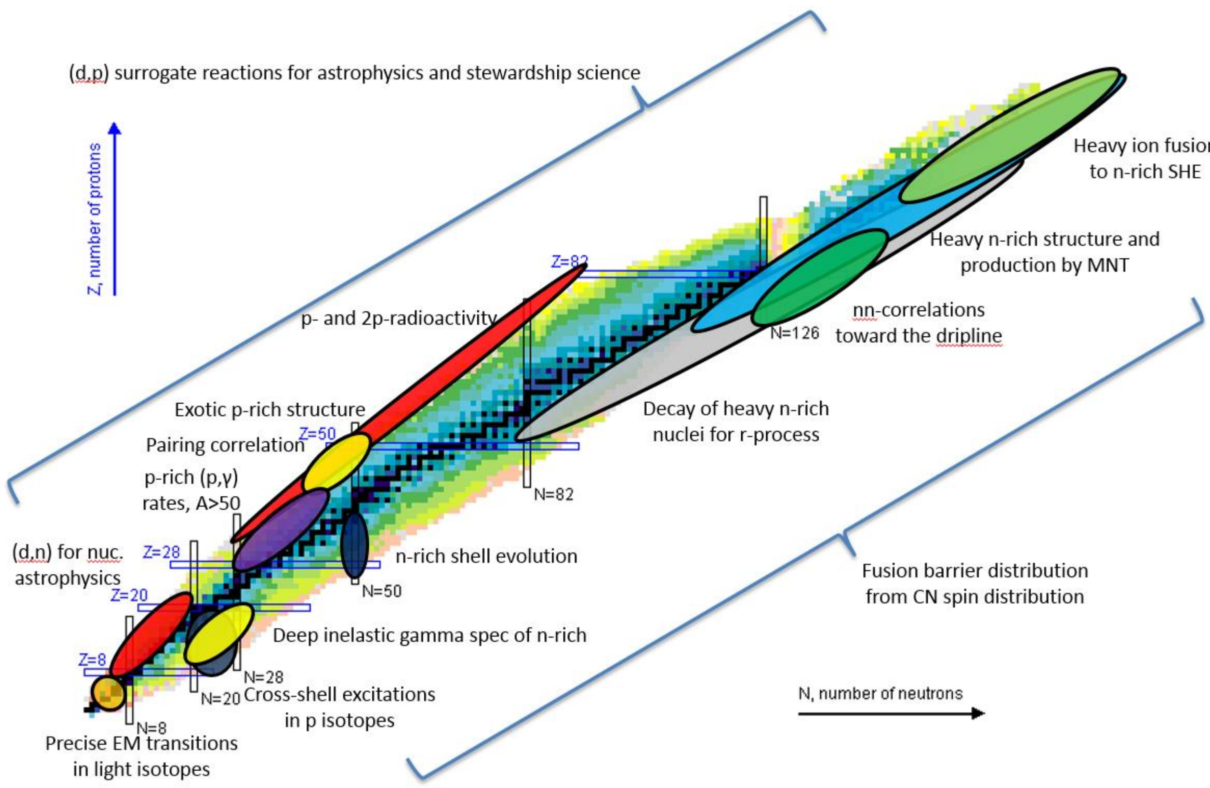

Figure 4: Already proposed physics cases for the ReA12 recoil spectrometer labelled by region on the chart of nuclides. The large brackets show the range of interest for cases that are proposed to involve a large fraction of the entire chart. Many other studies beyond those indicated here will be possible and will ultimately be pursued at the completed facility.

momentum, and charge state acceptance; a high M/Q resolving power; and the flexibility to couple to a variety of auxiliary detector systems for gamma, charged particle and neutron spectroscopy. ISLA, the Isochronous Separator with Large Acceptance, has been proposed and endorsed by the community to meet the goals of the ReA12 recoil separator.

The goals of the ReA12 accelerator and the associated recoil separator are congruent with the broader FRIB facility. Specific examples of physics cases, shown in Figure 4, are discussed in this section. These physics cases were submitted by interested experimenters to the recoil separator working group conveners in response to a call for possible experiments involving a recoil separator following ReA12. The proposals include experiments in light, medium and heavy isotopes; experiments in neutron-rich and neutron-deficient isotopes approaching both driplines as well as actinide and transactinide rare isotopes; experiments that will shed light on the astrophysical rp-process and r-process that operate in explosive stellar environments; experiments that will provide improvements in nuclear shell models near the gaps in major shells and our understanding of the evolving shell structure in rare isotope systems, of nuclear mass models, and of fission and fusion barrier models; techniques that will explore reactions on fissile nuclei and fission fragments for nuclear energy, nuclear forensics, and national nuclear security; experiments in high spin nuclear excitations; experiments on the effect of the pairing force; and experiments in static and dynamic nuclear symmetries. In all these areas the availability of a recoil separator at ReA12 is needed to accomplish the science goals of FRIB. Thus, even at this early stage in the process of the development of the recoil separator, proposals have already been submitted that address a majority of the benchmarks identified in the 2007 NSAC RIB taskforce report [4]. A more recent overview of the science case for FRIB, particularly in relation to important developments in nuclear theory, can be found in [5], where again, some of the new opportunities that will be enabled by FRIB are shown to depend on experimental facilities at ReA12. For example, studies of open quantum systems along the new frontier of proton and 2-proton decay or studies along the N = 126 isotone below ^{208}Pb to improve r-process nucleosynthesis models will depend on the availability of ReA12 coupled to a recoil spectrometer.

The discussion below contains examples that have been proposed to date by researchers in the FRIB users' community. These physics cases were also used to determine the appropriate specifications of the recoil spectrometer. The organization of the sections in some cases does not include all possible directions of multi-use experimental programs proposed. For example, the ANC (Asymptotic Normalization Coefficients) approach, discussed below in an astrophysical context in the section on chemical evolution, is also useful in stewardship science and other nuclear applications. Many other studies beyond those indicated here will be possible and will ultimately be pursued at the completed facility.

Chemical Evolution

Neutron-deficient nuclei: hydrogen burning and heavy element synthesis

Radiative capture reactions and more specifically (p,γ) reactions play a key role in many astrophysical scenarios. There has been a large effort in the nuclear astrophysics community to study these reactions directly or indirectly with a main focus on the light masses (below A = 40). A significant number of these short-lived radioactive nuclei participate in hydrogen burning processes of astrophysical interest. Sensitivity studies demonstrate the importance of reliable reaction rates for proton-capture reactions by unstable nuclei in the wide temperature range of 0.01 to 10 GK. For nuclei in the range 19< A< 40 the proton capture reaction rates on unstable nuclei are considered to be uncertain within a full range of factors as large as 10000 (x100, /100) [15] [16] [17]. Since the synthesis of the heavy elements is one of the major open questions in the field, radiative capture reactions also need to be explored for heavier masses (40<A<120). Scenarios such as nucleosynthesis in supernovae type Ia [18] , the rp-process in X-ray bursts [19], the νp-process in neutrinodriven winds [20] and the p-process in core-collapse supernovae [21] [22] are believed to contribute significantly to the abundances of the heavy neutron-deficient isotopes.

Particularly for the heavier masses, (p,γ) reactions that participate in these scenarios could be measured directly by applying the γ-ray summing technique in inverse kinematics [23] with the NSCL SuN detector [24] combined with the recoil spectrometer, ISLA. While for the lighter masses, direct measurement of the capture cross section down to very low energies is often impractical.

For the direct reaction rate measurements, there are several advantages to using reaccelerated beams from ReA12 in combination with ISLA, compared to alternative approaches, such as, for example, SECAR:

1. ISLA will have a much higher bending power allowing for the detection of the reaction products with the dominant charge state at higher energies. SECAR is designed and optimized for lighter masses and lower energies but is not optimized for the higher energies of this proposed program.
2. The large acceptance of ISLA will transmit more than one charge state at the same time. At these medium masses (40<A<120) the reaction products have a broad charge state distribution. Therefore, we expect to gain approximately a factor of four by simultaneously detecting more than one charge state.
3. The complete rejection of the incoming beam is not required in the proposed experiments. The reaction detection will be done with the SuN detector. ISLA will be used to reject a large fraction of the beam and reduce the particle rate in the detection system. In this way we can measure particle-gamma coincidences and use a tagging technique to reject the beam contaminants that will accompany the main radioactive beam.

In many cases, the relevant astrophysical environments correspond to beam energies well below the Coulomb barrier, where capture cross sections are very small. A high radioactive beam flux (about 10^8pps) and an efficient recoil separator are needed for a successful direct measurement above the particle emission threshold, while the lower end of the temperature range, typically below 0.08 GK, is dominated by contributions from direct capture to the ground and sub-threshold states and will not be accessible experimentally.

Use of indirect methods is a convenient alternative. Proton-transfer reactions like (d,n), feature a larger cross section than the corresponding (p,γ) and can efficiently populate the ground and excited states in the final nucleus. Information such as spectroscopic factors, ANC's and proton or gamma widths can be deduced by using the LENDA neutron detector array to detect the emitted neutrons, and a high acceptance recoil spectrometer to detect the heavy recoils. Due to the low beam energies in the area of interest, both the unreacted beam and heavy reaction recoils will emerge from the target in various charge states with different magnetic rigidities. Typically 20-30 % of the total reaction products end up in the most intense charge states [25]. Unless one can detect and separate most of the intense charge states, the corresponding dramatic loss of efficiency will limit the utility of the technique.

A large acceptance recoil spectrometer will be necessary to enable simultaneous detection of the majority of the most intense charge states of the heavy recoil distribution and to separate recoils from the unreacted beam. This will allow the (d,n) reaction to be used to experimentally constrain the hydrogen burning reaction rates for unstable nuclei in the 19<A<40 region.

Neutron-rich nuclei: r-process site, abundances and endpoint; heavy element synthesis; and cosmochronometers

Decay properties of very unstable nuclei are an essential input for models of nucleosynthesis during the rapid-neutron capture process (r-process). A recoil separator will open novel opportunities to produce beams for r-process experiments, for example through multi-nucleon transfer reactions, as described in the later section *Limits of Mass and Charge* (page 18). For some regions of the nuclear chart this might be the only experimental approach available for the production of such nuclei, especially for neutron-rich actinides with larger neutron emission probabilities (Pn-values) near the N = 126 neutron shell closure.

A distinctive feature of the r-process is its high yield for isotopes at mass numbers that correlate to the location of neutron shell closures far from stability (the abundance peaks). Nuclear structure features near closed neutron shells, such as relatively large neutron separation energies and long half-lives, result in the accumulation of matter in *waiting-point* isotopes, which form the abundance peaks after decay to stability. Comparing measured r-process abundances in the solar system and metal poor stars [26] with the results of astrophysical models is a prime tool to study the r-process, and the location of the abundance peaks is a particularly sensitive diagnostic to pin down the astrophysical conditions of the r-process site [27]. A decay station in the focal plane of the recoil separator presents the opportunity to measure half-lives and beta-delayed neutron emission probabilities of neutron-rich nuclei around the N = 126 neutron shell, responsible for the production of the third abundance peak (A≈195). This is the neutron shell where the reach of experiments is presently farthest from the r-process path, so new data will also provide critically needed tests to recent theoretical calculations of decay properties [28] [29] [30].

Data for heavier isotopes, such as the neutron-rich actinides, is necessary to understand other intriguing aspects of the r-process. One is the mechanism for the end-point of the reaction flow, which sets a limit for the heaviest elements that can be synthesized by nature. In sufficiently neutron-rich environments the r-process sequence of neutron captures and beta-decays is halted by competition with fission modes (e.g. neutron-induced and beta-delayed fission [31]). Fission is also proposed to play a role in the synthesis of specific isotopes, such as cosmochronometer isotopes of Th and U [32] (used to set a lower limit for the age of the galaxy [33]) or in the formation of the r-process abundance peak in the rare earth region [34]. Data on fission of unstable nuclei is scarce on the neutron-rich side of stability, and measurements of beta-delayed fission at a decay station would provide valuable information for a better understanding of the fission process [35].

In-flight techniques to measure the above mentioned decay properties with heavy secondary beams at FRIB energies will suffer from large contamination of charge states. Therefore the reaccelerator combined with the recoil separator is needed for the identification and separation of the heaviest secondary beams in these experiments.

Surrogate reactions for astrophysics and stewardship science

Neutron-induced reactions on unstable nuclei are important for understanding the synthesis of the heavy elements in stars and their explosions and reactions on fissile nuclei and fission fragments for nuclear energy, nuclear forensics, and national nuclear security. At low energies the neutron capture reaction dominates; neutron-induced fission occurs over a wide range of energies depending upon the fissile material. For over 10 years [36], considerable efforts have been made to validate surrogates for neutron-induced reactions on short-lived nuclei. Surrogate reactions in inverse kinematics require rare isotope beams of 8-12 MeV/u to populate the final nucleus above the neutron separation energies, at equivalent neutron energies from 100 keV to greater than 10 MeV. Usually light targets, such as protons and deuterons, are used, requiring an array of charged-particle detectors and the ability to detect the heavy recoil, as well as the final photon or fission channel. Because the heavy recoils are emitted at small angles and have velocities and masses close to those of the beam, a recoil separator needs to be able to analyze the 12 MeV/u beam-like recoils and identify them unambiguously by mass. ReA12 beam energies of rare isotopes from stopped FRIB beams coupled with the high-resolution mass spectrometer, ISLA, would provide a world-unique capability to undertake such studies.

Structure of Exotic Nuclei

Dynamical Symmetries

Broadly speaking, there are two complementary approaches to understanding atomic nuclei: a microscopic one in terms of their nucleonic constituents and interactions between them, and a macroscopic perspective for the many-body system as a whole. The latter seeks to understand the simple patterns and remarkable regularities that nuclei exhibit. A very successful approach has been in terms of the interacting boson approximation (IBA) model [37] with its three dynamical symmetries: U(5), describing a spherical vibrator, SU(3), describing a symmetric rotor, and O(6), describing a gamma soft axially asymmetric rotor. As these idealizations are seldom realized in actual nuclei, applications of this approach have usually relied on numerical diagonalizations of a collective Hamiltonian.

However, it has now been realized that important remnants of these symmetries, called Partial Dynamical Symmetries (PDS) and Quasi Dynamical Symmetries (QDS) often persist even when the symmetries themselves are broken. PDS preserve the symmetries of subsets of states and QDS preserve degeneracies of the parent symmetry.

Figure 5 illustrates some of these ideas. The triangle represents the Hilbert space of the IBA model where the vertices are the dynamical symmetries. Heretofore, the interior has been the realm of numerical calculations exhibiting increasingly chaotic spectra away from the vertices. However, special degeneracies lying along a trajectory linking U(5) and SU(3), where ordered spectra re-appear, revealed that the locus of this Arc of Regularity (AoR) [38] maps an SU(3) QDS [39]. Empirical manifestations of PDS based on SU(3) [40] and on O(6) – the latter simultaneously an O(6) PDS and an SU(3) QDS – have been identified [41]. In addition, simple models of phase/shape transition regions [42] [43], called X(5) and E(5), embodying special geometric

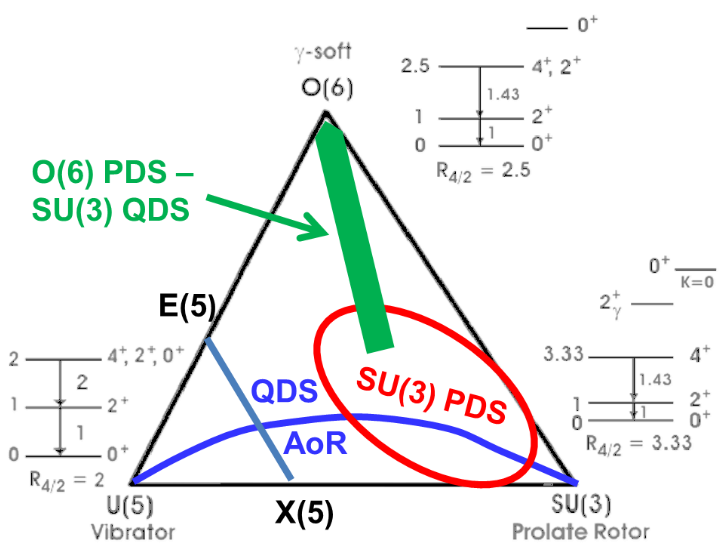

Figure 5: Symmetry triangle of the IBA model showing a number of Partial and Quasi symmetries permeating the triangle that are discussed in the accompanying text.

character, have been a major area of research for regions of rapid structural change [44]. Indeed, much of the triangle is suffused with significant symmetry remnants whose study can contribute new understanding of collective nuclei such as the roles of valence nucleon numbers (system size) and configuration mixing, thus greatly expanding the applicability of symmetry descriptions for collective nuclei.

Key to exploiting these ideas is access to new nuclei and in particular, information on their low-spin, non-yrast states including energy levels, decay patterns and absolute transition strengths. Coulomb excitation is an ideal tool to populate and study such states, requiring reaccelerated beams along with a recoil separator in coincidence with a γ-array, to select the desired beam species and to define the kinematics of the reaction.

Precise Measurement of electromagnetic transitions in light nuclei

Ab initio calculations of light nuclei, using Hamiltonians based on realistic two-body nucleon-nucleon forces and empirical three-body forces have been one of the major triumphs of nuclear structure in the last decade [45] [46]. They are leading to a more profound understanding of nuclear structure; the origin of the mean field, the source of the spin-orbit and tensor forces, and the causes of correlations like pairing and α clustering. A wide variety of experiments have tested the veracity of the new wave functions, including measuring charge radii [47], spectroscopic factors [48], knockout reaction probabilities [49], and electromagnetic transition rates [50] [51]. Electromagnetic transitions have proven to be a difficult challenge for the new theories [51] as they are sensitive to cancelations between many small components in the wave functions. The mixing induced by three-body forces has a surprisingly strong effect on predicted transition rates, to a point where these rates may eventually become a significant constraint for three-body formulations in the future. This research is aimed at precisely measuring transition rates, particularly M1 and E2 transitions, to test the models and constrain free parameters in the Hamiltonians.

Two-body reactions will be used to prepare the states under study in carefully controlled kinematic conditions. For example, an initial experiment might be d(8Li,p)9Li or p(9Li,p')9Li. Radioactive beams will be used, ideally with beam rates in the range of 10^8 to 10^{10} particles per second. Beam energies from 5 to 10MeV/u are best suited to these studies, depending on the reaction Q-value. γ–rays will be measured in coincidence with reaction recoils. Beam rejection will be less of an issue compared with stable beam facilities, but slits will be needed to provide mass and momentum selection, to make the focal plane clean. The spectrometer used for recoil identification should be at zero-degrees, with significant geometrical acceptance and the ability to transmit beams that are more rigid than those used at previous generation devices like the FMA or EMMA. Significant space around the target will be needed for a sizable γ-ray detector array (e.g. Gretina, Greta, or GammaSphere). The ISLA device meets all of these requirements.

Studies of excited states in exotic proton-rich nuclei

High-quality, intense proton-rich radioactive beams offer an exciting opportunity to push the limits of our knowledge towards more exotic proton-rich nuclei, which provide a stringent test for emerging universal nucleon-nucleon interactions. Of particular interest are nuclei located near the N = Z line which are an ideal testing ground for studies of

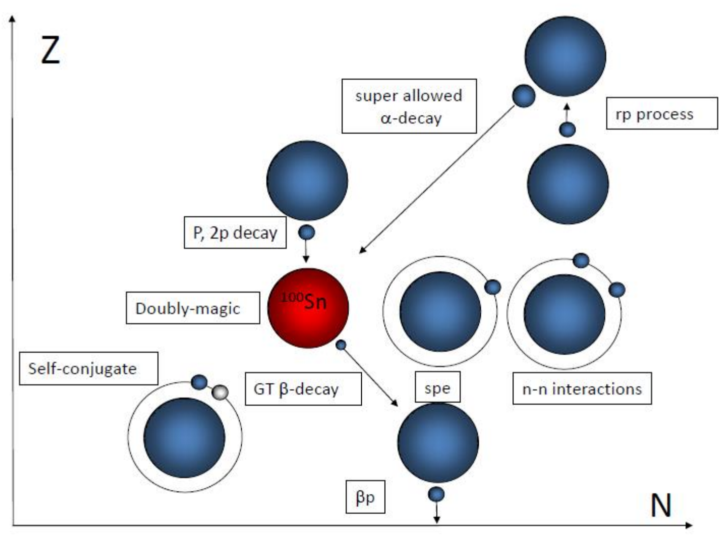

Figure 6: Nuclear physics topics in the 100Sn region.

neutron-proton pairing and isospin symmetry. Strong interaction between protons and neutrons leads to exotic shapes and shape coexistence in the mass A = 80 region. The doubly-magic, self-conjugate ^{100}Sn nucleus is one of the cornerstones of nuclear structure far away from the line of stability. The proton drip-line crosses the N = Z line near ^{100}Sn. It manifests itself in the presence of exotic decay modes such as β-delayed proton emission, one- and two-proton decay. This offers a unique opportunity to study the impact of weak binding on nuclear properties. The astrophysical rp-process path is situated in the vicinity of the N = Z line. In various astrophysical scenarios the nucleosynthesis proceeds via a series of proton captures to levels above the proton threshold in proton-rich nuclei. Properties of these levels determine the path and the time scale of the rp-process. The important nuclear physics aspects of current interest along the N = Z line and around ^{100}Sn are summarized in Figure 6.

Radioactive beams from ReA12 could also be used to characterize nuclei located along the proton drip-line between ^{100}Sn and ^{164}Pb. This region is not as readily accessible by fragmentation reactions. Fusion-evaporation reactions employing radioactive proton-rich beams from ReA12, however, can be used to populate and study exotic proton-rich nuclei. Such reactions offer larger cross sections and lower background from other less exotic reaction channels compared to reactions with stable beams. They provide a unique mechanism to populate moderate to high spin states, which can be characterized using in-beam γ-ray spectroscopic methods. A recoil mass spectrometer coupled to a γ-ray detector array will be essential to assign γ-ray transitions to individual reaction products, which will be separated from the beam and identified according to their mass-to-charge-state ratio (M/Q) in the spectrometer. The energy loss and total kinetic energy measurements behind the final focal plane can then be used to determine their atomic number. Alternatively, the reaction products can be implanted behind the focal plane so their decay properties can be determined. Characteristic decays of the reaction products can also be correlated with the implants to tag prompt γ-ray transitions.

The single-nucleon energies and nucleon-nucleon interactions deduced from properties of excited states of one quasi-particle and two quasi-particle neighbors are critical for a quantitative description of medium mass nuclei. Despite many attempts, not much is known about single-particle energies and nucleon-nucleon interaction in ^{100}Sn. There are many radioactive beam/target combinations, which could be used to study nuclei around ^{100}Sn. The ^{56}Ni radioactive beam, which has two fewer neutrons than stable ^{58}Ni, can be used to study nuclei along the N = Z line nuclei as heavy as ^{116}Xe. The ^{60}Zn radioactive beam combined with a ^{40}Ca target, which would form the ^{100}Sn compound nucleus, will be particularly well suited to study light Sn and In isotopes with N < 50. One can also use more exotic, heavier proton-rich beams in inverse kinematics to enhance exotic channels and increase recoil velocities which will help to deduce atomic number from energy loss and total kinetic energy measurements at the focal plane. A recoil mass separator coupled to a γ-ray detector array will be essential to assign γ-ray transitions to well identified individual reaction products.

Nucleon transfer reactions to investigate evolution of nuclear shell structure and pairing correlation

Nuclei far from stability provide access to investigate nucleon arrangement under extreme values of isospin. Under such conditions, deviations start to occur from our established knowledge of nuclear shells. A detailed discussion can be found for example in [52]. The change of nucleon pairing correlation from stable to unstable nuclei is also an important subject to explore in order to build a complete view of all aspects of the nuclear interaction. The pairing interaction is expected to be significantly modified in nuclei with extended neutron distributions [53]. The changing role of the different components of the nuclear interaction leads to migration of nuclear shells as one approaches the neutron and proton drip lines. Nuclear superconductivity has been understood in the framework of pairing theory [54] [55], since the Cooper pairs are building blocks of pairing, two-nucleon transfer reactions are ideal tools to investigate this phase. The (p,t) transfer reaction is a well-known probe of neutron-pair correlation. In particular, the magnitude of the differential cross section, reflects the strength of the correlation. Another interesting feature to identify is the existence of pairing vibrational states. The systematic study of two-neutron transfer reactions can elucidate how phase transition takes place from a pairing vibrational spectrum around closed shell nuclei to a rotational spectrum far from closed shells [55].

One-nucleon transfer reactions such as (d,^{3}He), (^{3}He,d), (^{3}He,^{4}He) and (d,p) provide spectroscopic factors and spin and parity of the states populated, and are therefore the ideal tool to determine the evolution of single particle states far from stability. In regions around the r-process nucleosynthesis path, the spectroscopic factors can be used to determine the direct neutron capture reaction rates relevant to r-process nucleosynthesis, in cases where no direct measurement is possible. The kinematics of transfer reactions focus the beam-like heavy reaction residue in a very small angle cone in heavy nuclei. A charged particle detector around the target will be used in coincidence with the detection of beam-like residues in the focal plane of the recoil spectrometer. In order to unambiguously identify the reaction channel, measure the scattering angles of heavy recoils and separate the products from the more intense unreacted beam, a recoil spectrometer is crucial.

Deep inelastic reactions and heavy ion transfer below the Coulomb barrier present a different approach to the study of pairing correlations. By using heavy-ions at Coulomb barrier energies, the transition from the quasielastic to the deep-inelastic regime and the channel coupling effects in sub-barrier fusion reactions can be explored [56]. Significant advances have been made in the past years on the nucleon-nucleon correlations, particularly in studies below the Coulomb barrier. In fact, at energies well below the Coulomb barrier, the interacting nuclei are only slightly influenced by the nuclear potential, and Q-values are restricted to a few MeV with only a few open transfer channels. Hence the complexity of coupled channel calculations is reduced and quantitative information may be extracted on the nucleon-nucleon correlations (see [57] and references therein). With the recent experimental and theoretical advances, the study of the interplay between single particle and pair transfer far below the Coulomb barrier is now possible. A recoil mass separator with excellent identification coupled to a Germanium array around the target will be essential to assign γ-ray transitions to well identified individual reaction products.

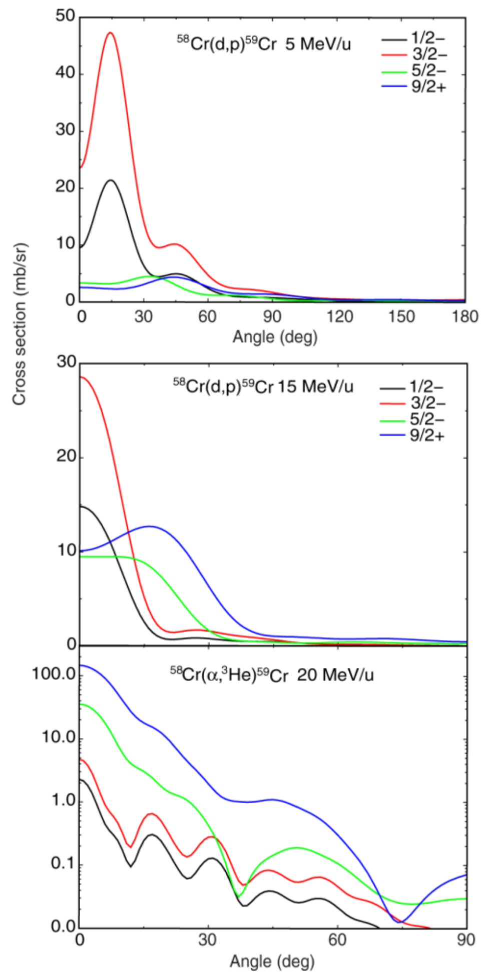

Figure 7: Theoretical prediction of the population of the 9/2+ intruder state in transfer reactions. The calculation is courtesy of Jeff Tostevin and assumes standard optical potentials, unity spectroscopic factors for all states, and a level scheme based on Ref. [86].

Tracking shell evolution with high-l intruder states populated in transfer reactions

Particle-hole excitations across a shell gap into the next higher oscillator shell can become energetically favored due to deformation and pairing correlations. The experimental identification of the resulting intruder configurations – typically high-l states – at low excitation energy and ultimately in the ground state can be selectively performed with transfer reactions at ReA12 beam energies.

Figure 7 illustrates this for neutron $g_{9/2}$ intruder configurations in neutron-rich Cr isotopes approaching *N = 40.* At ReA3 energies of ^{58}Cr (~ 5 MeV/u), the $9/2^+$ intruder state is hardly populated in a (d,p) transfer reaction due to linear and angular momentum mismatch; on the other hand, this beam energy is well matched to the population of states with orbital angular momentum l = 1. The ^{58}Cr rate is estimated to be 2 x 10^4 pps. The cross section for the population of the l = 4 intruder state of interest dominates at forward angles, starting at 15 MeV/u beam energy, and can be best studied at even higher beam energies and using the (α,^{3}He) reaction. Such a technique for the identification of high-l intruder states is of great interest for the study of shell evolution and the identification of new "Islands of Inversion". This program can be realized with a charged particle detector array around the target associated with the recoil spectrometer to separate the beam and beam impurities from the reaction products.

Medium- and high-spin, neutron-rich excitation structures

The goal is to access medium and higher spin configurations up to four neutrons away from the projectile beam. Multi-nucleon transfer with stable beams on stable targets has been very successful in providing first information on medium spin states in, e.g., neutron-rich Ca, Ni, Fe and Cr isotopes. This is one of the few methods available to populate higher spin states in neutron-rich nuclei. Indeed, fusion-evaporation reactions always drive the reaction residues back to neutron-deficient nuclei by neutron evaporation.

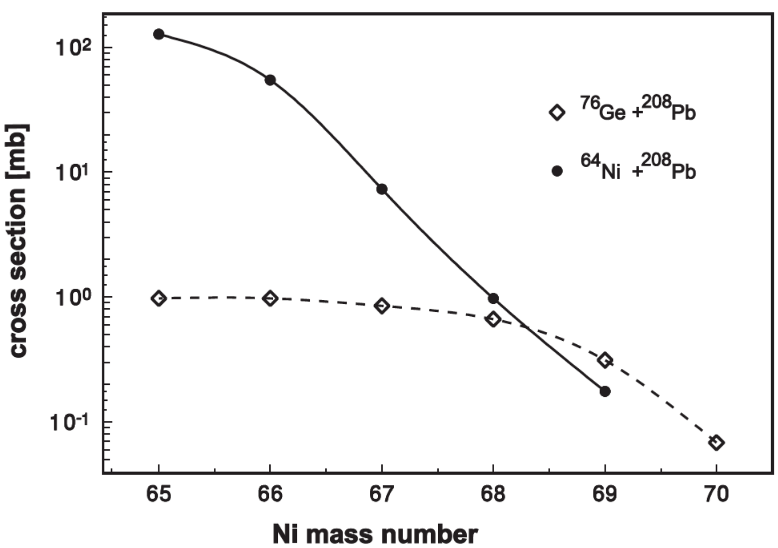

Figure 8: An illustration of the large cross sections for multi-neutron transfer that are possible with 5 to 10 MeV/u neutron-rich beams. The figure is taken from reference [10]. It illustrates that up to five neutrons can be transferred to a neutron-rich projectile (in this case ^{64}Ni) by interaction with a ^{208}Pb target. This coupled with γ-ray detection in GRETA could allow the study of very neutron rich nuclei approaching the drip lines.

Deep-inelastic collisions between neutron-rich projectiles and heavy target-nuclei with an even larger *N/Z* ratio can produce reaction residues that are more neutron rich than the beam nuclei. This process is driven by the exchange of protons and neutrons between the target and projectile during the collision. Typically, excited states with higher angular momentum are populated. Large cross sections for multi-neutron transfer possible with 5 to 10 MeV/u neutron-rich beams have been observed and hold great promise for reaching even more neutron-rich products with exotic projectiles at FRIB.

There are two approaches that have been pursued. The first involves medium-heavy, stable beams (e.g. Ca, Ni) on Pb or U targets with identification of the residues either in particle detector arrays (e.g. CHICO at ANL) or in spectrometers that allow operation away from zero degrees, since the deep-inelastic products are produced at large angles (e.g. ^{41}Ar produced via ^{40}Ar on a Pb target is produced at 40-50 degrees in the lab frame). If using particle detector arrays, the particles are not identified except to distinguish between "target-like" and "projectile-like" species, while γ-ray tagging of the binary partner is used to clarify the identification. Although the γ-ray tagging approach is likely not feasible with lower-intensity, reaccelerated rare-isotope beams. Hence the spectrometer approach would be preferred, but existing equipment, for example Clara-Prisma at Legnaro, does not provide the necessary mass resolution. The second approach, using inverse kinematics at GANIL, uses a U beam on lighter targets (e.g. Ca, Ni, Ge, Se) and uniquely identifies the target-like reaction residues in VAMOS. To exploit the wide variety of high-intensity radioactive beams that will be available from FRIB at ReA12, the approach of medium-mass rare isotopes on U or Pb targets should be pursued.

At FRIB, the goal would be to identify the projectile-like reaction residues event-by-event in the recoil separator to allow particle-gamma coincidence spectroscopy. The γ-ray detection would be accomplished by positioning GRETA at the secondary reaction target, in front of the ReA12 recoil separator. With FRIB and ReA12, in-beam γ-ray spectroscopy following deep-inelastic collisions could be extended to utilize high-intensity, exotic, reaccelerated beams at FRIB. For example, ^{34}Si, ^{40}S, ^{46}Ar (all expected to be produced at rates above 10^7 particles per second) and ^{70}Ni, ^{76}Zn, ^{66}Fe, ^{60}Cr, ^{50}Ca (expected at rates above 10^6 particles per second) will be available at intensities sufficient to perform γ-ray spectroscopy following deep-inelastic collisions. This choice of projectiles will allow one to build, for the first time, the medium-spin excitation level schemes of nuclei at and approaching ^{42}Si (N = 28), ^{50}Ar (N = 32), ^{64}Cr (N = 40), ^{70}Fe (beyond N = 40), ^{80}Zn (N = 50) and approaching ^{78}Ni (Z = 28, N = 50).

For some cases, fusion-evaporation may still be a valuable experimental option. One general technique would involve exciting higher-spin, highly-excited states in nuclei using fusion-evaporation reactions with radioactive beams to complement successful studies which had used stable beams and stable targets. An example of the results from this previous type of study is shown in Figure 9 [58] [59].

One physics goal of these studies would be to locate and characterize cross-shell excitations and to observe their progression with increasing neutron excess. The experimental results could then be used to test and refine, for example, the effective interaction across the N = 20 and N = 28 shells. Current s-d shell interactions such as USD, USDA, and USDB isospin-conserving, interaction Hamiltonians [60] have been very successful for nuclei with proton and neutron numbers between 8 and 20. Extensions of this interaction, such as WBP-a have been equally successful in the sd-pf shell gap for states with one neutron in the f7/2 orbital [58]. The frontier in such configuration interaction models lies with multiple, cross-shell excitations. The key question is whether it is possible to construct an effective interaction Hamiltonian which works well for a wide range of nuclei, including with multiple, shell-crossing particles. These studies would require: 1) a segmented, 4 π charged-particle array and recoil spectrometer for reaction channel selection; 2) a 4 π γ-ray detector array; 3) an ultra-pure beam of particle-bound, heavy O or F isotopes from ReA12 with energy in the few MeV/u range.

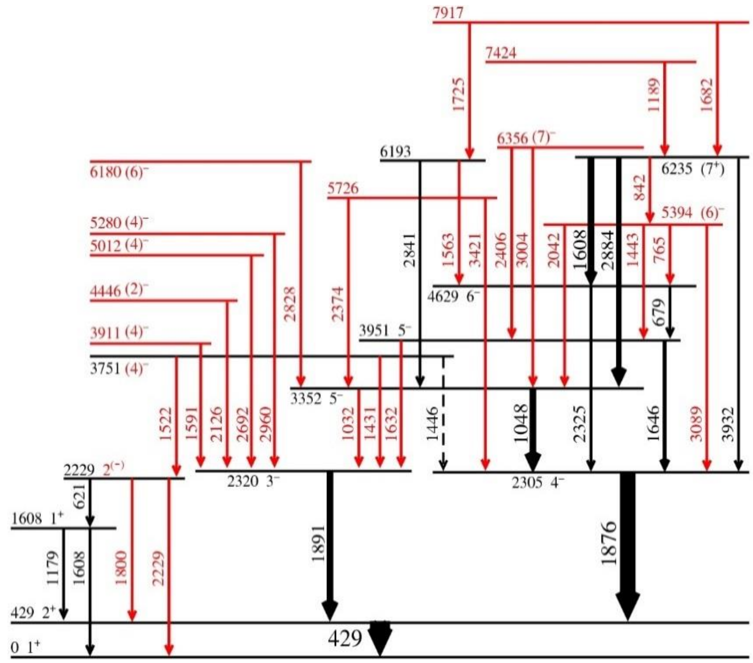

Figure 9: Results of a stable beam experiment using fusion-evaporation to excite higher spin, highly excited states in ^{34}P, including states with cross shell excitations.

Limits of Mass and Charge

The study and synthesis of heavy and superheavy elements (SHE) address many of the most prominent questions in nuclear science [61]:

- What are the limits of nuclear stability?
- How many neutrons and protons can be bound within a nucleus?
- Where are the next spherical shell closures? What is the landscape of the island of stability?
- Are there long-lived ($t_{1/2}$ > days) superheavy elements?
- How do the chemical properties of the SHEs evolve with respect to their location on the periodic table?

There are two promising heavy element research programs that are likely to be pursued at ReA12. The first of these involves the use of multi-nucleon transfer reactions to synthesize new neutron-rich heavy nuclei. We have long known that multi-nucleon transfer reactions with radioactive beams, such as the reaction of ^{144}Xe with ^{248}Cm, can be used to make—with cross sections of the order of 0.1-10 mb—new neutron-rich nuclei such as $^{244-253}$U, $^{245-255}$Np, $^{248-256}$Pu, $^{250-257}$Am, and $^{252-258}$Cm [62]. More recently, Zagrebaev and Greiner [63] have shown that due to the effect of nuclear shell structure, one may also form neutron-rich, trans-target heavy nuclei. In the reaction ^{238}U + ^{248}Cm ($E_{c.m.}$ = 750 MeV), they correctly described the measurements of transfer cross sections made in the 1980s and have predicted the formation of new neutron-rich isotopes of Sg. Other promising reactions, such as the ^{136}Xe + ^{208}Pb reaction populate nuclei near the N = 126 r-process waiting point [64].

A second area of heavy element research likely to be pursued at ReA12 is the use of fusion reactions with radioactive projectiles—such as ^{16}C, ^{20}O, ^{21}F—to form transactinide nuclei at rates greater than five atoms per day. The neutron-rich isotopes of Sg ($^{267-271}$Sg) can be made in fusion reactions with ^{20}O, $^{23-26}$Ne, and $^{29-30}$Mg. Special targeted FRIB beams of species like ^{46}Ar, can be used to produce $^{286-287}$Cn.

The importance of exploring SHE synthesis with RIBs at FRIB was specifically mentioned in the NSAC 2007 Long Range Plan Report [7], the National Academies Decadal Study of Nuclear Physics [3], and the RISAC Report [6]. The world-unique opportunity to explore SHE synthesis with RIBs will require a separator at ReA12 to allow for a clean separation of the evaporation residues from the incoming RIB. More specifically, a gas-filled mode of the separator could offer greatly enhanced efficiencies for collection of the heavy residues by minimizing the charge state distribution. Without the development of the ReA12 separator, this physics opportunity, which has been consistently discussed in the planning of FRIB, will be lost.

Multinucleon transfer

Traditionally, via multinucleon transfer reactions at Coulomb barrier energies one can investigate nucleon-nucleon correlations in nuclei, the transition from the quasielastic to the deep-inelastic regime and channel coupling effects in sub-barrier fusion reactions [56]. In this mechanism nuclear structure still plays a significant role in the dynamics. One of the important properties of MNT is the possibility to produce neutron-rich heavy nuclei, especially near Pb and in the actinide region, where other production methods, like projectile fission or fragmentation, have severe limitations.

To understand the optimal way to synthesize these neutron-rich nuclei, one has to keep in mind that transfer processes are governed by the structure of colliding nuclei and dynamics of nucleon exchange. In general, reactions using stable (medium-heavy) projectiles on (heavy) targets result in neutron transfer from target to projectile, while the protons are transferred from the projectile to the target, thus producing medium-heavy neutron-rich nuclei. By using radioactive neutron-rich ion beams, this flow of protons and neutrons may turn around, synthesizing heavy neutron-rich nuclei [65]. In the study of their production rate it is important to investigate transfer processes by using projectiles ranging from stable to neutron-rich isotopes, and to evaluate the main characteristics of the final nuclei, i.e. Z, A distributions and cross sections, excitation energy, and transferred angular momenta. It is especially important to evaluate the effect of the secondary processes that may strongly affect the final production yields, especially for the heavy partners.

The study of these processes will require the identification of heavy reaction products near the Pb region (and beyond) in a wide angular range (near grazing angles on the target, which depend on the bombarding energy and the specific reaction) either detecting the products directly or detecting the light partner in coincidence with the associated binary partner, possibly by way of coincident gamma ray detection. Hence a recoil spectrometer will be needed at ReA12 for most cases and will be particularly beneficial for rare isotopes with unknown excitation structure.

Heavy ion fusion

Currently, the ability to extend measurements of SHEs is limited by the available combinations of stable beams and stable/actinide targets. However, addressing the questions posed above would require the ability to extend SHE measurements to more neutron-rich isotopes. One possible mechanism to accomplish this would be through heavy-ion fusion reactions induced with neutron-rich radioactive ion beams. While reaching the island of stability or extending the periodic table through RIB induced reactions is extremely unlikely with ReA-FRIB, the opportunity to develop an understanding of RIB induced fusion reactions, produce new neutron-rich superheavy isotopes, and move towards the region of long-lived superheavy nuclei [66] [67] will be possible. Predictions have been made for ReA-FRIB indicating that the synthesis of new neutron-rich “light SHE” ($Z \leq 105$) will be possible [68] [69]. Production of these “light SHEs” would offer extended studies of the $N = 162$ deformed shell closure [70], and new, long-lived heavy nuclei [68]. Furthermore, the first synthesis of the new SHE isotopes using RIBs will represent a crucial step forward towards defining what will eventually be required to reach the expected region of long-lived SHEs. Figure 10 shows the production capabilities for SHE offered by RIBs relative to stable beam experiments, and the region of new neutron-rich isotopes that may be possible to

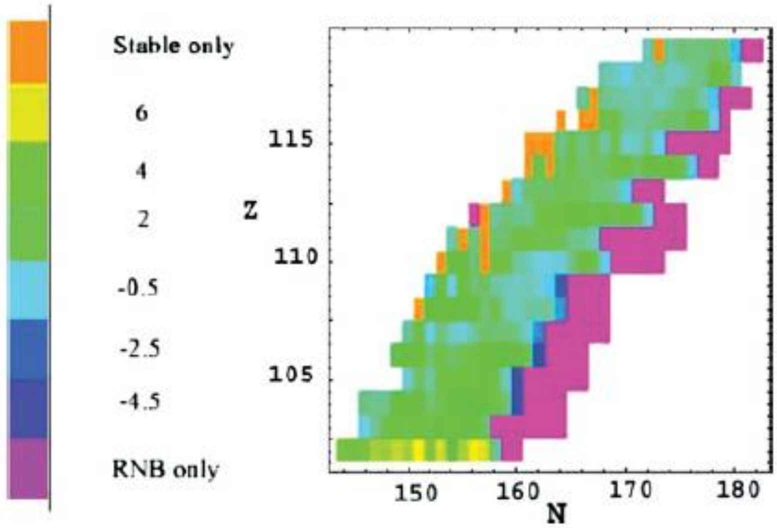

Figure 10: Ratio of the production rate for different SHE isotopes from stable and radioactive ion beam induced reactions. Taken from [68].

produce. Many isotopes are expected to be only produced using RIBs and a recoil separator at ReA12 will be needed to separate these products from unreacted beam and to identify them unambiguously from the products of other reaction channels.

Fusion barrier studies

The interaction barrier in a system of two colliding heavy ions is the major feature governing the reaction mechanism dynamics. The extraction of the fusion barrier distribution from precisely measured fusion excitation functions in corroboration with coupled channel calculations has successfully been employed to study detailed features of the barrier structure in heavy ion collisions [71]. For neutron rich projectiles, available at RIB facilities like FRIB, exhibiting exotic spatial nucleon distributions like halos or neutron skins, modifications of the interaction barrier are expected. A first indication of this has been seen in the comparison of nucleon transfer and fusion for $^{4,6,8}He$ + ^{197}Au [72]. The investigation of charge radii in collinear laser spectroscopy revealed—for neutron rich potassium isotopes—a steep increase of the root mean square radius beyond the closed neutron shell at N = 28 [73]. Given the limited RIB intensities an alternative tool to study the fusion barrier could be employed using the compound nucleus spin distribution.

With this method a complete barrier distribution [74] can be measured at just one beam energy. The high efficiency of γ multiplicity detector arrays like CAESAR or GRETA of typically $\approx$ 80 % helps to keep measurement times reasonably short.

Applications could range from reaction mechanism studies of exotic neutron-rich species, preparing eventually even for the production superheavy nuclei, to the investigation of exotic features of the neutron rich species themselves. Measurements using neutron rich potassium isotopes on spherical target nuclei could be a first series of key experiments, in particular by comparing the results with reaction studies performed with ^{48}Ca, successfully used to study the heaviest nuclei.

ISLA (Isochronous Separator with Large Acceptance) Technical Description

The future ReA12 linac re-accelerator planned at NSCL-FRIB will provide radioactive beams with intensities up to 10^{10} pps at energies up to 15 MeV/u. For many experiments reacting these radioactive beams on a stationary target, a recoil spectrometer is needed to collect, identify and separate the recoiling ions. Because these re-accelerated radioactive beams have relatively low intensities, this spectrometer should have large momentum and solid angle acceptances, to collect as many ions as possible, depending of their ionic charge state and the kinematics of the reaction. These requirements usually imply tradeoffs between the mass-to-charge (M/Q) resolution and the ability to separate and collect recoils. Good optical resolution typically implies small acceptances, such as in the FMA [75] or EMMA [76], whereas large acceptance typically implies poor optical resolution and large focal planes, such as in VAMOS [77], PRISMA [78] or MAGNEX [79]. For large acceptance spectrometers, resolution can be recovered by tracking and software corrections, but this method becomes impractical at low recoil energy.

To solve this conundrum, ISLA uses different separation and measurement methods to combine large acceptances with excellent M/Q resolution. Based on the concept of the TOFI spectrometer [80], ISLA is an isochronous device where the time-of-flight from the target to the final focus is independent of the energy and scattering angle after the reaction. The time-of-flight is therefore a direct measurement of the M/Q ratio. Since it is a magnetic spectrometer, the beam charge states can be filtered out at the intermediate dispersive focal plane, while the transmitted ions are selected according to their magnetic rigidity within the acceptance.

The physics case driving the requirements of this spectrometer is diverse. Radioactive beams are presently used extensively in studies involving simple reactions such as transfer of one or two nucleons or Coulomb excitation from a high Z target but also for more complex reactions such as fusion-evaporation or multi-nucleon transfer (also called deep-inelastic) used to populate high spin states, to cite a few. A crucial feature of the spectrometer is its ability to identify and tag recoiling ions while collecting as many as possible within its acceptances. The innovative method used in ISLA is especially well designed to accomplish this task. In order to make best use of available beams, most experiments will have a powerful gamma or reaction particle detector around the target. Many will include a recoil decay detection station to study the properties of the reaction products. Many of the studies described above will imply systems with medium to heavy mass beams, and therefore high resolution is necessary to achieve M and Z identification. An event-by-event beam identification will also be necessary to separate beam contaminants.

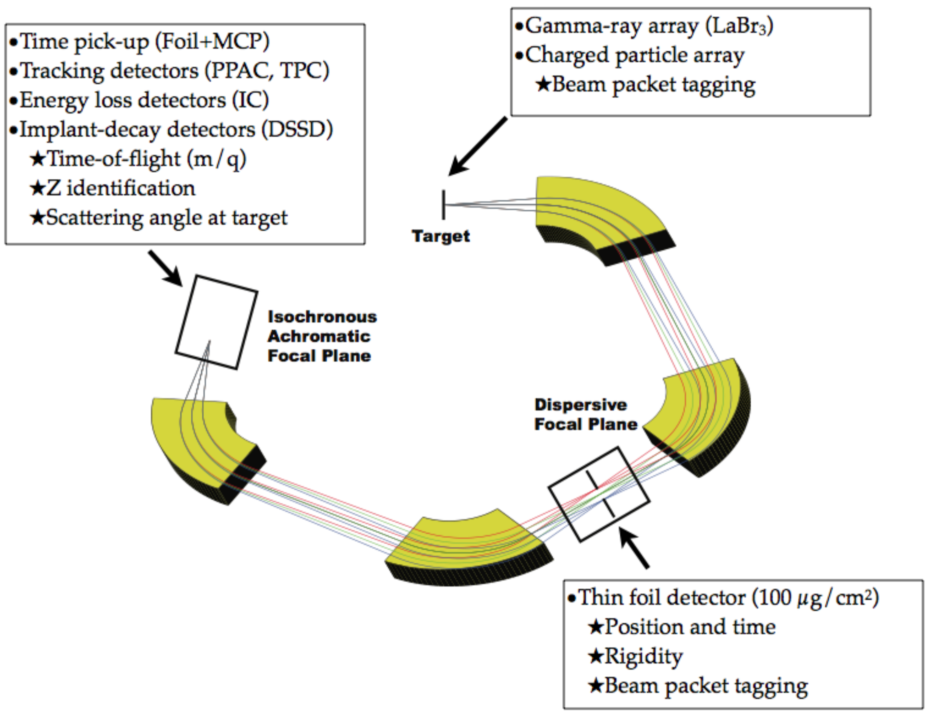

Figure 11: A schematic view of the ISLA spectrometer. A measure of the time-of-flight between the target and the isochronous focus is a direct measure of the M/Q ratio of the selected ions, independent from their momentum vector. Slits or fingers located at the dispersive focal plane are used to filter out charge states of the unreacted beam if they happen to lie within the momentum acceptance. The text boxes describe possible detector arrangements and their corresponding measurements. The detector configuration is highly dependent on the energy of the ions traveling through the spectrometer.

Preliminary Design

The acceptances of ISLA are 64 msr in solid angle and ±10 % in momentum. Contrary to most spectrometers with large acceptances, the focal plane of ISLA is very small. This is due to its highly symmetrical layout, in which the optics provide a point-to-point relationship between the target and the focus. As a result, the scattering angle of the reaction products emitted from the target can be directly deduced from position and angle measurements at the focus. In addition, the symmetry of the design helps to reduce the high order aberrations to very small values, despite the large acceptances.

The design of ISLA is geared towards its use with re-accelerated radioactive beams. Contrary to most spectrometers using high-intensity stable beams, a spectrometer for radioactive beams only needs moderate selectivity, mostly to reject unreacted or scattered beam particles. One advantage in using radioactive beams to induce nuclear reactions lies in the low background that can be achieved by selecting a reaction where the reaction channels of interest are not among the weakest. One prominent usage of radioactive beams are in inverse kinematics reactions, where the probe is a light target (p, d, ^{6,7}Li or ^{9}Be) and structure information can be obtained on both the projectile and the reaction products. Existing examples of such devices are the VAMOS spectrometer at GANIL [77], or the S800 spectrometer at NSCL [81]. In both instances, the selectivity is only in magnetic rigidity. The large acceptances require large focal planes and sophisticated tracking to achieve a reasonable resolution and particle identification. ISLA will have an M/Q resolution of better than 1 part in

1,000, important for the heavy mass region. An example of a simulation of the α2n fusion-evaporation reaction between a ^{56}Ni beam and a ^{50}Cr target to produce ^{100}Sn is shown in Figure 12. Even though this reaction is clearly not the strongest channel in this case, the tagging of the ^{100}Sn charge states is very clean, with few to no contaminants superposed on the M/Q peaks. In addition, a small RF kicker placed at the isochronous focal plane can provide physical separation between the ^{100}Sn and most of the other evaporation residues produced in the reaction, as well as regroup the most intense charge states of ^{100}Sn at a single location. The details of this unique capability are discussed in a recent publication [82].

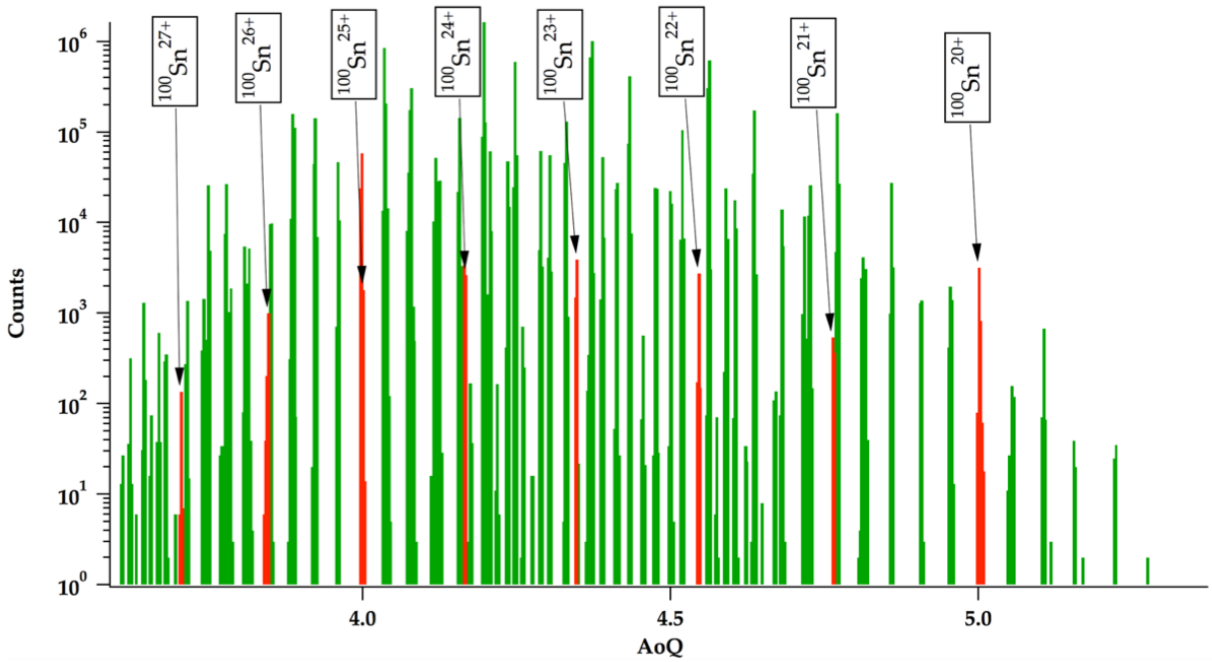

Figure 12: Simulation of the M/Q spectrum obtained from the time-of-flight measurement in ISLA, in the case of the $^{50}Cr(^{56}Ni,\alpha 2n)^{100}Sn$ reaction at 3.7 MeV/u. The peaks colored in red and labeled indicate the position of the ^{100}Sn charge states. The M/Q assumed in this simulation is 1 part in 2,000.

The novelty of the ISLA design opens new possibilities, where one envisions γ-ray and/or charged particle arrays around both the target and focal plane locations. For example, the beta-decay of a nucleus could be studied at the same time as its level structure, or long-lived isomeric decays populated in a reaction could be detected. It is also worth mentioning that some experiments might use the first half of this spectrometer only, taking advantage of the dispersive plane to measure the kinematic properties of reaction products for reaction studies.

The M/Q resolution of ISLA depends primarily on the time-of-flight measurement resolution from target to focus and flight time through the spectrometer. A stop signal can easily be obtained from a micro-channel plate (MCP) detector located at the focus, with a typical resolution around 100 ps. The time reference can be provided by an MCP at the target or the radio frequency (RF) signal of the accelerator, giving bunches separated by about 12.5 ns. Time-of-flight—and therefore M/Q—resolution can be estimated to 0.1 ns for an MCP and 1 ns for a RF bunch time reference. For a 1 ns bunch resolution and flight time of about 1 µs, the M/Q resolution is 1 part in 1,000. The 12.5 ns period of the RF will cause several wrap-arounds of the time-of-flight measurement, which may severely impair the ability to identify the transmitted ions. The accelerator group has put forward a solution to regroup bunches by a factor of 5, without any loss in the acceptance of the RFQ and the rest of the accelerator [83]. Combined with the resulting 62.5 ns longer period, a pulsed mode of the EBIT charge breeder could allow even longer periods, hence eliminating or greatly reducing the number of wrap-arounds. An alternative way to avoid ambiguity due to wrap-arounds would be to use the timing information from a detector array placed around the target to tag the beam bunch that induced the reaction. This coincidence experiment configuration is common among experiments that are planned with a recoil spectrometer (see the section titled *Physics Case*). This method can also possibly provide a better time reference than the RF signal, depending on the time resolution of the detector array. With resolutions around 300 ps, the M/Q resolution can reach values closer to 1 part in 2,000, taking into account the largest higher order aberrations.

The novel concepts used in the design of the ISLA spectrometer make it the ideal instrument for collecting, identifying and separating recoils from a wide range of nuclear reactions to be used with the re-accelerated radioactive beams of the future ReA12 accelerator at NSCL-FRIB. The maximum magnetic rigidity of the spectrometer should match that of the incoming beamline, which was fixed to 2.6 Tm, in order to be able to detect beamlike reaction products. In a gas-filled mode rigidities of up to 2.5 Tm have been requested. ISLA is designed to achieve this value. For reactions with cross sections peaked away from zero degrees, a beam swinger can be installed in front of the spectrometer to avoid its rotation and minimize its footprint. The large solid angle and momentum acceptances could be realized with a new technology using superconducting helicoidal windings, which offers promising options for manufacturing the dipole magnets with active shielding [84]. A more conventional dipole structure of iron and superconducting coils will be compared to this solution.

Gas-filled separator modes

A gas-filled spectrometer was not chosen as basic spectrometer solution because it did not meet the needs of many experiments, with respect to M/Q resolution for example. However, in fusion-evaporation experiments, a gas-filled mode may be useful for two main reasons: 1) getting physically rid of the incoming beam at 0°, 2) increasing the efficiency for evaporation residues and determining, for example, absolute reaction cross sections without a specific influence of charge state distributions. A gas-filled separator is considered to be relevant also for multi-nucleon transfer reactions. It was shown for the VAMOS spectrometer that such a mode may be used even in a spectrometer that was not specifically designed for it [85]. The performance of ISLA has been evaluated in a gas-filled mode. The results indicate that the implementation of a gas-filled operation would be useful and possible at ISLA for a very wide range of kinematics. We may distinguish two distinct modes of gas-filled operation—with detectors at the intermediate dispersive focal plane or at the final achromatic focal plane. The shorter system with detection at the dispersive plane may be necessary in direct kinematics with large asymmetry, because evaporation residues will be very slow, and the 16 m of the total ISLA device may be too long.

Reaction	**$B\rho_{beam}$[Tm]**	**$B\rho_{product}$[Tm]**	**$\Delta B\rho$[%]**	**ΔTheta[mrad]**
^{48}Ca(214MeV) + ^{208}Pb → ^{254}No	0.9	1.99	8	50
^{208}Pb(1039MeV) + ^{48}Ca → ^{254}No	1.55	1.77	3	60
^{54}Ca(195MeV) + ^{58}Ni → ^{110}Xe	0.79	0.95	3	25
^{238}U(1200MeV) + ^{48}Ca → ^{284}112	1.85	1.96	4	10
^{238}U(1350MeV) + ^{64}Ni → ^{300}120	1.88	2.01	4	10
^{136}Xe(870MeV) + ^{208}Pb → ^{204}Pt	1.36	1.59	As acceptance	As acceptance
^{136}Xe(870MeV) + ^{208}Pb → ^{204}Pt	1.45	1.67	As acceptance	As acceptance

Table 1: Examples of reactions with a gas-filled spectrometer, Bρ: central value of beam and product in gas, ΔBρ FWHM, ΔTheta: FWHM; in the last two examples, the spectrometer has an angle of 45 and 15 degrees with respect to the beam.

The quoted Bρ values correspond to the Q_{gas} parameterization which was estimated to be the most reliable in each specific case. The numbers include the target thickness and also the widths induced due to the continuous interaction with the gas. They should be relevant for the sizes. The images in the dispersive direction of the reaction products are up to 40 cm wide at the intermediate focal plane, and 10-14 cm at the non-dispersive final focal plane.

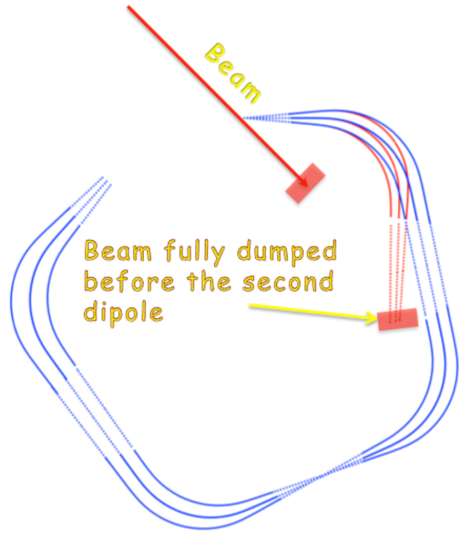

Figure 13: An example of particle envelopes produced in the deep-inelastic, multi-nucleon transfer reaction $^{136}Xe + {}^{208}Pb \rightarrow {}^{204}Pt$, with ISLA operating in a gas-filled mode.

In Table 1 (and Figure 13) selected examples of reactions that are well documented in the literature are shown. In all cases a good or reasonable separation of beam and products, and an excellent transmission were obtained. The maximum Bρ value is below the design value of 2.6 Tm.

Installation

ISLA will be installed in an experimental vault that has yet to be constructed but is within the existing NSCL building. The space will be repurposed and shielded as the ReA12 experimental vault before ReA12 becomes fully operational (see Figure 14). The beam line is proposed to enter the room through the south vault shielding wall. The facility beam line will include basic beam diagnostics and a Faraday cup. A beam swinger, part of the ISLA project, will follow the diagnostics to provide incoming beam trajectories on the target that are up to 50 degrees off of the central axis of ISLA. The swinger is not included in the current design drawing, as alternative configurations are currently being considered, but sufficient space is available along the incoming beam line. The GRETA system provides the most significant requirement for open space around the target. The layout shown would provide space for GRETA around the target, allow space to one side for the frame to be installed and retracted, and leave additional open vault space for the required auxiliary systems. For the focal plane, space is available for the installation of the necessary standard detection as well as for the use of an RF kicker at the achromatic, isochronous focus with detectors—including a possible implantation decay station—to be placed further downstream.

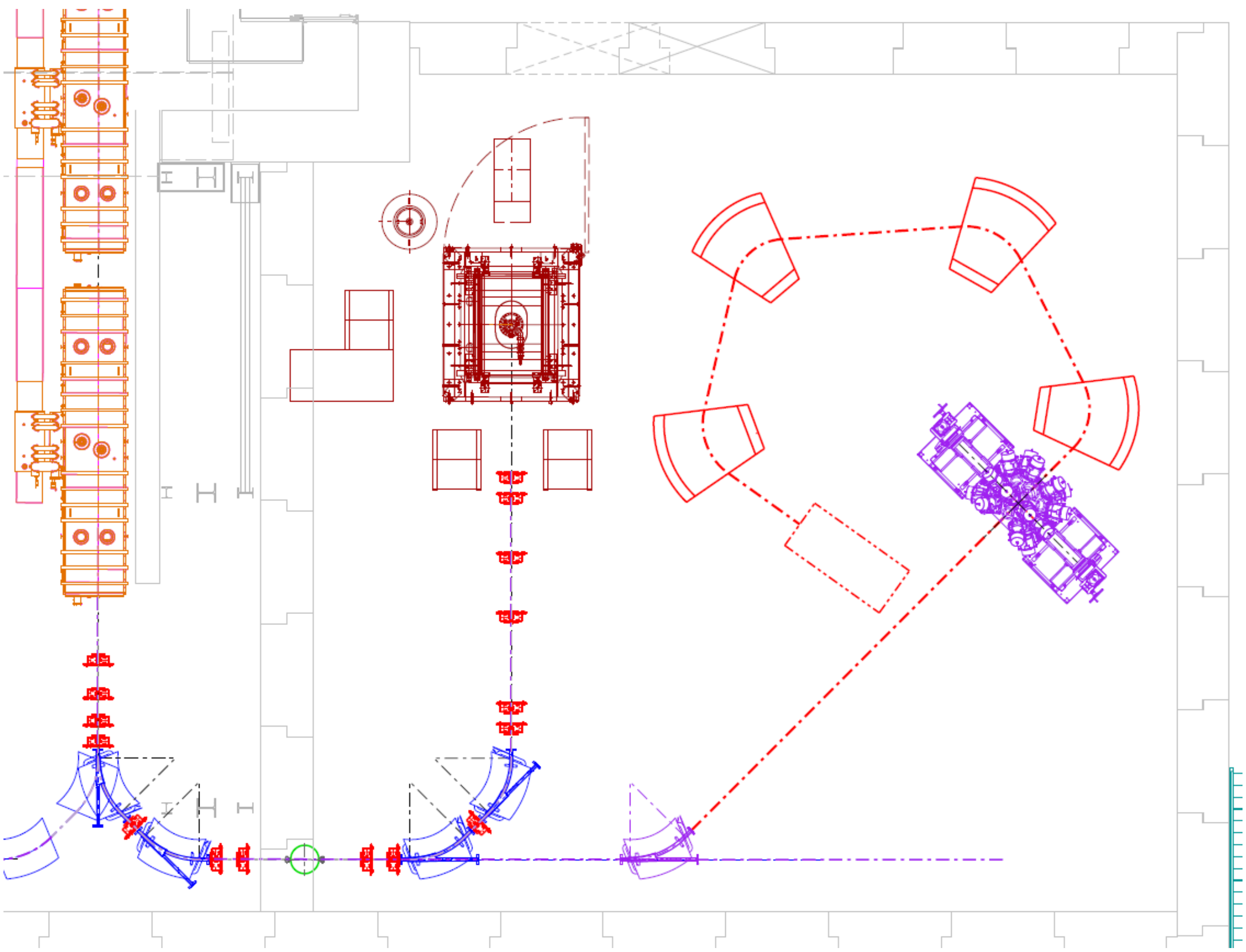

Figure 14: Mechanical design drawing showing the possible positioning of ISLA (right) in the ReA12 experimental vault alongside the AT-TPC (center) and in the context of the final cryomodules of ReA12 (far left). GRETA is shown installed at the target position of ISLA. The box drawn at the end of ISLA encloses a space 2.25 meters long—downstream of the focal plane—that will be available for experimental equipment.

Budget

The price of designing, acquiring and installing ISLA has been estimated on the basis of actual cost estimates from prior projects conducted at the NSCL. These costs include equipment procurement and manufacturing, labor, as well as indirect costs priced with a 52 % rate on non-equipment expenditures. A contingency of 25 % for equipment and 20 % for labor has been included in the final figures. The table below shows the cost break down.

The dipole cost is estimated assuming in-house construction, with 30 % of the dipole cost itemized as “materials” and the remaining 70 % of the dipole cost itemized under “labor.” The cost of cryogenic supply and return lines is included under Infrastructure. Cryogenic capacity of the existing 900W plant is expected to be sufficient to supply the ISLA dipoles in addition to ReA6 and ReA12, though this may require careful consideration of efficiency in the design of the ISLA dipoles.

The facility will bring beam lines into a ReA12 experimental vault to be constructed for experimental equipment inside an existing building space at NSCL. The facility provided beam line will terminate with basic diagnostic detection, developed in coordination with the ISLA design group, and a Faraday cup. For ISLA, diagnostic detectors near the target should indicate the beam position and size as well as the time structure of the beam, since the time structure is critical to achieving the desired M/Q resolution. A rebuncher may be necessary near the end of the incoming beam line to provide the desired, narrow bunch width, depending on the energy of a particular reaccelerated beam and the final performance characteristics of the ReA6 and ReA12 accelerators. This cost of this rebuncher is included under “Beam line components” as is also the cost of the incoming beam swinger.

Item	Cost in M$
Dipoles (materials only)	1.5
Beam line components	0.8
RF kicker	0.4
Infrastructure	0.6
Detectors	0.3
Labor	4.2
Indirect	2.2
Total	**10.0**

Table 2: Cost estimate for ISLA.

Appendix: Working Group Recommendations

The ReA12 recoil separator working group was constituted on August 18, 2012. It was formed by the combination of previously separate working groups: the gas-filled separator working group, the electromagnetic low-energy recoil separator working group, and the high efficiency spectrometer working group, each with a concept for an experimental device to perform experiments with ReA12 beams. Subsequent efforts, including multiple working group meetings and discussions considered these options in detail in light of physics cases proposed by the community to take advantage of the reaccelerated FRIB beams. On July 12, 2014 a workshop was held with the goal of selecting a single concept that best addressed the proposed physics cases.

At the close of the workshop, attendees unanimously endorsed the following recommendations on behalf of the recoil separator working group:

- The ReA12 recoil separator working group recommends construction of the ISLA spectrometer following ReA12 to enable the pursuit of the important physics cases to be made possible only by such a system.
- We recommend developments in the reaccelerator at NSCL to provide time structure with flexible spacing between bunches equal to or greater than 500 ns and bunch widths equal to or less than 200 ps (1 sigma) at the entrance to ISLA, without significant losses in total rate.
- We recommend including design and construction of a low-energy RF kicker following ISLA, to provide physical separation of the recoils by M/Q when needed or beneficial.
- We recommend a design study of the beam swinger to provide incoming beam angles up to 50 degrees with a more compact design that is compatible with simultaneous use of presently desired auxiliary detector systems.
- We recommend the development of detailed plans for installing GRETA at the ISLA target station, including necessary support structure and computing infrastructure, while also accommodating significant experimental equipment in the focal plane of ISLA (e.g. the RF kicker, implantation decay station with gamma or neutron detection, etc.)

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