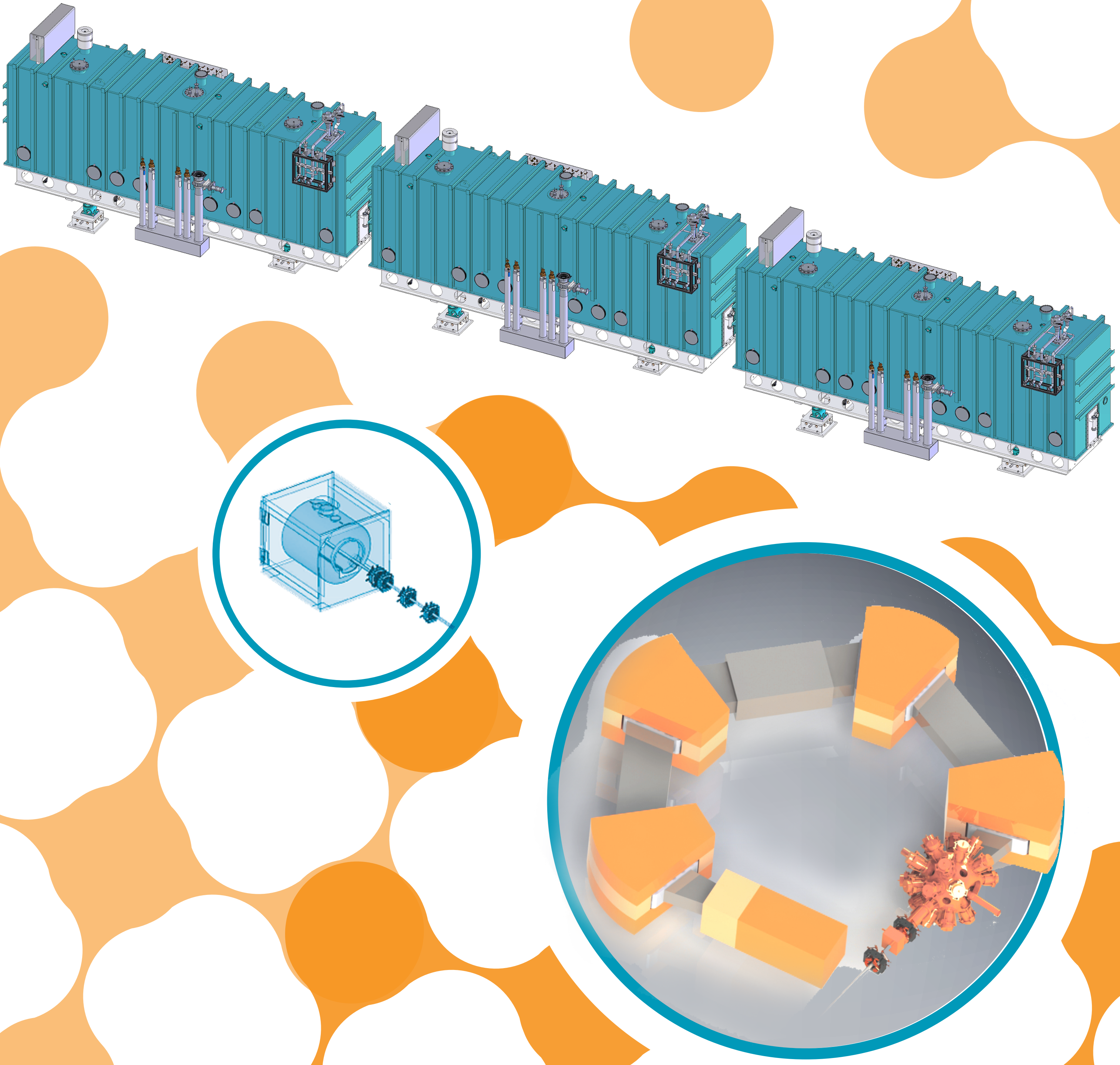
ReA

ENERGY UPGRADE



WHITE PAPER ON REA ENERGY UPGRADE

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1. Introduction and Executive Summary

The Facility for Rare Isotope Beams (FRIB) will provide beams of rare isotopes with unprecedented intensities and will allow scientists to map the nuclear landscape, to understand the forces that bind nucleons into nuclei, to answer questions about the astrophysical origin of nuclear matter and to address societal needs related to nuclear science and technology. Central to the FRIB concept is the in-flight separation of rare isotopes and use of these beams at low and high energies [LRP15,NSAC07]. The full complement of the fast, stopped, and reaccelerated beam capability offers a broad spectrum of rare-isotope science programs with beam energies from a few keV/nucleon up to at least 200 MeV/nucleon, maximizing the science discovery potential at FRIB.

The Low-Energy Nuclear Physics community has strongly endorsed the early implementation of reaccelerated beams with energies up to 12 MeV/nucleon at FRIB [FRIB09,NSCL09,ReA12] and as soon as possible at NSCL [LRP15,LECM15]. The combination of in-flight separation, gas stopping and reacceleration is a world-unique approach to produce low-energy beams of rare isotopes at sufficient energies to exploit well-established reaction techniques and to further develop experimental and theoretical tools necessary for emerging nuclear physics programs at NSCL and FRIB.

The National Research Council Committee posed four overarching questions for nuclear physics [NRC13];

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

How does subatomic matter organize itself and what phenomena emerge?

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 2015 Long Range Plan [LRP15] reaffirmed these questions and stated "*since the last Long Range Plan in 2007, we have considerably increased our understanding of the nucleus and its role in the universe. But answers to the overarching questions that drive the field require still deeper understanding of atomic nuclei, both theoretically and experimentally. The breadth of the research questions requires complementary approaches with a variety of tools and techniques*", identifying needs for a diverse set of nuclear science programs to answer the above overarching questions.

This whitepaper presents scientific opportunities afforded by an energy upgrade to the present ReA facility at NSCL. ReA3 is operational [ReA3], delivering reaccelerated beams of rare isotopes to experiment as part of NSCL's user program. Unique physics programs have started with major equipment such as ANASEN [Lin12], JENSA [Chi14,Bar15] and the AT−TPC [Suz12]. An energy upgrade of ReA up to 6 MeV/nucleon and eventually up to 12 MeV/nucleon opens up a variety of new physics opportunities as outlined in this whitepaper. The capability to produce world-unique beams of rare isotopes up to 12 MeV/nucleon is achieved at ReA through a multi-stage operation of the facility including in-flight separation after fragmentation or fission, gas stropping, charge-breeding and subsequent reacceleration. The use of stopping in a helium gas and charge breeding provides a nearly chemistry-independent source of ions, thereby complementing the ISOL technique. Low-energy rare-isotope beams with well-defined beam energies and small emittance have been pursued at ISOL facilities worldwide, whereas no other facility than

ReA will have the full range of elements available from in-flight separation. At NSCL, and in the future at FRIB, state-of-the-art equipment such as GRETINA/GRETA [Pas13], a solenoidal spectrometer [Wuo07,Lig10], the AT−TPC [Suz12], and ISLA [ISLA15] as well as a variety of complementary detection systems will be available or are envisioned for science programs with higher-energy reaccelerated beams.

The NRC’s Rare Isotope Science Assessment Committee (RISAC) report from 2007 [RISAC07] articulated the science drivers for FRIB encompassing a broad range of nuclear science: nuclear structure physics, nuclear astrophysics, fundamental symmetries, and societal applications. They are summarized below and listed together with the relevant section numbers of this whitepaper. The physics programs enabled by a ReA energy upgrade cover a large fraction of science drivers of FRIB.

Nuclear Structure Physics

- Testing Nuclear Structure Concepts (2.4)
- Probing the modification of shell structure (2.1, 2.2, 2.3)
- Pairing and superfluidity (3.3)
- The evolution of collective motion in complex nuclei (3.1, 3.2, 3.4)
- Production and properties of the heaviest nuclei (4.1, 4.2)
- Probing neutron skins (2.4)

Nuclear Astrophysics

- The origin of the heaviest elements (5.2)
- Explosive nucleosynthesis (5.1)
- Composition of neutron stars (4.3)

Fundamental Symmetries

- Test of fundamental symmetries with rare isotopes (6.1)

Other Scientific Applications

- Applications for the benefit of stockpile stewardship, materials science, medical research, and nuclear reactors (7.1, 7.2, 7.3)

To meet the scientific goals at FRIB listed above, key nuclear reactions are identified in the RISAC report [RISAC07] that include single- and two-nucleon transfer reactions at 10−20 MeV/nucleon, single-step or multiple Coulomb excitation of heavy nuclei, fusion and multi-neutron transfer, and (quasi) elastic scattering. These reactions are best or exclusively studied with low-emittance beams of precisely controlled energies, which is the exactly the scope of the energy upgrade of the ReA facility. High-quality data from these reaction studies spanning a wide beam-energy range will also provide important benchmarks for advanced *ab-initio* theory that has taken first steps to unify the fields of nuclear structure and reactions [LRP15], enabling insights into the nature of the nuclear force and nuclear dynamics.

FRIB will provide rare-isotope beams with unmatched intensities, exceeding what is available today by orders of magnitude. It will make the unique reacceleration scheme for in-flight separated beams a vital tool for providing exotic beams at the desired low energies for experiments. Physics programs with the reaccelerated beams will complement the fast-beam programs, in particular, aiming at aspects of the structure and reactions of exotic nuclei only accessible in experiments at the ReA beam energies. The reach and extent of the scientific motivations described in this whitepaper is illustrated in the nuclear chart shown in Fig.1.1. The whole program covers the full mass range from light to medium-mass and to very heavy nuclei, approaching the neutron and proton driplines as well as actinide isotopes. At the same time, a wide variety of subjects are addressed including nuclear structure and reaction studies, nuclear astrophysics, fundamental symmetries, and applications, all of which are essential to answer the overarching questions [NRC13] reaffirmed by the 2015 Long Range Plan [LPR15] and for meeting the science goals at FRIB as articulated by the RISAC report [RISAC07].

The ReA energy upgrade will provide unique beams to:

- facilitate reaction studies with well-established probes, mapping out the evolution of structural phenomena throughout the nuclear chart
- reach medium- and high-spin states in neutron-rich exotic nuclei, elucidating the interplay between neutron excess and angular momentum
- extend the new-isotope discovery potential at FRIB to heavier neutron-rich nuclei
- address broad topics of astrophysics and societal applications of nuclear science

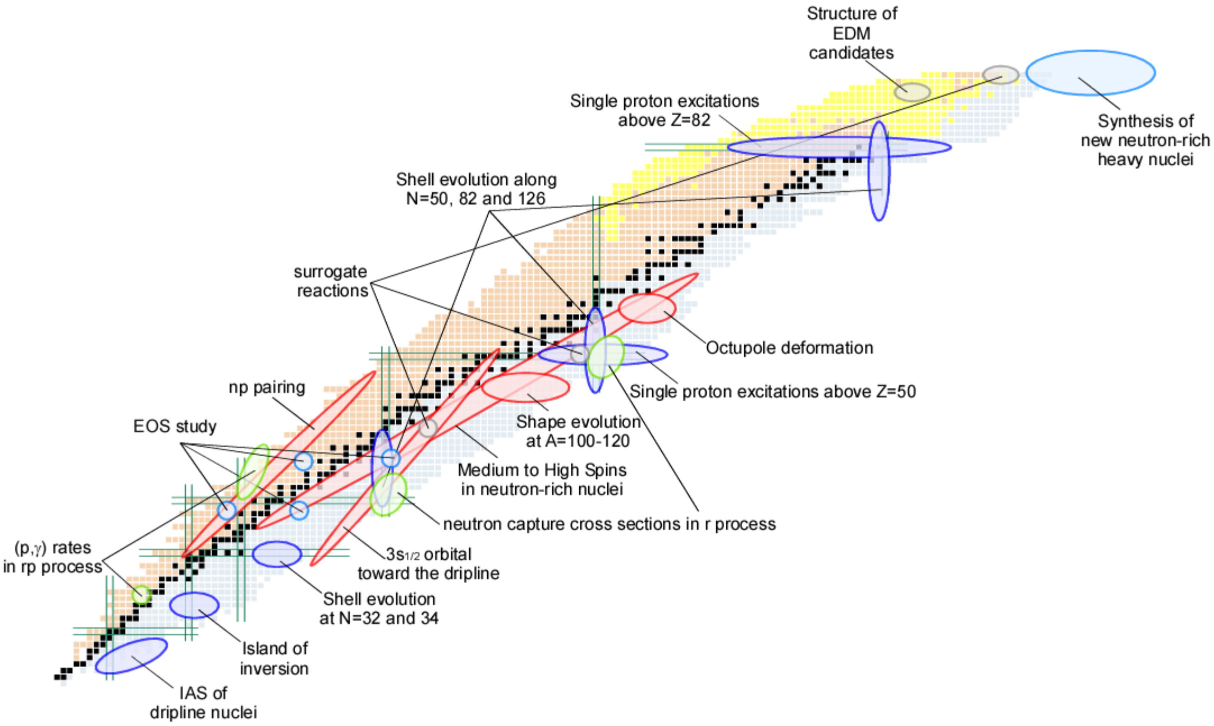


Fig.1.1: Science opportunities at ReA6−12 described in this whitepaper. Example physics cases in selected regions of interest are shown for single-particle structure (dark blue), nuclear collectivity and configuration mixing (red), nuclear reaction studies (light blue), nuclear astrophysics (green), and fundamental symmetries and applications (grey).

The ReA facility provides reaccelerated beams of rare isotopes at the well-controlled beam energies that are required for a broad set of low-energy nuclear reactions at and above the Coulomb barrier. Compared to fast beams that are produced from fragmentation or fission reactions and separated in-flight, the small emittance of the reaccelerated beams following gas stopping and charge breeding is a great advantage since the required resolutions can be achieved without beam tracking. Figure 1.2 summarizes suitable beam energies for representative nuclear reactions and experimental techniques discussed in this whitepaper. Experimental tools for nuclear structure studies include fusion and Coulomb excitation of heavy nuclei at and below the Coulomb barrier and multiple Coulomb excitation at barrier energies that require ReA6 beam energies. Direct transfer reactions such as (*d*,*p*) and (*p*,*d*) become reliable at and above 9 MeV/nucleon, and higher beam energies are preferable to have better momentum matching conditions for high-*l* single-particle states in medium-mass and heavy nuclei. Finally, an energy of 12 MeV/nucleon or above is required for some one- and most two-nucleon transfer reactions as well as for fragmentation-type reactions for studies of the nuclear equation of state.

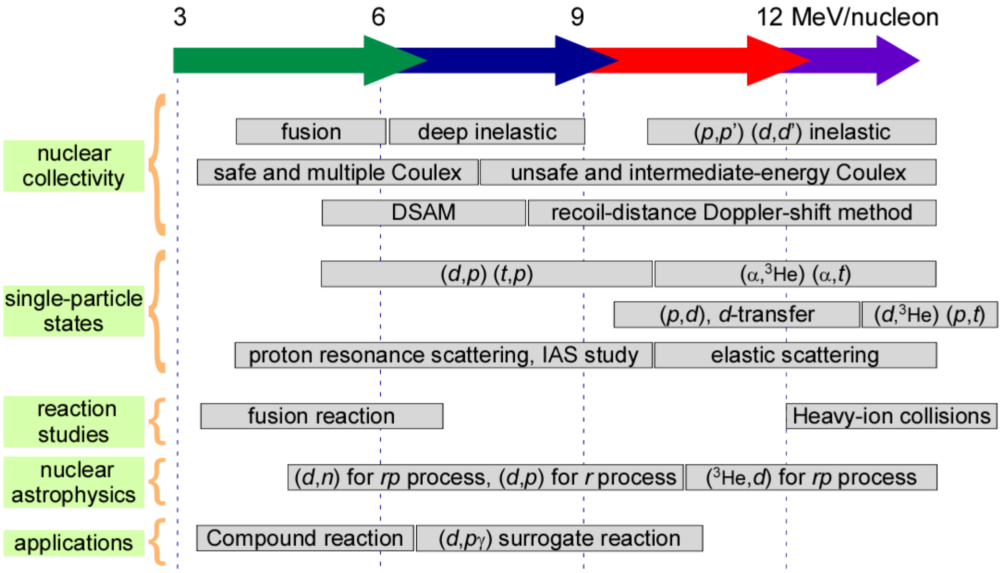


Fig.1.2: Nuclear reactions and experimental techniques envisioned for science programs at ReA. The reaction Q values depend largely on the case of interest, therefore, the energy information was chosen based on examples given in this whitepaper.

A pre-conceptual design of the ReA12 experimental area is shown in Fig.1.3. Three additional cryomodules (β=0.085) are planned as an extension to the current ReA3 beam line, and each module adds about 3 MeV/nucleon beam energy. In this preliminary concept, the experimental area accommodates two dedicated beam lines for a solenoidal spectrometer and the ISLA recoil separator and includes one general-purpose beam line.

A wide variety of nuclear structure and reaction studies with state-of-the-art instrumentation are anticipated at ISLA as outlined in the ISLA whitepaper [ISLA15]. GRETINA/GRETA can be installed at the target position of ISLA or at the general-purpose beam line together with auxiliary detectors. For reaction studies, the AT−TPC [Suz12] and a silicon detection system as presently used in HELIOS [Wuo07] are both considered to share the solenoidal magnet for their experiments. The general-purpose beam line serves as the main beam line for a wide variety of complementary detection systems envisioned by the community.

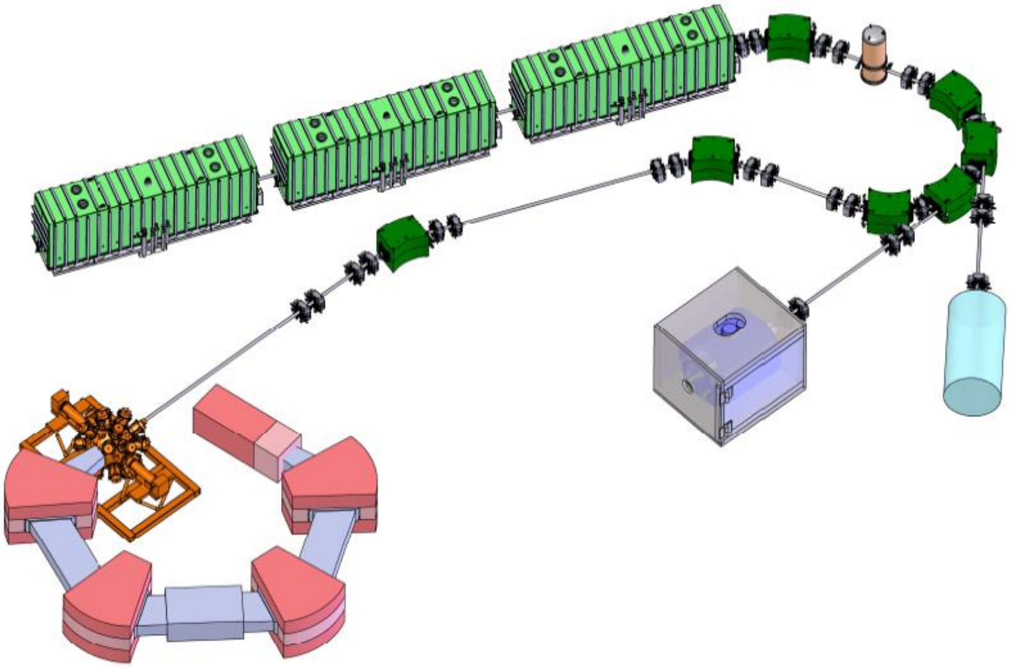


Fig.1.3: Pre-conceptual design of the ReA12 experimental area, which includes two beam lines dedicated to a solenoidal spectrometer and ISLA as well as one general-purpose beam line.

The expected available energies for the ReA upgrade are given in Fig.1.4. The available maximum energy depends on the Q/A ratio of the beams and ReAX (X=3, 6, 9, 12) is designed to provide at least X MeV/nucleon for very neutron-rich isotopes with Q/A of 0.25. This specification results in much higher beam energies for proton-rich or N=Z nuclei. For instance, the maximum energies available for ^{30}S at ReA12 would exceed 20 MeV/nucleon. The additional energy increase available for proton-rich beams is important to employ transfer reactions with highly negative Q values such as (*p*,*d*) and (*p*,*t*). The detailed maximum beam energy information for each isotope is given in Fig.1.5 for ReA6 (left) and ReA12 (right).

This whitepaper was compiled on the basis of presentations and discussions initiated by a one-day workshop on the science opportunities afforded by an energy upgrade to ReA3 held in August 2015 at Michigan State University. In the following, the science motivations for a ReA energy upgrade are discussed, with opportunities encompassing nuclear structure and reaction studies, nuclear astrophysics, fundamental symmetries, and applications. The last section briefly summarizes the conceptual layout of the ReA12 experimental area and provides cost estimates and possible staging options for the ReA energy upgrade.

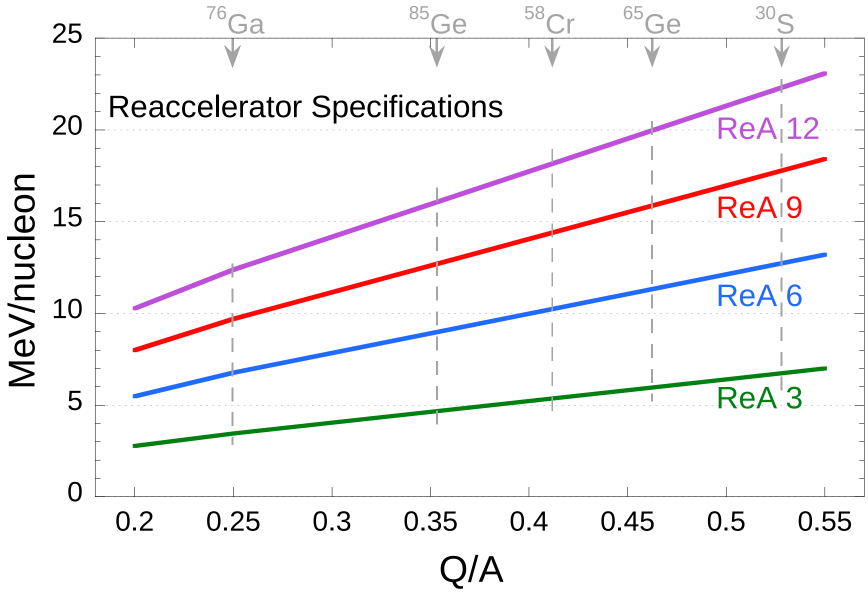


Fig.1.4: Maximum energies expected for ReA3-ReA12 shown as a function of the Q/A ratio of rare-isotope beams.

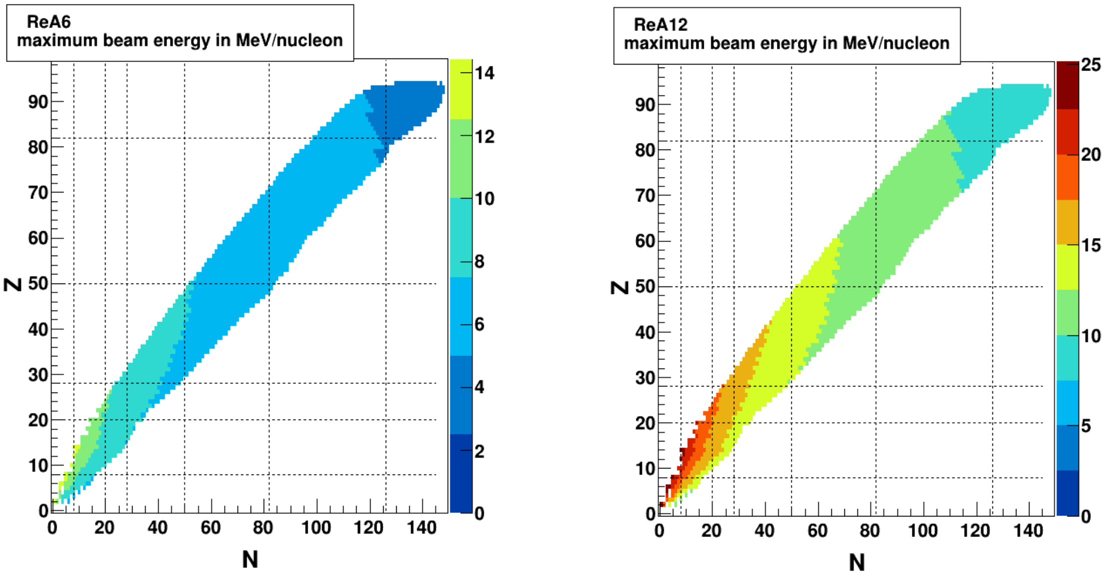


Fig.1.5: *Maximum beam energies expected from ReA6 (left) and ReA12 (right) shown across the nuclear chart. The dashed lines indicate the traditional magic numbers 8, 20, 28, 50, 82, and 126 to guide the eye.*

2. Evolution of structural phenomena

2.1 Shell evolution in exotic nuclei probed by direct reactions

The advent of rare-isotope beams has opened the door to detailed studies of nuclei very far from stability. It is now well established that the properties of such nuclei are very different from those found near the valley of stability, representing the need to redefine the paradigms of nuclear structure physics. One of the most notable observations is that the standard shell model of the nucleus requires dramatic revisions in some regions of the nuclear chart. While measured masses, separation energies, and electromagnetic transitions between low-lying excited states provided the first indications of these changes, data from nucleon-transfer reactions performed in inverse kinematics with more intense rare-isotope beams can characterize shell structure on the microscopic level. Single-nucleon stripping reactions such as (d,p) can be used to identify energy levels, determine their spins and parities, deduce spectroscopic strength, and provide information about residual interactions. Two-nucleon transfer reactions such as (^{3}He,p), (α,d), (d,α) and (t,p) provide information about pairing correlations, configuration mixing, and shape coexistence. Nucleon-removal reactions such as (d,t) or (d,^{3}He) are complementary to knockout reactions and able to provide information on the occupancies of shell-model orbitals.

The most useful information for such reactions is obtained from measurements done at energies near or above the Coulomb barrier. The appropriate energies depend on momentum and angular-momentum matching conditions, which in turn depend on the reaction Q value. For example, (d,p) or (t,p) reactions typically have Q values that are near 0 MeV, and require only modest beam energies between 5−10 MeV/nucleon. The most suitable energies for deuteron transfer reactions are between 10−15 MeV/nucleon. Due to very negative Q values, which can be less than −15 MeV, (d,^{3}He) reactions must often be performed at energies of at least 15−20 MeV/nucleon or higher. Only high-quality reaccelerated rare-isotope beams with well-controlled energies and emittances have the necessary properties for such studies.

Two important areas in the nuclear chart where the shell properties markedly deviate from the common wisdom are very neutron-rich nuclei near N=20 (^{32}Mg) and N=32 (^{52}Ca). Near ^{32}Mg – in the famous “Island of Inversion” – the shell closure at N=20 disappears. Particularly in ^{32}Mg, phenomena such as deformation and shape coexistence become important. The single-particle strengths may become fragmented and the distribution of that strength can be studied experimentally with reactions such as ^{32}Mg(d,p)^{33}Mg or ^{28}Ne(d,p)^{29}Ne. Shape coexistence and configuration as well as the impact of neutron excess on pairing correlations in neutron-rich nuclei [Tan08] can also be studied with the (t,p) or (p,t) reaction in inverse kinematics. Recently, the ^{30}Mg(t,p)^{32}Mg reaction has been studied at low beam energy (1.8 MeV/nucleon) at REX-ISOLDE [Wim10], however, the measurement suffered from limited resolution; hence, the conclusions are uncertain. New measurements for this system performed at higher energies with favorable kinematic conditions should clarify the situation.

Another region full of surprises is near ^{52}Ca, where changes in the $1f_{7/2}$, $2p_{3/2}$ and $2p_{1/2}$ neutron shells produce alleged shell closures at N=32 and N=34 [Wie13,Ste13,Gar16]. Here, very few data exist and nucleon-transfer studies before FRIB will be challenging. Once a reaccelerated ^{52}Ca beam from FRIB becomes available, one- and two-nucleon stripping and pickup measurements will be possible at ReA as well.

2.2 Direct reaction studies around 100 < A < 200

Tracking the evolution of single-particle excitations across the nuclear chart is a key focus of exotic-beam physics programs, which aims at establishing a unified theoretical picture for stable and exotic nuclei. Heavier beams with A>100 will be available at ReA with FRIB, allowing long chains of closed-shell isotopes and isotones to be studied at energies in the proximity of the Coulomb barrier. Here, direct reactions provide crucial information. The most suitable energy for transfer reaction studies is a few MeV/nucleon above the Coulomb barrier in both the entrance and exit channels. At such energies, the reactions can be reliably modeled as a direct and single-step process. The cross sections are favorable and forward peaked, with the angular distributions indicative of different angular momenta transferred in the reaction.

In heavier systems, for example those around tin and above, high-*j* orbitals lie close to the Fermi surface. To probe them via a neutron- or proton-adding reaction, one typically needs to employ probes such as (α,^{3}He) and (α,*t*) instead of the commonly used (*d*,*p*) and (^{3}He,*d*) reactions. While these probes are equivalent in terms of adding a nucleon, the former reactions, with the large Q values, result in more favorable angular momentum matching for transfer to high-*j* states, and thus are more reliable in terms of determining the spectroscopic information for such states. To track single-proton $g_{7/2}$ and $h_{11/2}$ excitations from the lighter Sn isotopes to those beyond N = 82, one can exploit the Sn(α,*t*) reaction. At FRIB, studies on $^{103\text{-}135}$Sb will be possible. Similarly, single-proton excitations near the Pb isotopes as well as single-neutron excitations outside the N = 50, 82, and 126 isotones can be studied via the (α,*t*) and (α,^{3}He) reactions, respectively. In all cases, one requires beams in the 10−15 MeV/nucleon range, due to the large reaction Q values as well as the larger Coulomb barrier presented by the helium species in the entrance and exit channel.

Single-particle excitations in nuclei one or two nucleons away from stable doubly-magic nuclei are well studied and have been used to derive effective shell-model interactions. Fairly complete datasets are available for the stable doubly-magic ^{16}O, ^{40,48}Ca, and ^{208}Pb nuclei, and to a lesser extent ^{90}Zr. However, no such studies have been possible for unstable doubly-magic nuclei. With ReA, detailed studies around ^{56}Ni, ^{68}Ni, and ^{132}Sn will be possible. Taking ^{132}Sn as an example, determining the location of each member of the mulitplets in the particle-particle, particle-hole, and hole-hole systems (^{134}Te, ^{134}Sb, ^{134}Sn, ^{130}Sn, ^{130}In, ^{130}Cd, ^{132}Sb, and ^{132}In) allows one to extract effective interactions. The states can be probed through neutron/proton adding and removing reactions on beams of ^{133}Sb, ^{133}Sn, ^{131}Sn, and ^{131}In projectiles. While in some cases charged-particle spectroscopy should be sufficient, simultaneous or complementary γ-ray spectroscopy may be required as the level density in these systems could be high. For example, the coupling of the $g_{7/2}$ proton to the $h_{11/2}$ neutron hole results in eight states which tend to span only a small excitation-energy range. To clearly identify these states, a range of probes, which have different matching conditions for low and high angular momentum transfers, are required. The option to use these beams at energies exceeding 10 MeV/nucleon also opens up the possibility of inelastic scattering reactions and transfer reactions to high-*j* states.

A challenge with these direct-reaction techniques is the charged-particle spectroscopy. Beams of high purity and intensities greater than about 10^4 particles per second are required. In general, the charged-particle spectroscopy in inverse kinematics requires zero-degree recoil detection and beam separation as well as excellent beam properties in terms of energy resolution, spatial extent, and emittance which will be available at ReA. Concerning targets, the range of species is limited, *p*, *d*, *t*, ^{3}He, ^{4}He, etc., but once conditions such as purity, number density, and stability are met, a diverse set of reactions can be studied for rare isotopes available as reaccelerated beams.

2.3 Proton resonance scattering and direct reaction studies near the continuum

Properties of nuclear states in the proximity of the particle continuum may challenge shell-model descriptions of atomic nuclei and will provide new insights in the understanding of open quantum systems where the nuclear structure is impacted by coupling to the continuum and particle-decay channels [Dob07]. Among complementary reaction approaches available at ReA6−12 (Fig.1.2) for the study of nuclear structure far from stability, proton resonance scattering in inverse kinematics has been demonstrated to be a very effective approach to study shell structure at the proton and neutron driplines [Gol12].

The theory of resonance reactions is well understood and allows for a reliable determination of quantum numbers and decay properties of unbound states. In proton-rich nuclei, states of interest can be populated directly in resonance scattering. In such experiments, large reaction cross sections and very good energy resolution (~20−50 keV in center-of-mass energies) are typically achieved, presenting the strong potential of resonance reactions as a spectroscopic tool. These reactions have been used extensively over the last two decades and a large body of detailed spectroscopic information has been obtained, including the discovery of new unbound isotopes (see for example [Axe96,Gol10]). Similar studies can be carried out at ReA6−12, moving towards heavier proton-rich nuclei. The desired beam energies for these studies are determined by the excitation-energy range of interest for the specific case. The typical choice of beam energy is between 5 and 10 MeV/nucleon and in general, heavier beams require higher energies. This calls for an upgrade of ReA3 to at least ReA6 or ReA9 for heavier nuclei.

The resonance scattering approach can also be applied to study the structure of neutron-rich nuclei by populating Isobaric Analog States (IAS). For example, the structure of ^{9}He has been explored by populating the T=5/2 IAS in ^{9}Li in ^{8}He+p resonance elastic scattering [Rog03,Ube16]. One of the important features of this technique is that it allows both bound and unbound states in neutron-rich nuclei to be probed via their analog states that appear in neighboring isobars. The energies of IAS are shifted up with respect to their analogs; hence, IAS can be populated by resonance scattering. As an example, the drip-line nucleus ^{19}C is bound by 0.6 MeV with respect to neutron emission. However, the lowest T=7/2 IAS in ^{19}N should be unbound by about 1.5 MeV with respect to the proton decay and therefore can be observed as a narrow resonance in ^{18}C+p elastic scattering. For heavier nuclei, the Coulomb shift naturally becomes larger due to the higher Z values, pushing the IAS of interest to higher excitation energies. This requires higher beam energies for IAS studies as compared to those required for resonance reaction studies on the proton-rich side. Energies in the range of ReA9 will be best suited for the IAS studies of the most neutron-rich nuclei with Z>20.

The experimental technique suited for resonance reaction studies is an active target approach, where the detector gas serves as the reaction target. The energy of the beam decreases as it traverses the target, and this allows reactions that occur at various center-of-mass energies to be studied. This technique not only allows for elastic-scattering measurements over wide energy and angular ranges but also enables studies of other reactions, such as direct nucleon transfer reactions (*p*,*d*) and (*p*,*t*), simultaneously. The structure of several exotic nuclei can be investigated in a single experiment, although the center-of-mass energy resolution for transfer reactions is significantly worse than that for resonance scattering due to unfavorable kinematics. Combining active targets with neutron detection is particularly important for nuclear structure studies on the neutron-rich side through the IAS approach. Due to favorable isospin coupling coefficients, the IAS in neutron-rich nuclei predominantly decay by neutron emission through the isospin allowed channel(s) if such a decay is energetically allowed. Measuring this neutron decay channel provides a clean signal for the IAS [Rog04]. This will require a new design for an active target detector that facilitates the use of efficient neutron detection as well.

NSCL's AT−TPC and its prototype are examples of active-target devices which have already been used in several experiments with low-energy rare-isotope beams. Recent work includes a study of the cluster structure of ^{10}Be using resonant scattering of a ^{6}He beam on a ^{4}He target [Suz13]. At ReA3, the first experiment using a reaccelerated beam of ^{46}Ar at 4.2 MeV/nucleon was recently performed to investigate the single-particle strength in ^{47}Ar through measurements of its isobaric analog states in ^{47}K. The trajectory of a proton scattered off the ^{46}Ar beam is shown in Fig.2.1, where the reaction vertex has been reconstructed in the AT−TPC, defining the beam energy (4.0 MeV/nucleon) at which the reaction occurred. However, the present energy limitations of ReA3 severely restrict the variety of reactions that could be used with this new detector. Inverse-kinematics transfer reactions such as (*d*,*p*), (*p*,*d*), (*p*,*t*), and (*d*,^{3}He) are examples for which an energy upgrade of ReA is highly desirable to realize the full potential of these high-luminosity reaction tools. Unlike traditional experimental setups that use a thin inert target, the active-target technique enables one to determine the reaction point in the target volume by reconstructing the vertex of particle trajectories and hence deduce the beam energy at which the reaction occurred. Angular distributions measured at different beam energies can be summed up by taking into account the energy dependence of the diffraction patterns. This feature is particularly well suited for studies of the most exotic isotopes at ReA for which transfer reactions would be possible in a TPC with intensities down to a few hundred particles per second.

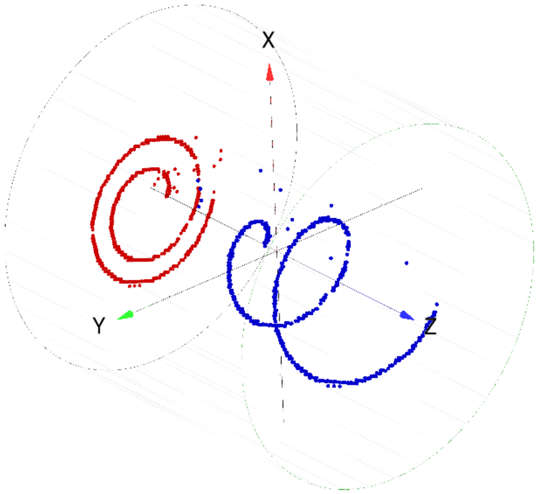


Fig.2.1: Observed trajectory of a scattered proton (blue) from C_4H_{10} gas used as an active target. The track follows a spiral trajectory due to the applied longitudinal solenoid field of 1.7 Tesla, combined with the slowing down of the proton due to its energy loss in the gas. The projection of the proton track on a plane normal to the beam direction is shown in red. The event corresponds to proton resonant scattering on ^{46}Ar at 4.0 MeV/nucleon.

2.4 Properties of weakly-bound neutron-rich nuclei probed by hadronic scattering

Structure and excitation properties of atomic nuclei have often been interpreted based on the concept of the atomic nucleus being a quantum liquid composed of protons and neutrons. It is now well established that very neutron-rich nuclei often exhibit unusual density profiles such as neutron skins and halos, where valence neutrons have spatially extended wave functions [Rii94]. Unique density profiles of weakly-bound nuclei are expected to modify dynamical properties at the limits of nuclear binding or neutron excess, requiring measurements of quadrupole, octupole, and higher-order excitation modes in very neutron-rich nuclei. These data are also crucial to the understanding of possible new correlations and continuum effects in the proximity of the threshold [Fos16].

Inelastic scattering with hadronic probes provides unique opportunities to investigate transition modes characteristic of neutron-rich nuclei. Unlike the electromagnetic probes, which are sensitive predominantly to proton distributions in nuclei, hadronic inelastic scattering can gauge both proton and neutron contributions to excitation. The magnitude of the cross section scales with the deformation length of a given excitation. Inelastic reactions directly probe low-lying excitation modes with moderate cross sections, comparable to those in transfer reactions. Proton inelastic scattering in the low-energy domain (10−50 MeV/nucleon) is known to have a dominant sensitivity to quadrupole deformation of the neutron distribution [Ber81]. This feature has been utilized so far for spectroscopic studies of neutron-rich nuclei up to A≈50 [Ril14] and similar studies can be extended for heavier neutron-rich nuclei at ReA. Inelastic scattering with deuteron, an isoscalar probe, is suited to extract the deformation lengths for the E2 and E3 transitions. These measurements are best carried out at energies well above the Coulomb barrier at 10−15 MeV/nucleon. Key studies at ReA would be on nuclei around A=140 where octupole correlations are strong and on nuclei in regions where shape evolution and coexistence occur.

Elastic-scattering measurements are also important to determine parameters for optical-model potentials which are required to interpret data from inelastic scattering and transfer reactions. The optical-model potential is also useful to evaluate effects due to unknown levels in the proton resonance scattering [Ube16]. Besides, analyzing powers for proton elastic scattering can be measured using a polarized proton target, which provides a unique way to investigate the neutron skin and its influence on optical model potentials. From the recent measurement on ^{6,8}He [Sak13], a possible modification of the spin-orbit potential is suggested and ascribed to diffused density distributions in these neutron-rich nuclei. The availability of rare-isotope beams at sufficiently high energies facilitates a diverse set of well-established direct reaction approaches, thus providing crucial tools to characterize the dynamics of neutron-rich nuclei and identify emerging phenomena at the limit of stability.

3. Correlations, collectivity and configuration coexistence in exotic nuclei

One of the challenges in nuclear science is to understand how the nucleus, a complex fermionic many-body system, can be described in terms of degrees of freedom of its constituents and, conversely, how simple patterns, like rotational and vibrational spectra, emerge. As outlined in the following sections, these challenges can be addressed by a multi-pronged approach based on an energy upgrade of ReA3. Precision excited-state lifetime studies for low-lying states, medium- and high-spin spectroscopy, and explorations of the elusive proton-neutron pairing correlations address the emergence of regularities from complex many-body correlations. The last section points out the importance of benchmarking the theoretical description of nuclear shapes in regions relevant to the *r*-process where our understanding of astrophysical scenarios largely relies on nuclear theory inputs.

3.1 Precision lifetime measurements of low-lying states with Doppler-shift techniques

The modified shell structure will induce a competition between normal and intruder configurations in the vicinity of nuclear ground states, which results in collective phenomena such as shape coexistence and enhanced nuclear deformation [For13]. Precision lifetime measurements with Doppler-shift techniques are particularly important to access low-lying excited states with picosecond or sub-picosecond lifetimes, which provide key experimental inputs to characterize collective modes. The energy upgrade for the reaccelerated beams at NSCL and in the future FRIB from 3 MeV/nucleon to 12 MeV/nucleon considerably increases the potential of excited-state lifetime measurements with reaccelerated beams, either populated through Coulomb excitation, inelastic scattering or transfer reactions.

Towards the neutron dripline, the single-particle structure of exotic nuclei is expected to evolve drastically due to the enhanced role of the proton-neutron interaction and weak-binding effects [Ots05,Dob07,Sor13,Hof14]. A good example of this evolution in medium-mass nuclei can be found in the behavior of the $3s_{1/2}$ orbital across the nuclear chart. In the vicinity of the stable Sn isotopes at N=70, the $3s_{1/2}$ strength dominates the ground-state configurations. However, the $3s_{1/2}$ energy is expected to be lowered significantly with respect to other higher-*l* orbitals as moving toward the lower-mass neutron-rich region. Wood-Saxon models with weakly-bound potentials for neutron-rich nuclei [Oza00,Hof14] indicate that the $3s_{1/2}$ strength could appear already in the configurations of low-lying states in very neutron-rich nuclei at N=40-50. If this picture is true, the $3s_{1/2}$ state will play a significant role in defining the evolution of the shell structure in medium-mass nuclei and even have a significant impact on the location of the drip-line of the Ca isotopes beyond N=40 [Hag13]. It may also induce exotic nuclear collectivity and valence-neutron correlations in these Ca isotopes as characteristic features of weakly-bound nuclei [Hag13,For13]. To draw a complete picture, it is important to accumulate experimental information for the $3s_{1/2}$ state and track its single-particle strength from the stable Sn region toward the dripline.

The energy upgrade at ReA will allow a diverse set of spectroscopy and reaction studies to be performed to locate and quantify the $3s_{1/2}$ strength across the nuclear chart. A particularly important region to identify the $3s_{1/2}$ strength is the neutron-rich medium-mass region spanning from the stable Sn isotopes at N=70, via the N=50 region around ^{78}Ni, and to the exotic Ca isotopes near the dripline (as shown in Fig. 1.1). Excited-state lifetime measurements are well suited to identify the single-particle $s_{1/2}$ states through studies of the *l*-forbidden M1 transitions expected to occur between the neighboring $3s_{1/2}$ and $2d_{3/2}$ orbitals. The relevant transitions are known in stable ^{116,118}Sn isotopes and expected to occur in neutron-rich Pd and Cd isotopes. These experiments can be performed by applying the Doppler-shift attenuation method (DSAM) or recoil distance method with reaccelerated beams at ReA6–12. Inverse-kinematics transfer reactions such as $d(^{A}Z,^{A+1}Z)p$ and $p(^{A}Z,^{A-1}Z)d$ can be employed to populate the excited states of interest. An energy upgrade towards 12 MeV/nucleon facilitates the detection of light recoiling particles or beam-like reaction products which is essential to identify reaction channels. In addition, the measurements at high beam velocities, where stopping powers are best characterized, can reduce the systematic uncertainties considerably [McC09].

3.2 Nuclear structure studies at medium and high spins

The experimental investigation of high-spin states in atomic nuclei has shown that simple patterns emerge in nuclear spectra, indicative of rotations, vibrations, and transitional behavior, posing questions as to how such simplicity can develop from the complex interactions between individual nucleons. Furthermore, a possible interplay between neutron excess and angular momentum in collective phenomena adds another interest, calling for the experimental investigation of nuclear structure at medium and high spins across the nuclear chart.

The identification of high-spin states which often cannot be accessed in β-decay or reached with direct reactions has provided key information across a broad excitation energy range and up to high angular momentum. These types of studies have been carried out on the proton-rich side using fusion-evaporation reactions with stable beams at beam energies between 5–6 MeV/nucleon which can leave the residual nucleus in an initial, excited state at a spin in excess of 40 $\hbar$. The de-excitation of the nucleus occurs via the emission of γ-rays, which can be measured using large γ-ray spectrometers such as Gammasphere or now GRETINA/GRETA. One classic example is shown in Fig. 3.1 for ^{152}Dy where excited states associated with spherical, triaxial, and superdeformed shapes have been identified.

At ReA6, the major focus of studies will be on neutron-rich nuclei whose collective behavior at higher-spin levels is not well understood. While fusion-evaporation reactions excite the nucleus to the highest spins, they also heavily favor neutron over proton evaporation, thus limiting the applicability of these reactions when probing the neutron-rich region. However, the ReA6 upgrade will provide the capability of re-accelerating the isotopes one wishes to study, and thus excited states can be probed by the direct excitation of the rare-isotope beam interacting with a high-Z target ("unsafe" Coulomb excitation above Coulomb-barrier energies). It has been shown that the best energies to maximize the reaction cross section and the input angular momentum are at 5–6 MeV/nucleon. Using these reactions, one has identified states at spin values as high as 38 $\hbar$ in ^{232}Th with cross sections on the order of 100's of mb [Abu02]. Alternative reaction to access higher-spin states in neutron-rich nuclei is deep-inelastic elastic scattering between neutron-rich projectiles and heavy-target nuclei, while the clear identification of reaction products using a recoil separator such as the planned ISLA [ISLA15] would be necessary to identify elusive events.

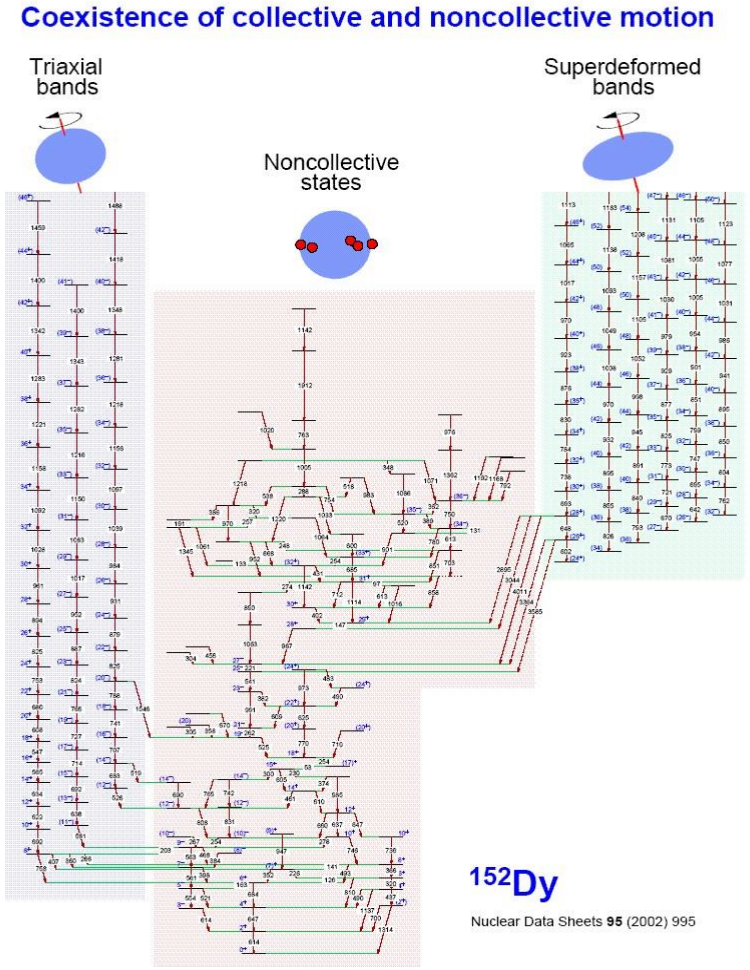


Fig.3.1: Detailed level structure for the neutron-deficient isotope ^{152}Dy obtained from γ-ray spectroscopy highlights co-existing collective and non-collective motions in atomic nuclei. The ReA energy upgrade will provide access to medium- and high-spin states of neutron-rich nuclei, addressing effects of extra neutrons on collective phenomena at high-spin.

GRETINA will provide excellent Doppler reconstruction which will be necessary since the reaction products emit γ rays while moving at substantial velocity. Utilizing a detector such as CHICO2 to measure the angle of the scattered beam relative to the beam direction will also enhance the final γ-ray energy resolution. In the long term, a complete GRETA with ~25% photo-peak efficiency will provide sufficient statistics to study medium- and high-spin states even with only 1×10^4 particles per second on target.

While level structures as detailed as those shown in Fig. 3.1 would not be delineated at the lowest rare-isotope beam intensities, yrast states in the 10−20 $\hbar$ region can still be identified. Such information would allow for the study of the interplay of collective and non-collective states in both even-even and odd-mass isotopes on the neutron-rich region. This new opportunity thus adds both spin and isospin dimensions to our investigation of the evolving nuclear structure, providing a comprehensive understanding of nuclear patterns manifested in complex nuclei.

3.3 Studies of neutron-proton pairing correlations in N=Z nuclei

On the proton-rich side of the nuclear chart, the role of neutron-proton (*np*) pairing correlations in N=Z nuclei remains a subject of much interest in nuclear-structure physics [Fra14]. Assuming charge independence of the nuclear force, isovector (T=1) *np* pairing should exist on an equal footing with T=1 *nn* and *pp* pairing. However, it is still an open question whether there exist strongly correlated isoscalar (T=0) *np* pairs (deuteron-like pairs) in atomic nuclei. A number of theoretical studies have examined the possible T=0 *np* pairing condensation in N=Z nuclei and resultant collective effects [Mac00,Gez11], whereas clear signals have not yet been identified in experiments.

Two-nucleon transfer reactions such as (*t*,*p*) and (*p*,*t*) provide a unique tool to probe pairing correlations in nuclei [Bro73,Tan08], and suggest that the transfer of an *np*-pair from even-even to odd-odd self-conjugate nuclei may stand out as the best tool to study these correlations. The (*p*,^{3}He) and (^{3}He,*p*) reactions appear to be the best choice since the *np*-pair can be transferred in both T=0 and T=1 isospin channels. Beyond ^{40}Ca along the N=Z line, these studies require rare-isotope beams and the use of inverse-kinematics techniques. In particular, the feasibility of the (^{3}He,*p*) reaction in inverse kinematics has been demonstrated in a series of experiments at the ATLAS facility [Mac02] using a gas-cell target and a simple setup with an annular segmented silicon detector. In these experiments, one measures cross sections for *np* transfers from an even-even projectile to the lowest $J^\pi=0^+$, 1^+ states in the odd-odd neighbor. While absolute cross sections will be of interest, it is noted that the cross-section ratio of $\sigma(0^+)/\sigma(1^+)$ itself is sensitive to the isospin character of the pair correlations, thus providing reliable experimental evidence which is free from systematic uncertainties due to an absolute normalization.

Reaccelerated N=Z beams, with energies of 5−20 MeV/nucleon, will only become available with the ReA6−12 upgrade at FRIB and offer the unique opportunity to study the (^{3}He,*p*) and (*p*,^{3}He) reactions using beams from ^{40}Ca to ^{88}Ru. Complementary reactions of (α,*d*) and (*d*,α) can also be studied. The Active Target – Time Projection Chamber (AT−TPC) constructed at NSCL [Suz12], combining both target and detection systems in a single device, will be the perfect instrument to carry out such a program. A region of

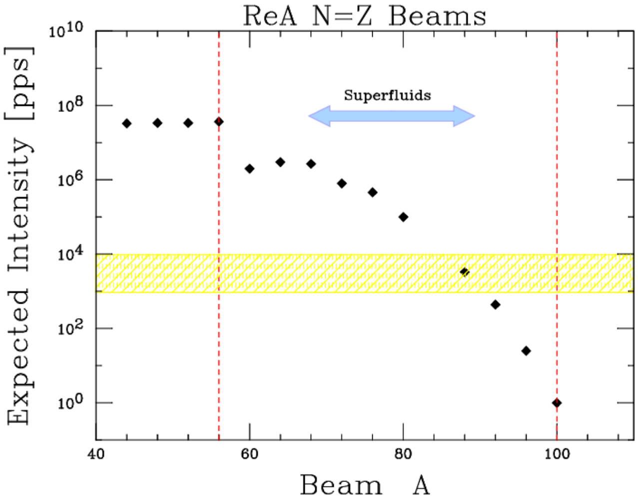


Fig.3.2: Estimated yields for reaccelerated N=Z beams. Using the AT−TPC, beam intensities of ~10^3 particles per second (yellow shaded area) will be required to study possible superfluidity (collective pairing states) expected in open-shell nuclei. A systematic study up to ^{88}Ru will become possible. Red dashed lines indicate the N=Z closed shells at ^{56}Ni and ^{100}Sn.

interest is illustrated in Fig.3.2, where the expected yields are shown as a function of the mass of the beam. A successful measurement will require intensities of ~10^3 particles per second, thus reaching nuclei in between the closed shells of ^{56}Ni and ^{100}Sn, the region where collective pairing effects (superfluidity) are expected to fully develop. These systematic studies of *np*-pair transfers are likely the only probe that could address the fascinating *np* pairing mode in atomic nuclei.

3.4 Shape evolution in neutron-rich nuclei near the *r*-process path

In regions around magic numbers, spherical shell closures and nuclear shape changes have significant impacts on nuclear masses, thereby affecting astrophysical scenarios such as the abundances and the origin of heavy elements in the *r* process [Mar16]. The strength of the N=82 shell closure has a major impact on the nucleosynthesis of elements with mass number A~130 since it affects the neutron capture and β-decay rates for neutron-rich nuclei along the *r*-process path in the neighborhood of Z=40. The N=82 shell closure can be probed by the spectroscopy of neutron-rich nuclei near the *r*-process path with mass numbers ranging from A~100 to A~120 as studied in previous works measuring the prompt γ-ray emission of fission fragments. For example, the population of ground-state and K=2 bands up to spin 22^+ and 19^+, respectively, was observed for ^{112}Ru ($T_{1/2}$=1.75 s) by using the ^{238}U(α,2nf) reaction with Gammasphere/CHICO [Wu06]. In addition, the lifetimes of states with spins between 8^+ and 16^+ in ^{112}Ru were measured using the spontaneous fission of ^{248}Cm [Smi12] and ^{252}Cf [Sny13]. Thus, the strength of the quadrupole deformation can be easily determined from the excited-state lifetimes. However, theoretically, nuclear shapes are expected to evolve rapidly in the vicinity of ^{112}Ru [Nom10] and the sign of quadrupole deformation has not yet been obtained, since it requires the realization of Coulomb excitation of the reaccelerated ^{112}Ru rare-isotope beam at sub-barrier energy (around 4.0–4.5 MeV/nucleon). The determination of the sign is essential for studying the shape evolution in neutron-rich nuclei adjacent the *r*-process path, which is sensitive to the strength of the shell closure at N=82 and the single-particle structure around.

To estimate the requirements for a successful and quantitative measurement that would advance our knowledge on shape evolution, a numerical calculation of the Coulomb excitation for ^{112}Ru at 460 MeV bombarding energy on a ^{208}Pb target of 1 mg/cm^2 was carried out with a semi-classical code GOSIA [Czo83] based on the GRETINA/CHICO2 setup [Wu16]. Assuming a beam intensity of 10^5 particles per second and a reaction cross section of 1 mb, a statistical uncertainty ~10% can be achieved for the γ-ray yields in a 3-day experiment. With this lower bound set, it is possible to reach a precision measurement for the transitional matrix elements up to spin 8^+ or 10^+ of the ground-state band and up to 6^+ of the K=2 band. Quadrupole moments up to spin 6^+ of the ground-state band and up to 4^+ of the K=2 band can also be determined. Therefore, the sign and magnitude of quadrupole deformation as well as possible triaxiality would be well characterized based on the measured electromagnetic properties. The evolution of the shape degrees of freedom along the neutron-rich Ru isotopes with neutron number N up to 74 can be explored at the upgraded ReA facility. This study can be extended to N=76 and beyond once FRIB is online and the new instruments GRETA and CHICOx are available, where the latter would be a modified version of CHICO2 to be coupled with GRETA. This unique instrument is useful not only for the proposed Coulomb excitation work but also for any experiment requiring the measurement of two-body kinematics, such as quasi-elastic reactions, deep-inelastic reactions, and fission.

4. Heavy elements and the equation of state

Low-energy reactions have provided essential information for the synthesis of super-heavy elements as well as the understanding of the nuclear matter equation of state. However, the role of the proton-neutron asymmetry in these reactions is still an open question, causing large uncertainties in our understanding of the reaction mechanisms. Reaccelerated rare-isotope beams facilitate reaction studies with a wide range of isotopes from neutron-deficient to neutron-rich regions, providing experimental inputs to examine the proton-neutron asymmetry dependence of nuclear-reaction observables. In this section, prospects for future studies of fusion-evaporation reactions and multi-fragmentation at ReA are described.

4.1 The path to heavy elements at FRIB

The unmatched intensities of the fast rare-isotope beams that will be available at FRIB provide tremendous discovery potential, enabling the production of new isotopes from in-flight fission or fragmentation reactions. However, the rare-isotope production with fast beams is limited to elements up to uranium, and, therefore, low-energy reactions with rare-isotope beams such as fusion reactions and multi-neutron transfer reactions have recently attracted attention as a possible path to the synthesis of new neutron-rich moderately-heavy nuclei [Lov07].

The cross section for producing a heavy evaporation residue (σ_{EVR}) depends on the spin-weighted product of the capture cross section $\sigma_{cap}(E_{cm}, J)$, the fusion probability P_{CN}, and the survival probability W_{sur}. To understand and predict the formation of heavy nuclei, one must know each of these three factors (σ_{cap}, P_{CN}, W_{sur}) and their isospin dependence. While the intensity of rare-isotope beams represents a central issue in the heavy-element synthesis, enhanced fusion cross sections have been suggested for reactions with neutron-rich projectiles due to a lowering of the fusion barrier as well as neutron flow effects [Lov07]. Excess neutrons in reaction systems are also expected to increase the survival probability of heavy reaction products due to the reduced fissility and the lower excitation energies of the products.

While it is understood that FRIB may not be able to synthesize new super-heavy elements, there are excellent opportunities for using FRIB to synthesize new neutron-rich heavy nuclei. Most of the use of FRIB in this area will involve making neutron-rich isotopes of elements 103−108 using neutron-rich light beams like $^{20-24}$O with neutron-rich actinide targets. Recently, there has been interest in using FRIB beams in the Ar − Ca region to do these syntheses since available intensities for reaccelerated beams can be as high as 10^7 particles per second. Therefore, the possibility to test various features of heavy-element synthesis using the potassium beams made available at ReA is especially exciting and relevant. Clearly, ReA3 allows one to study relevant capture reactions with targets in the Ta − Pb region. Reaction studies with actinide targets require the higher beam energies of ReA6.

Recently relevant capture reactions were studied at ReA3 using both neutron-deficient and neutron-rich K isotopes. Preliminary results are shown in Figs.4.1, 4.2. A possible fusion enhancement at barrier energies is observed for ^{46}K, representing promising data for the use of neutron-rich projectiles in the heavy-element production. At ReA6−12, if beam intensities of 10^4 particles per second are available, all targets (including Ta, Pb, and neutron-rich actinide targets) can be used for such reaction studies. New data will refine our understanding of the isospin dependence of the fusion-evaporation reaction mechanisms, paving the way for the synthesis of new neutron-rich heavy nuclei at FRIB.

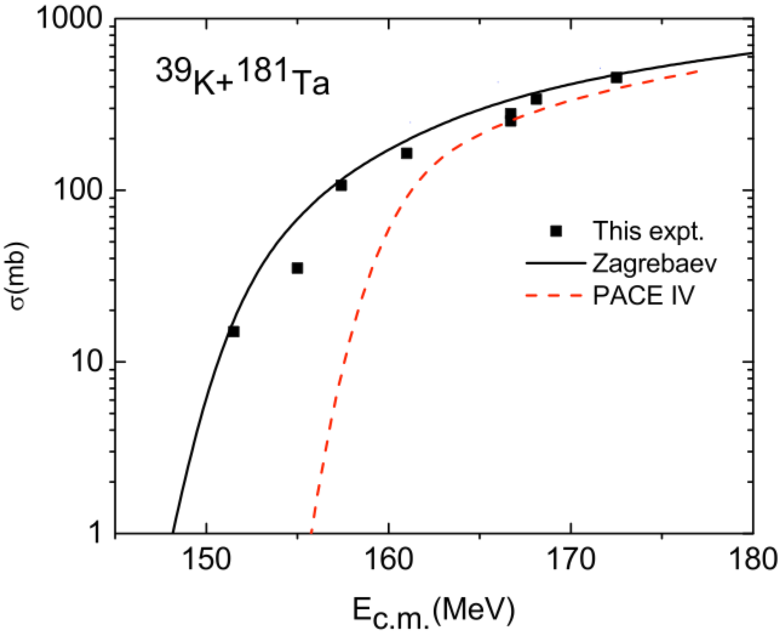


Fig. 4.1: The capture-fission excitation function for ^{39}K + ^{181}Ta [Wak16]. Model predictions are made using the fusion calculator of Zagrebaev et al. [NRV], and the statistical model code PACE4 [Gav80,Tar03].

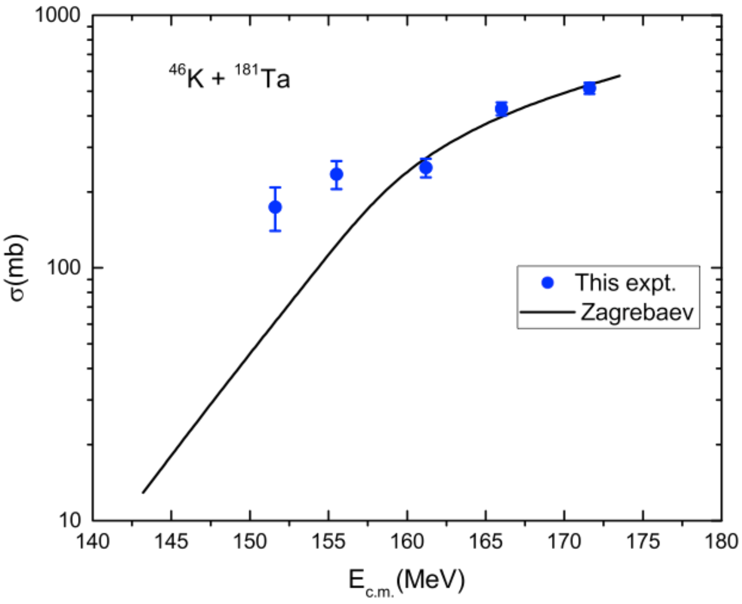


Fig.4.2: The capture-fission excitation function for ^{46}K + ^{181}Ta [Wak16]. Model predictions are made using the fusion calculator of Zagrebaev et al. [NRV].

4.2 Understanding the fusion-evaporation process for heavy element studies

The upgrade from ReA3 to ReA6 provides a diverse set of the beam-target combination, allowing for systematics studies of fusion-evaporation reactions as well as detailed investigation of the reaction process which is modeled theoretically by the product of three factors: the capture cross section σ_{cap}, the fusion probability P_{CN}, and the survival probability W_{sur}. Although the final reaction cross sections are reproduced in calculations by several groups, there is still substantial disagreement on the contributions of the individual terms and the relative importance of certain phenomena. This is largely due to a lack of experimental data and therefore dedicated experimental studies are called for.

A number of super-heavy elements have been discovered during recent decades using the fusion-evaporation mechanism, where a medium-mass projectile completely fuses with a heavy target to form a compound nucleus with moderate excitation energy (40–50 MeV) followed by particle emission. The production of new elements in recent years has been dominated by the use of ^{48}Ca projectiles reacting with actinide targets [Oga15]. There has been research suggesting that neutron-rich projectiles may lead to enhanced fusion cross sections [Lov06, Lia03], but additional measurements are needed to confirm this. The Coincident Fission Fragment Detector at NSCL is capable of making such measurements and should continue to be utilized. This device is also capable of measuring P_{CN}, which is by far the most poorly understood among the three factors to describe the fusion-evaporation process. There is an order-of-magnitude uncertainty in theoretical calculations of P_{CN} [Yan13], and the calculations often depend severely on projectile energies [Siw08]. Characterizing this term is therefore critical to understanding the fusion-evaporation mechanism and hence excitation functions.

The understanding of the final term, the survival probability W_{sur}, can also be improved by experiments using ReA beams. The survival probability cannot be measured directly, so it is typically estimated using transition-state theory. Recent work has suggested that collective effects increase the fission decay width of the compound nuclei [Wer15,May14], but the interpretation depends on correct estimation of fission barriers. It would be extremely helpful to estimate the fission barrier parameter B_f by studying electron capture-delayed fission, where the decay populates excited states above the effective barrier. This work could be complemented by direct measurements of the fission probability $\Gamma_n/\Gamma_{\text{tot}}$ (such as [Yan14]), which requires a combination of experiments with stable and neutron-deficient beams.

A large number of neutron-deficient beams are already available at ReA3 at energies slightly below and above the Coulomb barrier (≈5 MeV/nucleon) for these studies. The upgrade to ReA6 would make more important neutron-rich beams available at all energies of interest, contributing significantly to the understanding of all three steps of the fusion-evaporation mechanism.

4.3 Isospin transport, nuclear dynamics, and nuclear thermodynamics

The nuclear matter equation of state (EOS), which arises from the microscopic interactions of nucleons, represents the relationship between temperature, internal energy, density and pressure of the bulk nuclear matter. The nuclear EOS is of considerable interest due to its importance in understanding heavy-ion collisions and astrophysical phenomena such as properties of neutron stars. The dependence on the neutron-proton asymmetry represents the largest uncertainty in our knowledge of the EOS and, therefore, research programs with beams and devices available at ReA will focus on this aspect.

In earlier studies on intermediate-energy heavy-ion collisions, it has been observed that the relation between the temperature and the excitation energy of nuclear system (often referred to as the nuclear caloric curve) shifts to lower temperatures as the neutron-proton asymmetry increases [McI14]. Moreover, the density−energy correlation is dependent on the asymmetry, which implies the critical point also depends on the asymmetry [McI14]. An independent assessment of this asymmetry dependence of the EOS can be obtained through ongoing studies of Kr+C fusion reactions. The fusion reaction studies at ReA will provide an excited system with well-controlled asymmetry and excitation energy. The measurements can also cover a wide range of the proton-neutron asymmetry in the reaction system, providing the cleanest way to establish the isospin dependence of nuclear temperatures and densities. By varying the beam energy, one can control the excitation energy of the compound nucleus. For instance, a beam energy of 18 MeV/nucleon (ReA12 energies) for ^{74}Kr and ^{88}Kr would allow for excitation energies up to $E^{*}/\mathrm{A} = 2.2$ MeV in the total internal energy of the composite Kr+C systems. For experiments, a charged-particle detector array needs to be employed in combination with a large-acceptance spectrometer (e.g. ISLA) proposed at ReA12. Additional space around the target would allow for coincident detection of neutrons and hard γ rays ($10<E_{\gamma}<70$ MeV) which provide complementary probes of the thermodynamics quantities.

In addition to equilibrated systems mentioned above, nuclear systems out of equilibrium also provide important constraints on the EOS. The evolution of these systems toward equilibrium is sensitive to details of the nuclear potential driving the equilibration, for instance, the neutron-proton transport can probe the gradient of the nuclear potential [Sou89]. Recent works [Sou14, May15] studied details of N/Z equilibration in heavy-ion collisions using stable beam and target combinations. Model calculations successfully reproduce the observed trends, but do not show a strong sensitivity to the density dependence of the symmetry potential. Extension of these studies to systems with extreme neutron-proton asymmetries using rare-isotope beams is therefore an attractive step for the EOS studies since it could place stronger constrains on the asymmetry term in the EOS. Examining a neutron-deficient system (with N<Z) would also allow for the first direct tests of the isospin symmetry, which is often assumed in describing the equilibrium processes. Past studies have focused on the isospin equilibration between the target and projectile, while the equilibration can also occur within an excited and deformed projectile-like fragment [Hud12, Bro13]. Very recently, the first direct evidence was obtained [Jed16] that the timescale for the equilibration within the projectile-like fragment is as long as a zepto (10^{-21}) second. This is shown in Fig.4.3, where the (N−Z)/A composition of the two fragments emitted from projectile-like fragment is shown to approach each other as the breakup angle increases. Here, a larger breakup angle indicates a longer contact time between the fragments, therefore resulting in more equilibration. All of these observations can be used to constrain the asymmetry term in the equation of state. The next generation of these type of experiments can be performed at ReA12 with extremely asymmetric pairs of heavy-ion beams like ^{74}Kr, ^{88}Kr, ^{53}Co, and ^{64}Co. The ^{53}Co beam is particularly interesting since it provides a case with N<Z for the first time to study the equilibrium process in neutron-deficient systems. In experiments, a coincidence measurement for light charged particles, heavy fragments, and neutrons is essential, that requires a combination of large-

scale equipment including a silicon array, the large acceptance spectrometer ISLA, and neutron detection systems such as MoNA-LISA, LENDA or VANDLE.

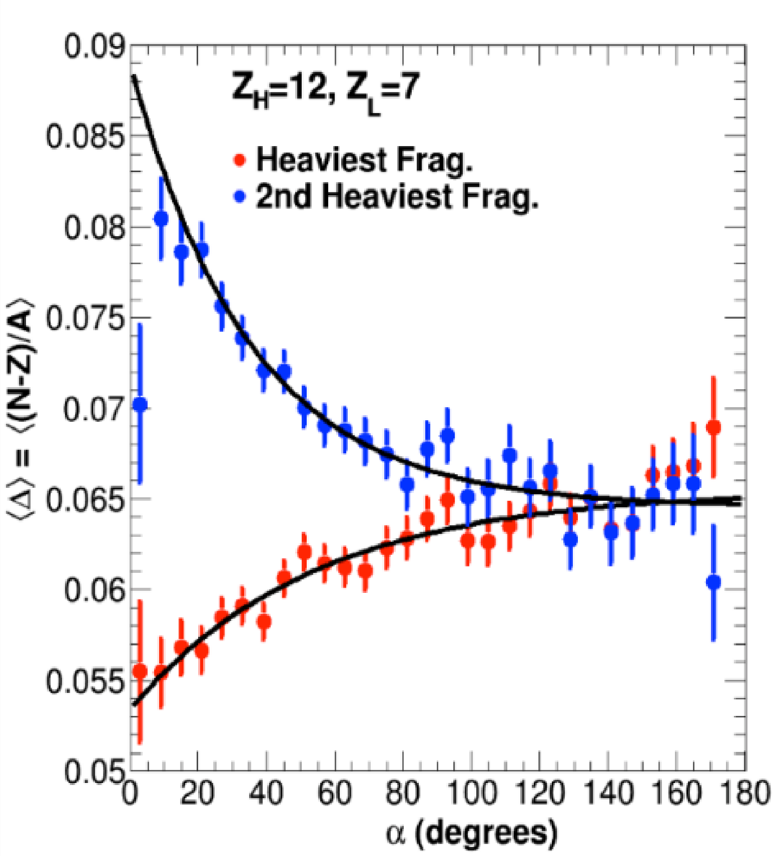


Fig.4.3: Equilibration of N/Z in binary breakup of a largely deformed projectile-like fragment [Jed16]. The composition (N−Z)/A is plotted as a function of the breakup angle α. The time scale for the equilibrium is on the order of a zeptosecond.

5. Nuclear Astrophysics

5.1 Rapid proton capture process (*rp* process)

Classical novae and Type I X-ray bursts (XRBs) are explosive stellar events that occur in binary star systems where hydrogen-rich matter is accreted onto the surface of a white dwarf or neutron star, respectively. As the accreted matter builds up, nuclear reactions cause temperatures to increase until breakout from stable burning occurs and nucleosynthesis proceeds along the proton-rich side of the chart of nuclides via thermonuclear runaway. In the case of classical ONe novae, peak temperatures of approximately 0.1–0.4 GK are reached synthesizing nuclei up to ^{40}Ca, while XRBs reach higher temperatures, $T_{peak}=1-2$ GK, and produce nuclei perhaps up to the SnTeSb region at A~100 [Ili02,Sch06].

As these are the most common explosions in the Galaxy, there is a wealth of observational data on XRBs that can be directly probed by astrophysical models that rely on accurate nuclear physics data, including nuclear masses, β-decay lifetimes, and reaction rates. This allows direct comparisons of the predicted effects of specific reaction rates to observations of these astrophysical events, and indeed it has been shown (Fig.5.1) that specific reactions can have significant effects on light curves, final elemental abundances, and energy output of both novae and XRBs [Ili02,Fis04,Par08,Amt08,Cyb16].

Classical novae and Type I X-ray bursts are driven by a series of (p,γ) reactions and β-decays (the rapid proton capture or *rp* process), the majority of which occur on unstable isotopes making direct measurements challenging. While recoil separators, such as the TRIUMF DRAGON system, have allowed for a handful of direct (p,γ) measurements (e.g. [Rui06]), in the majority of cases sufficient intensities of the rare-isotope beams needed are not yet available. Therefore, these reaction rates, which are often dominated by isolated, narrow resonances, must be calculated using energies, spins, and particle partial widths determined via transfer reactions and other methods. While the planned, state-of-the-art recoil separator (SECAR) coupled to FRIB will be able to measure many of these (p,γ) reactions directly (up to A~64), indirect studies will still be necessary as they provide the resonance energy and spin information needed to guide such direct measurement campaigns. In addition, there will still be a need for indirect studies to provide the nuclear data required to calculate reaction rates where direct measurements remain unattainable.

While direct reaction rate measurements of astrophysical importance typically require relatively low-energy beams ($E_{beam} \leq 3$ MeV/nucleon), transfer reaction measurements used to populate resonances of interest are performed at energies closer to or above the Coulomb barrier. Furthermore, many of the compound nuclei of interest are far from stability and require unstable beams for transfer reaction measurements. As such, higher-energy rare-isotope beams from energy upgrades to ReA3 are needed.

In the case of classical novae, nucleosynthesis proceeds close enough to stability that some experimental information exists on many of the reactions involved. However, several key reaction rates still have large associated uncertainties such as ^{30}P$(p,\gamma)^{31}$S, which may vary by as much as a factor of 20 over peak temperatures in novae due to the uncertainties in spin assignments and the lack of partial width and spectroscopic information [Par11,Wre14]. The situation in XRBs, where the *rp* process proceeds farther from stability, is much more uncertain and there is very little experimental information available on the (p,γ) reaction rates of interest, including those where direct measurements will remain inaccessible into the FRIB era (e.g. of those at A > 64).

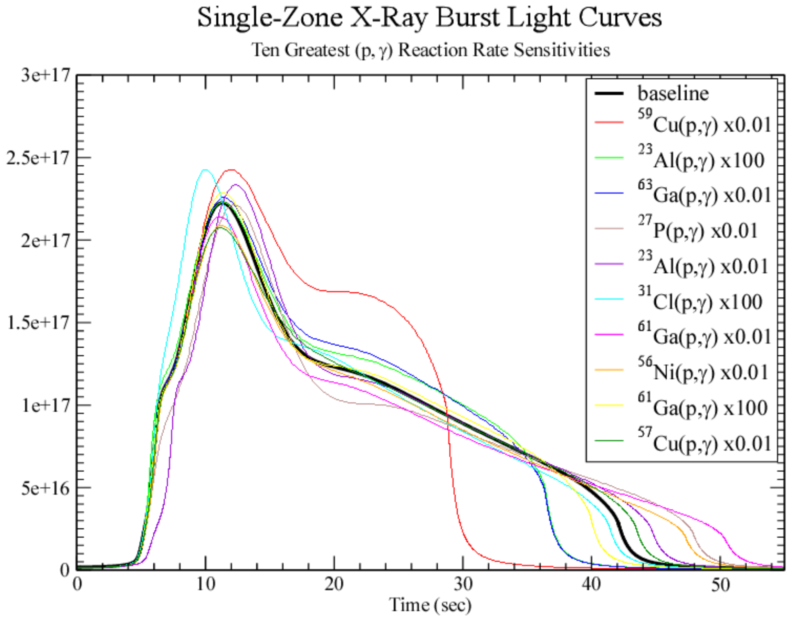


Fig.5.1: Changes in X-ray burst light curves induced by variations in (p,γ) reaction rates [Amt08]. The reaction rates are increased or decreased by a factor of 100.

A variety of instrumentation currently available and planned for the future will allow transfer reaction studies to be carried out on unstable beams that will be available from a ReA energy upgrade. A recent study of the ^{57}Cu(p,γ)^{58}Zn reaction via ^{57}Cu(d,n)^{58}Zn with GRETINA [Lan14] gives an example of one type of measurement that would be possible with ReA beams in the future. With the increased availability of beams farther from stability, the (d,n) proton transfer reaction can be used to selectively populate proton capture resonances in *rp* process reactions of interest, such as ^{59}Cu(p,γ)^{60}Zn, ^{61}Ga(p,γ)^{62}Ge, and ^{65}As(p,γ)^{66}Se. Using γ-ray detection with GRETINA, or GRETA in the future, in coincidence with heavy recoil detection with, for example, the planned ISLA recoil separator would allow determination of the excitation energies and spins of the states of interest. Furthermore, the study of transfer reactions coupled with γ-ray detection can also be used to determine γ–ray partial widths needed to calculate resonance strengths. In addition, proton- and neutron-adding reactions, such as (^{3}He,d) and (d,p), respectively, can be used to determine the partial widths of proton capture resonances. For example, a HELIOS-type device coupled with ReA6−12 would allow a study of resonance strengths via the ^{30}P(^{3}He,d)^{31}S reaction. Both reactions that require a gas target, such as (^{3}He,d), as well as those where high target purity is needed may also make use of gas jet targets, such as JENSA [Chi14].

The availability of rare-isotope beams at energies higher than currently available at ReA3 will have a major impact on our understanding of the nuclear reactions that govern the *rp* process. While direct measurements of the reactions of interest are desirable, information on proton-capture resonances, such as resonance energies and strengths, is needed in order to have such a program be successful. Furthermore, even in the FRIB era, certain reactions will remain inaccessible via direct means. Thus, a strong program of indirect measurements of astrophysically relevant reactions is crucial now and will continue to be so well into the future.

5.2 Rapid neutron capture nucleosynthesis (*r* process)

Recent precision measurements of elemental distributions of the envelopes of individual low-metallicity halo stars are placing unprecedented constraints on heavy-element abundance patterns [Sne08] produced through rapid neutron capture (see Fig.5.2). The rapid neutron-capture process (*r*-process) occurs in high entropy environments (with core-collapse supernovae and neutron-star mergers being the leading candidates for the sites) in which intense neutron fluxes result in extremely rapid, successive neutron captures, driving the populated isotopic distribution very neutron-rich. These isotopes eventually β-decay back toward stability via a network of reactions, thereby contributing to the observable abundance pattern of stable (and very long-lived) nuclei. However, understanding *r*-process abundances requires a variety of physics inputs, including neutron densities, fluxes, temperatures and entropies of *r*-process sites. 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. Due to the unavailability of neutron-capture cross sections on many of these very short-lived nuclei, constraints must come from nuclear structure models, which need to be calibrated in the neutron-rich region. Key to this endeavor is a systematic program of spectroscopic measurements of states with single-neutron character, particularly in the vicinity of the N=50 and 82 shell closures. Furthermore, network calculations of late-stage *r*-process nucleosynthesis indicate that the final abundance pattern is sensitive to neutron-capture cross sections on a particular subset of nuclei (see, for example, Fig. 5.3) at the onset of the fragmentation of single-particle strengths around shell closures, including ^{81}Ni, ^{76}Cu, ^{78}Zn, ^{80}Ga, ^{86,88}As, ^{131,133,135}Cd, ^{133,135,137}Sn, and ^{137}Te [Sur09,Sur14]. 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 which selectively populate states of importance for neutron capture, can be used to constrain neutron-capture cross sections, and are critical in benchmarking nuclear structure models, yielding excitation energies and spin-parity assignments, along with spectroscopic factors required for constraining both structure models and calculations of neutron-capture cross sections. Beam energy, however, is critical to such transfer-reaction studies, as sufficient energy is required to ensure distinctive angular distributions and reliable reaction theory. Particularly for nuclei around the N=82 shell closure important for the *r* process, such reactions require beam energies of around 10 MeV/nucleon or higher to be performed optimally. As such, this research program depends critically on the proposed energy upgrade to ReA being realized.

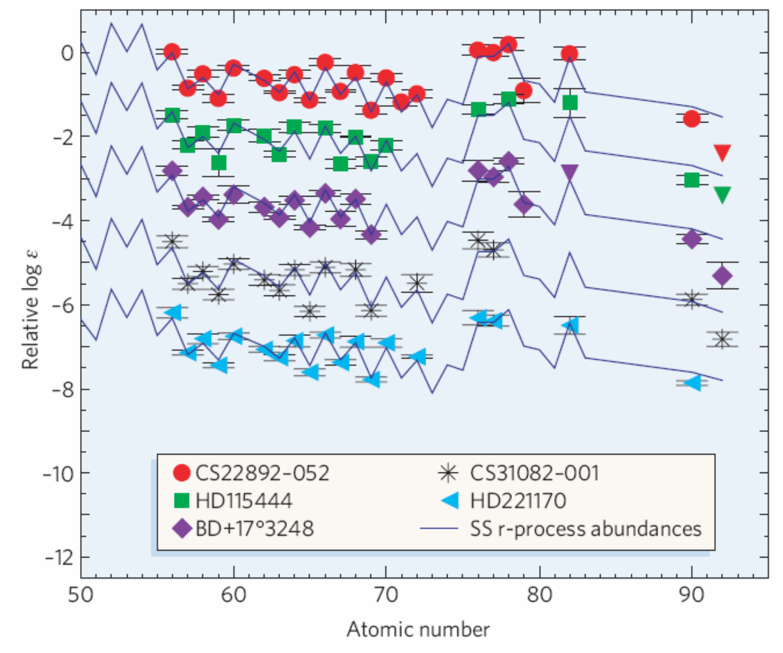
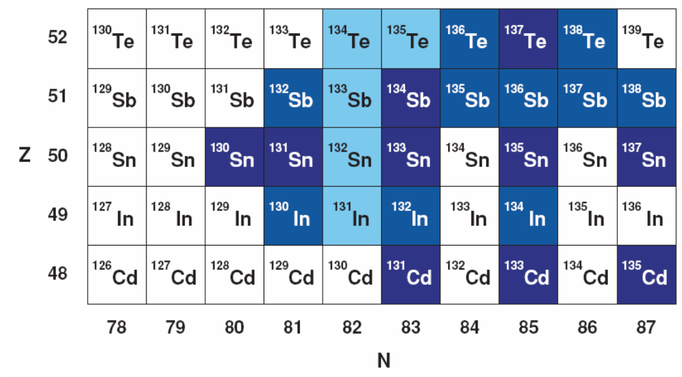


Fig.5.2: Abundances determined from independent high-resolution spectral measurements of five halo stars (offset vertically for display purposes) [Cow06]. The consistency of the data with the Solar System (SS) r-process abundances strongly suggests that a unique r-process exists in nature.



Z										
52	^{130}Te	^{131}Te	^{132}Te	^{133}Te	^{134}Te	^{135}Te	^{136}Te	^{137}Te	^{138}Te	^{139}Te
51	^{129}Sb	^{130}Sb	^{131}Sb	^{132}Sb	^{133}Sb	^{134}Sb	^{135}Sb	^{136}Sb	^{137}Sb	^{138}Sb
50	^{128}Sn	^{129}Sn	^{130}Sn	^{131}Sn	^{132}Sn	^{133}Sn	^{134}Sn	^{135}Sn	^{136}Sn	^{137}Sn
49	^{127}In	^{128}In	^{129}In	^{130}In	^{131}In	^{132}In	^{133}In	^{134}In	^{135}In	^{136}In
48	^{126}Cd	^{127}Cd	^{128}Cd	^{129}Cd	^{130}Cd	^{131}Cd	^{132}Cd	^{133}Cd	^{134}Cd	^{135}Cd
N	78	79	80	81	82	83	84	85	86	87

Fig. 5.3: Sensitivity study of global abundances in an r-process event to nuclear structure properties; the color (light to dark) shows increasing sensitivity of global abundances to the capture rate on individual isotopes in the A=132 region [Sur09]. Single-neutron transfer reactions at ReA provide important constraints on nuclear structure models around the N=82 shell closure and hence on calculations of neutron-capture cross sections.

6. Fundamental Symmetries

6.1 Exploring octupole-deformed nuclei

Octupole-deformed pear-shaped nuclei are reflection asymmetric and have low-lying excited states of opposite parity with respect to that of the ground state (Fig. 6.1). These two features amplify the observable effect of parity violating interactions originating within the nuclear medium [Hax83], which makes them attractive candidates for tests of fundamental symmetries. As one of such examples, electric dipole moment (EDM) [Spe97] is a particularly clean signature of new sources of CP-violation [For03], which are needed to explain the matter-antimatter asymmetry of the universe and are predicted by various extensions to the Standard Model such as supersymmetry.

Atomic EDMs of octupole-deformed species are expected to be orders of magnitude larger than those of spherical nuclei such as ^{199}Hg [Gri09], which currently sets the best limits on CP-violating interactions within the nucleus. The sensitivity enhancement compared to ^{199}Hg depends on the size of the quadrupole and octupole deformations and inversely on the energy splitting of the parity doublet. EDM searches are already underway in some octupole-deformed nuclei such as ^{225}Ra [Par15] and ^{221,223}Rn, but more sensitive candidates may exist.

At FRIB, Coulomb excitation measurements on the EDM candidates will be possible with GRETA and ReA beams. Since the charge breeding of nuclei in the A~200 region will result in small Q/A values (≈0.2−0.25), the energy upgrade of ReA up to ReA6 or ReA9 is critical to have sufficiently high beam energies (Fig.1.4) for the measurements. Level schemes and electromagnetic transition strengths will be determined for new candidate nuclei and a possible presence or absence of octupole deformation can be studied. For example, ^{229}Pa is calculated to have an unusually small parity doublet splitting, which, if confirmed, would make its observable atomic EDM several orders of magnitude larger than ^{199}Hg. Nuclear structure studies which are sensitive to the relevant parameters are needed to help both interpret EDM limits as well as identify the most promising candidates [Gaf13].

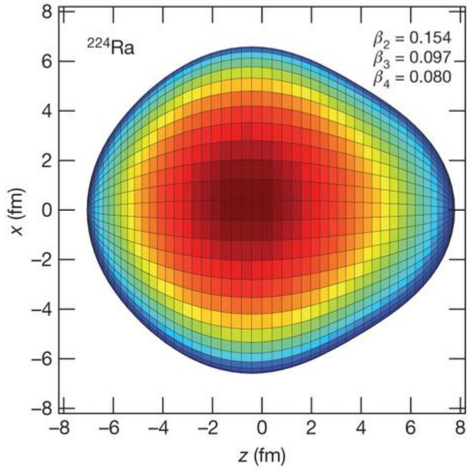


Fig. 6.1: Illustration of the reflection-asymmetric deformation observed in nuclei [Gaf13]. Coulomb excitation measurements have revealed the octupole collectivity of ^{224}Ra, pointing to a possible octupole-enhanced signal of an EDM in this nucleus.

7. Applications

7.1 Surrogate reactions

Neutron-induced reactions on unstable nuclei are important for fundamental and applied nuclear physics. Neutron capture reactions give rise to almost all of the elements heavier than iron through both the slow *s*-process that occurs in AGB stars and the *r*-process that occurs in explosive scenarios such as supernovae or neutron star mergers. The *r*-process nucleosynthesis occurs in nuclei far from stability. The lack of knowledge of neutron capture rates in nuclei near closed shells on the *r*-process path limits our ability to reliably predict *r*-process abundance patterns following freeze out and in various *r*-process astrophysical sites. Neutron capture also occurs in nuclear reactors on unstable species such as fission products. And understanding neutron-induced reactions on unstable isotopes and actinides is important for national security. Because pure neutron targets are not possible, the only way to inform about neutron-induced reactions on short-lived isotopes and far from stability is with a surrogate reaction involving reaccelerated rare-isotope beams. The inverse kinematics ($d,p\gamma$) reaction is a promising surrogate for neutron-induced reactions because of the positive Q-value (requiring lower beam energies) and that the recoiling protons will preferentially be detected at backward angles in the laboratory, with no competing direct reaction channels.

A specific example is the ^{130}Sn(n,γ) reaction rate. An increase in this rate from standard predictions can significantly impact *r*-process nucleosynthesis not only in the A≈130 region but also for heavier masses [Sur09]. The nuclide ^{130}Sn is also an important ^{239}Pu fission fragment that has been used in modeling of nuclear devices. If indeed the ^{130}Sn(n,γ) cross section is significantly larger than predicted, fewer neutrons could be available for other neutron-induced reactions in reactors and nuclear devices. The direct component of the ^{130}Sn(n,γ) has been measured [Koz12]. However, the statistical component, which proceeds via a compound nucleus, could be orders of magnitude larger. A measurement of the ($d,p\gamma$) surrogate reaction with 8-MeV/nucleon ^{130}Sn beams could be used to populate the ^{131}Sn nucleus above the neutron separation energy. This reaction would require ReA9 beams of at least 8 MeV/nucleon. Rare-isotope beams would also provide the capability of measuring surrogates for neutron-induced reactions on isomers. In the case of ^{130}Sn, it is likely that the 1.7-min 7^- isomer of ^{130}Sn will have significant ReA yields (the isomer ratio was 10% for the ^{130}Sn beam at HRIBF produced in proton-induced ^{238}U fission [Jon16]). Informing the ^{130m}Sn(n,γ) cross section could impact nuclear security applications since the isomer could also be produced in neutron-induced fission.

Neutron-induced fission cross sections on short-lived actinides (ground states and isomers) in the actinide region are also important for nuclear energy, forensics and national security. Specific examples could be studies of (n,f) cross sections on ^{236m}Np ($t_{1/2}$ = 23 h) or ^{238}Np ($t_{1/2}$ = 2.1 days) with a surrogate (d,pf) reaction. Actinide studies would require ReA12 beams to populate the final nuclei above the neutron-separation energy.

Other examples are neutron-induced reactions on ^{95}Sr. This is a fission fragment used in the modeling of nuclear devices and could also impact nuclear forensics since its daughter is the relatively long-lived ^{95}Zr ($t_{1/2}$ = 64 days). The uncertainty in the ^{95}Sr(n,γ) cross section has been assessed to have significant implications on the production of ^{95}Zr [LRPI15]. The ($d,p\gamma$) surrogate reaction could be measured with 7-MeV/nucleon beams that would be available at ReA6.

7.2 Nuclear structure from compound-nucleus reactions

Nuclear structure properties, such as the nuclear level density, γ-ray strength functions and optical-model potentials, are required to understand compound-nucleus reactions far from stability, as the direct study of these reactions is often challenging. In the compound reaction mechanism, the projectile and target fuse to create an compound nucleus which decays independently of its formation by emission of particles and γ rays. For medium-mass and heavy nuclei, the compound mechanism almost entirely determines reaction cross section at beam energies up to 6−9 MeV/nucleon. Compound-nucleus reactions also play an important role in nucleosynthesis processes, in particular, for creating elements heavier than iron in the cosmos. The theory of such reactions has been developed by Hauser and Feshbach [Hau52] and suggests that the cross section of compound-nucleus reactions is determined by nuclear structure input parameters such as transmission coefficients, nuclear level densities, and γ-ray strength functions. For nuclei along the stability line, these nuclear structure ingredients have been studied for many years and although they are still the subject of continued studies to improve the accuracy of calculations, some regularities are known. For nuclei off the stability line, however, experimental data are scarce and theoretical extrapolations into this region are uncertain.

Experimentally, in a purely compound-nucleus reaction, nuclear structure ingredients can be assessed from decay characteristics. With rare-isotope beams, neutron or proton-rich compound states can be created by impinging rare-isotope beams on stable targets. Generally, if beam intensities permit, nuclear level densities could be studied from double differential cross sections of outgoing particles (neutrons, protons, α-particles) and the γ-ray strength functions from particle-γ coincidences using the Oslo method [Sch00].

Another strong motivation to study neutron optical potentials for neutron-rich nuclei is based on the experimental observation of Ref.[Tel71] that the neutron strength function, which is related to transmission coefficients, decreases with increasing neutron number of a particular element. This effect cannot be explained with existing parametrizations of the optical model. Later, it was shown [Gor07] that if such decrease is extrapolated to neutron-rich nuclei, it would result in a huge, up to several orders of magnitude, decrease in the rate of the *r*-process nucleosynthesis, which is governed by neutron capture reactions. The neutron strength function is determined by the imaginary isovector optical potential, which is highly uncertain for unstable nuclei. Because there are no neutron targets to study the interaction of rare-isotope beams with neutrons, the way to study optical potentials for neutron-rich nuclei is to study decay channels of excited compound states. Specifically, the ratio of proton/neutron cross sections in outgoing channels is determined by the ratio of both level densities in corresponding channels and strength functions (optical potentials) of outgoing particles. If the neutron strength decreases as one moves towards neutron-rich nuclei, the cross section for outgoing protons and the ratio of proton/neutron cross sections will increase according to the theory of Ref.[Hau52].

The above-mentioned studies to constrain nuclear structure quantities such as optical-model parameters, nuclear level densities, and γ-ray strength functions from particle and γ decay of compound neutron-rich or proton-rich nuclei are based on techniques established with stable beams and can be applied to rare-isotope beams at ReA when optimal beam energies of 3−9 MeV/nucleon become available.

7.3 Nuclear structure inputs for reaction rate calculations above A=200

Some of the major questions in both astrophysics and stockpile stewardship require knowledge of neutron-induced reaction rates which are largely unknown, on nuclei which are too short-lived to be studied directly. Theoretical calculations are an alternative, but their reliability is ultimately limited by our incomplete knowledge of the nuclear physics inputs such as optical potentials, nuclear level densities, and electromagnetic strength functions. Recent work on ^{238}U in forward kinematics has shown that γ-ray cascades following reactions which populate levels near the neutron separation energy can constrain the strength function and improve the theoretical calculations [Ull14]. The basic method is shown in Fig.7.1, where the left panel shows measured capture γ-ray cascades (points) and predictions using various input parameters.

Extending the basic approach from Ref.[Ull14] to reach short-lived nuclei can be accomplished by using transfer reactions such as (*d*,*p*) in inverse kinematics at 5−10 MeV/nucleon to preferentially populate statistical (non-collective) states below the neutron separation energy for the compound nucleus in question. Coincidences between the recoiling charged particles and γ rays can then be used to constrain the strength function and improve the nuclear reaction models. ReA12 beams resulting from FRIB would provide unprecedented access to the necessary nuclei, particularly for the heavy mass region near the actinides. Knowledge of the reaction cross sections in the mass 230−240 range would benefit applications of nuclear physics.

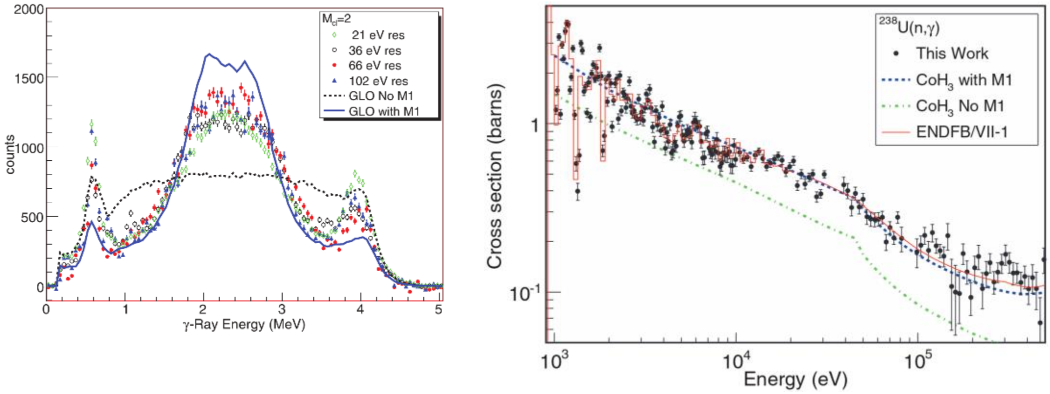


Fig.7.1: ^{238}U capture γ-ray cascades (points) compared to theoretical models (dashed, solid lines) (left) and measured cross section (black points) compared to calculations (right) from Ref.[Ull14]. The model "GLO with M1" is clearly a better description of the cascades, and ultimately using these parameters as inputs to a cross section calculation improves the prediction significantly (right panel, blue line compared to green).

8. Equipment

At the energy-upgraded ReA facility, state-of-the-art equipment and instrument including GRETINA/GRETA, a solenoidal spectrometer, and ISLA will be installed for experiments. In this section, the use of these equipment items at ReA is briefly described. In addition, an extensive set of complementary and auxiliary detection systems is envisioned for ReA experiments at the present NSCL facility and in the future at FRIB. A few examples of such systems that are discussed in the preceding science sections are also given below.

8.1 GRETINA/GRETA

The Gamma-Ray Energy Tracking In-beam Nuclear Array, GRETINA [Pas13], is composed of more than 7 detector modules each of which has four 36-fold segmented Ge crystals. As of early 2016, 9 modules have been available for experiments at NSCL covering a solid angle range exceeding 1π. When FRIB comes online, close to the full 4π array GRETA (Gamma-Ray Energy Tracking Array) [GRE14] is anticipated for in-beam γ-ray detection. Compared to fast-beam experiments with the strong Lorentz boost, experiments with reaccelerated beams will remain in the low-energy domain where the difference between the projectile and laboratory frames is less pronounced. Therefore, experiments can fully exploit the advantage of the 4π coverage, offering significant advantages in γ-ray detection efficiencies for single and coincidence measurements. In view of diverse reaction channels that are open at Coulomb-barrier energies, the installation of recoil detection systems or a recoil separator is essential to achieve superior signal-to-background ratios and to realize measurements of rare events.

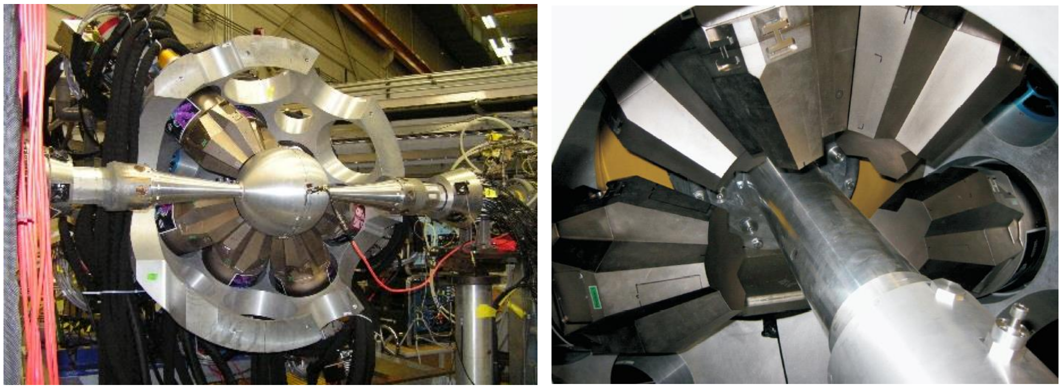


Fig.8.1: GRETINA combined with CHICO2 (left) and a plunger device for lifetime measurement (right).

A number of auxiliary detection systems will be used in combination with GRETINA/GRETA at ReA. They include CHICO-type systems for the recoil particle detection and a plunger system for lifetime measurements (Fig.8.1). CHICOx, a modified version of CHICO2 [Wu16] is in the planning stage to alter the exterior design to fit inside the cavity of GRETA. This unique instrument is useful not only for Coulomb excitation studies but also for any experiments requiring measurements of two-body kinematics, such as the quasi-elastic, deep-inelastic or fission reactions, for example. A plunger system [Dew12,Iwa16] for lifetime measurements facilitates the recoil-distance Doppler-shift method to measure excited-state lifetimes on the order of picoseconds. In experiments, detectors at forward or backward angles are essential to fully exploit Doppler-shift effects arising from recoil velocity changes due to the level lifetimes.

8.2 Solenoidal spectrometer

The possibility to use pure rare-isotope beams at energies close to or above the Coulomb barrier enables a number of reaction tools and studies that have been proven on stable isotopes over many decades. The main difference when using rare-isotope beams is the extensive use of inverse kinematics and the typically low available beam intensities. The target nucleus is the (usually light) probe, and scattered particles have low energies. These features require new types of experimental techniques where high luminosity is paramount. In recent years, two innovative approaches to measure inverse-kinematics direct reactions in the magnetic field of a solenoidal magnet were developed [Wuo07,Lig10,Suz12]. Such studies with a solenoidal spectrometer are anticipated for ReA. One approach exploits missing-mass spectroscopy at HELIOS [Wuo07,Lig10], utilizing the helical orbits of recoiling particles that provide a linear relationship between the energy and the laboratory angle. The other technique employs an active-target TPC [Suz12]. The advantage of these new techniques is the achievement of very good excitation-energy resolution without sacrificing luminosity, which is particularly important for direct-reaction studies with rare-isotope beams at ReA.

A solenoidal spectrometer with charged-particle detection has demonstrated unique features for nucleon transfer reactions in inverse kinematics. This technique, developed several years ago [Lig10], is now well established. The method involves embedding the charge-particle detection system into the uniform magnetic field produced by a large, superconducting solenoid. The solenoid and magnetic field axes are along the beam direction. The beam strikes a target on the solenoid axis and light charged particles such as protons, deuterons, α particles, ^{3}He or tritons follow helical orbits until they return to the solenoid axis where they can be detected with position-sensitive silicon detectors. These detectors measure the particle’s energy and the distance between the target and the point where the particle returns to the solenoid axis. Although the relationship between kinetic energies and laboratory-frame scattering angles is complex in inverse kinematics, in a solenoidal geometry the relationship between kinetic energies and return distances is simple and linear. Measurements of this type can provide excitation energies of high resolution for the residual nucleus and enhance the sensitivity to weak transitions that might otherwise be missed. The simple experimental scheme also makes the analysis of data straightforward. Another advantage of this technique is that the recoiling heavy nuclei can be detected in coincidence with the light-charged particles. This coincidence mechanism not only reduces background, it can be used to isolate different decay modes.

The Active Target − Time Projection Chamber (AT−TPC) provides an alternative approach for direct reaction studies at ReA [Suz12]. In this detector, a gas volume is used both as a reaction target and detector medium. Because charged particles can be tracked from the location where the reaction takes place (vertex), there is no loss of resolution or dead layer of material depending on the target thickness as opposed to conventional inert targets. In addition, the energy at which the reactions take place can be determined for each event. This brings the possibility to efficiently measure excitation functions using the slowing down of beam particles within the gas volume. The solid angle coverage essentially approaching 4π is also a main asset of this technique that compensates for the low intensities of rare-isotope beams as compared to stable beams.

8.3 ISLA

A recoil separator has been identified as a key instrument to collect and identify recoiling particles from low-energy reactions. In 2014, the community endorsed the Isochronous Separator with Large Acceptance (ISLA) [ISLA15] which provides excellent M/Q resolution (<1/1000) together with large acceptances in solid angle (64 msr) and momentum (±10%). Based on the concept of the TOFI spectrometer [Wou87], ISLA is an isochronous device where the time-of-flight from the target to the final focal plane is independent of the energy and scattering angle after the reaction (Fig.8.2). The expected M/Q resolution is on the order of 1/1000 allowing unambiguous identification of recoil particles in a wide mass range. A high rejection power of the unreacted primary beam with various charge states is also considered. A beam swinger is envisioned in front of the spectrometer to cover grazing angles for two-body reactions at and above Coulomb-barrier energies. Many of the experiments with major equipment such as GRETINA/GRETA and ORRUBA (Fig.8.3) may be run in combination with ISLA.

A gas-filled mode for ISLA was also evaluated and found to be useful for a wide range of kinematics in fusion-evaporation and multi-nucleon transfer reactions [ISLA15].

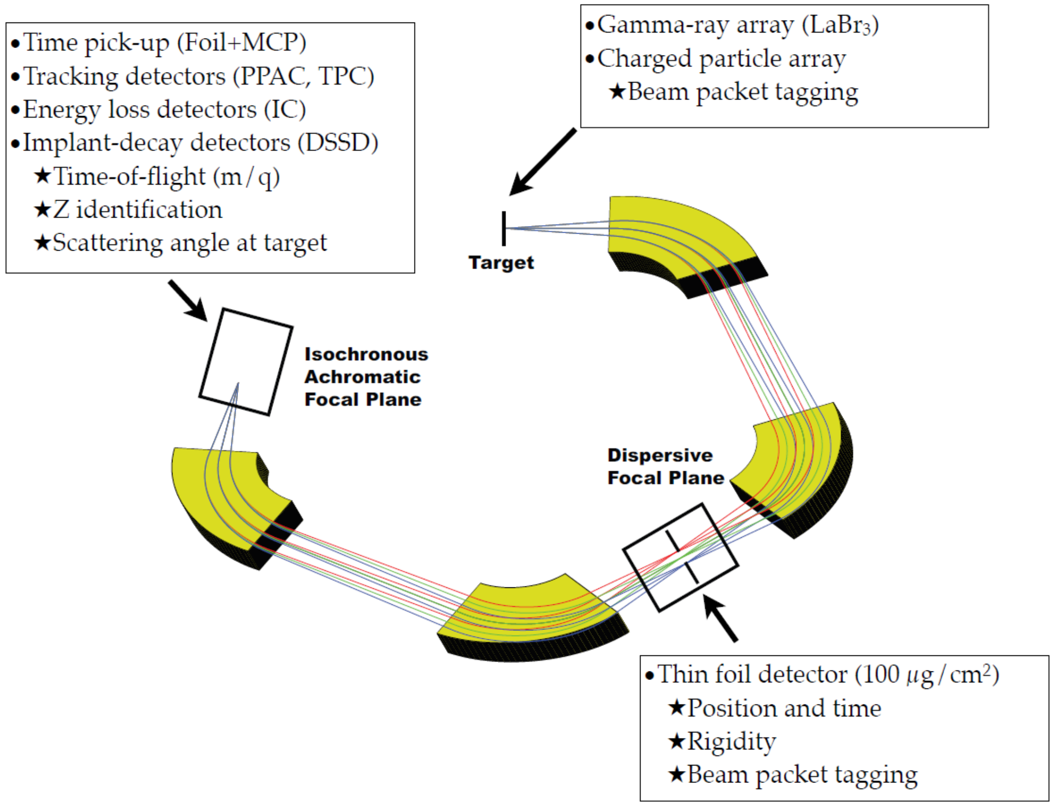


Fig. 8.2: A schematic view of the Isochronous Separator with Large Acceptance (ISLA) and associated detector system described in the text boxes. The time-of-flight between the target and the isochronous achromatic focal plane is measured using the charged-particle or γ-ray array surrounding the target and the focal-plane timing detector, providing a direct measure of the M/Q ratio of reaction products independent from their momentum vector.

8.4 Auxiliary detection systems

A diverse set of complementary and auxiliary detection systems are anticipated for experiments with reaccelerated beams at NSCL and FRIB. Examples of such devices include ANASEN [Lin12] and ORRUBA [Pai07]. Experiments with these equipment should be run in a stand-alone mode or in combination with other major equipment such as GRETINA/GRETA and ISLA.

As an example of possible experiments at ReA, transfer reaction measurements can be performed with the 2000-channel super ORRUBA array [Bar13], possibly coupled to a single-pass gas-jet target, maximizing charged-particle resolution and minimizing target effects (energy straggling, fusion-evaporation backgrounds). For measurements involving higher level density, and surrogate measurements for statistical neutron capture, where charged-particle detection alone is insufficient [Pai08], experiments including high-resolution γ-ray measurements will be undertaken with the GODDESS system [Rat13]. The γ rays emitted in such reactions vastly improve the sensitivity and information yielded in such experiments, and are critical to surrogate measurements for statistical neutron capture [Hat10]. GODDESS (see Fig. 8.3 left) couples ~720 channels of highly-segmented silicon detectors, providing ~30 keV energy resolution and better than 1 degree angular resolution of 15 to 165 degrees for charged particles, with the high-efficiency germanium detector array Gammasphere. For future programs, such as envisioned at the ReA facility for *r*-process nuclei, a version of GODDESS using GRETINA is under development (Fig.8.3 right), which will provide increased resolving power due to the position sensitivity of GRETINA. This system, along with ReA beams, will provide unprecedented resolution for transfer reaction studies with *r*-process beams.

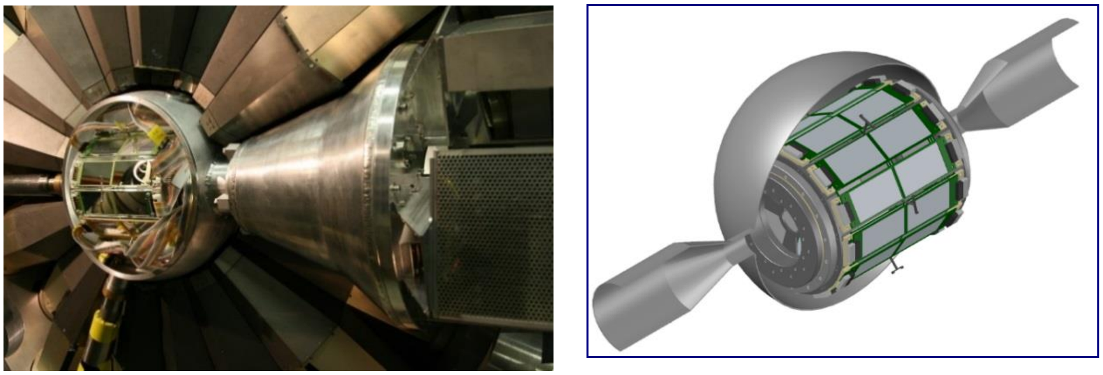


Fig. 8.3: GODDESS (left) comprises the ORRUBA silicon-detector array, optimized for transfer reactions, mounted inside Gammasphere. A coupling of ORRUBA to GRETINA (right) is currently under development, which would be well suited to measurements at an energy-upgraded ReA facility.

9. ReA energy upgrade

9.1 Conceptual layout of the ReA6-12 experimental area

One possible conceptual layout of the energy-upgraded ReA facility is shown in Fig.9.1. In addition to the existing experimental vault at NSCL, the design shown in Fig.9.1 is based on the use of both areas north and south of the reacceleration cryomodules. When ReA12 is completed, two beam lines to the south will deliver reaccelerated beams to end stations that may host a solenoidal spectrometer and ISLA, and additional beam lines are envisioned for the general-purpose experimental area. The maximum magnetic rigidity of the beam line is at least ~2.2 Tm to accept both neutron-rich and neutron-deficient beams from ReA12 (Figs.1.4,1.5).

The ReA energy upgrade will be realized by extending the current ReA3 accelerator and adding up to 3 new cryomodules. The energy specification for each step is shown in Fig.1.4. Time or energy resolution of the reaccelerated beams can be controlled and improved if a rebuncher is installed at the exit of the cryomodules before sending the beams to each experimental area. Up to four independent experimental vaults are possible which will be separately shielded to avoid conflicts between ongoing runs and experiment preparations.

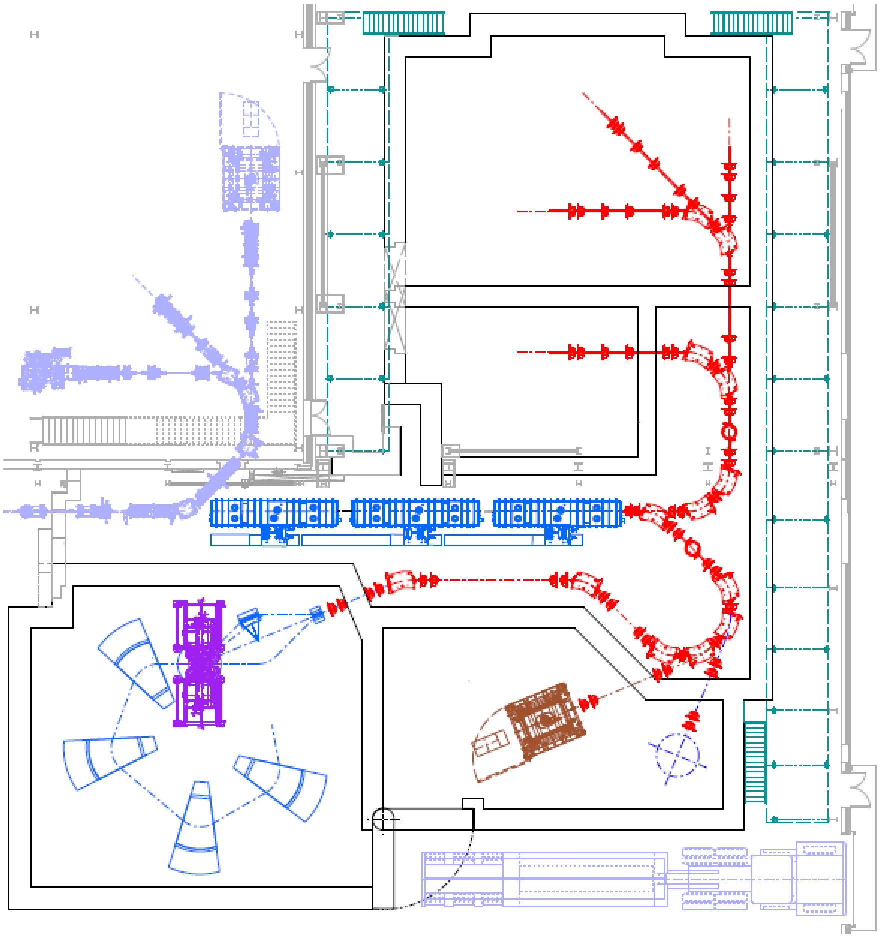


Fig.9.1: Possible layout plan for ReA6-12 in the existing experimental hall of NSCL.

9.2 Cost estimates for the ReA energy upgrade

The cost of the ReA energy upgrade as well as the associated infrastructure and diagnostic systems were estimated based on the layout plan described in the previous section. These estimates are approximate and detailed cost estimates have not been developed. These costs include procurement, manufacturing, installation and labor costs. Contingencies of 25% were added for magnets and associated components. These are summarized in Table 9.1 below. The cryogenic loads are uncertain and additional cryogenic capacity may be needed in addition to the listed items in Table 9.1. A 40T crane is available in the ReA experimental area, but new vault shielding (walls and roof beams) needs to be implemented for each experimental area as described in the layout plan (Fig. 9.1).

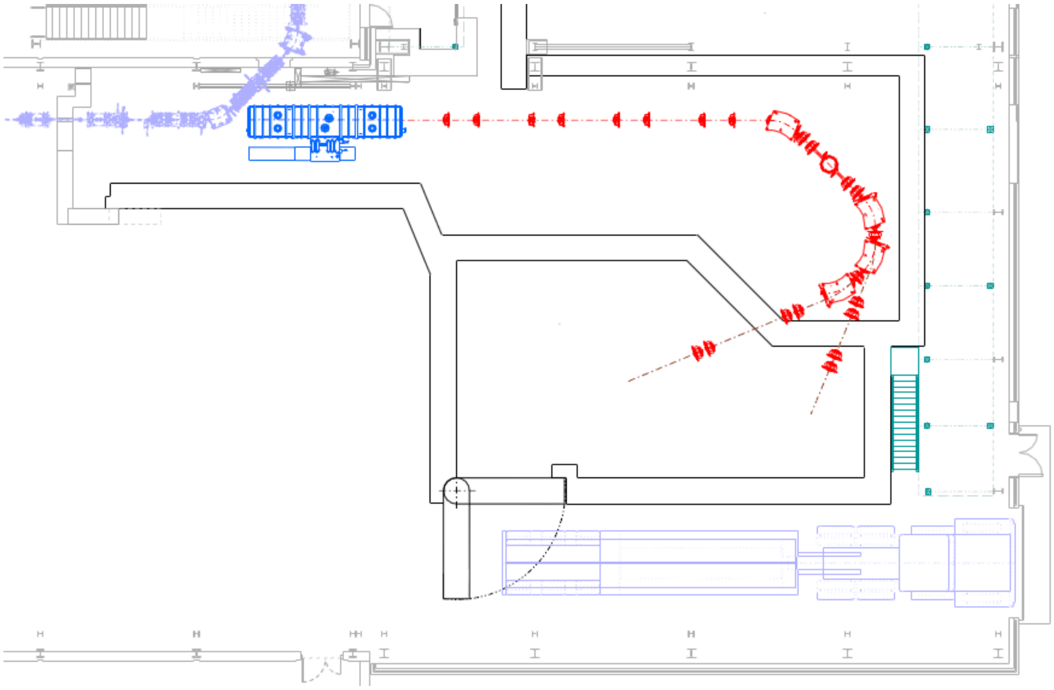
Table 9.1: Summary of the cost estimates for the ReA energy upgrade up to ReA12

Item	Cost	Note
Beam line magnets and components	\$6.1M	Including beam line dipole and quadrupole magnets and associated infrastructure
Cyromodules	\$17.0M	Including rebunchers
Vault Construction	\$1.9M	Shielding and roof beams
Total	\$25.0M	

9.3 Staging options

Staging options are considered where the ReA energy is upgraded in a maximum of three steps depending on the available funding for cryomodules and associated infrastructure. Starting with the current ReA3 beam line, each additional cryomodule increases the available beam energy by at least 3 MeV/nucleon (Fig. 1.4), defining the energy profiles for ReA6, ReA9 and ReA12, respectively. Each stage utilizes the same experimental area as described in the layout shown in Fig. 9.2, but associated beam lines and infrastructure are to be installed in steps. Separate budget scenarios would amount to \$8.5 M, \$6.9 M, and \$9.6 M for the ReA6, ReA9 and ReA12 upgrades, respectively. The ReA6 upgrade project includes the construction of one experimental area including shielding. One beam line can be dedicated to large-scale equipment such as GRETINA/GRETA and a solenoidal spectrometer. In addition, in this scenario one general-purpose beam line and associated infrastructure will be prepared. The ReA9 upgrade includes the addition of one cryomodule as well as an additional beam line to a separate vault where ISLA can be accommodated. Finally, the ReA12 upgrade completes the set of three cryomodules and installs the beam lines which could host large-scale equipment such as GRETINA/GRETA and a solenoidal spectrometer in an independent dedicated area. Gamma-ray and particle detection systems can also be used in combination with the ISLA recoil separator. On the north side, there will be additional general-purpose end stations for user-developed equipment with strong complementary capabilities and a possible full extension within the existing high bay area is illustrated in Fig.9.1. A pre-conceptual layout for the intermediate upgrades ReA6 and ReA9 is shown in Fig.9.2.

(a)



(b)

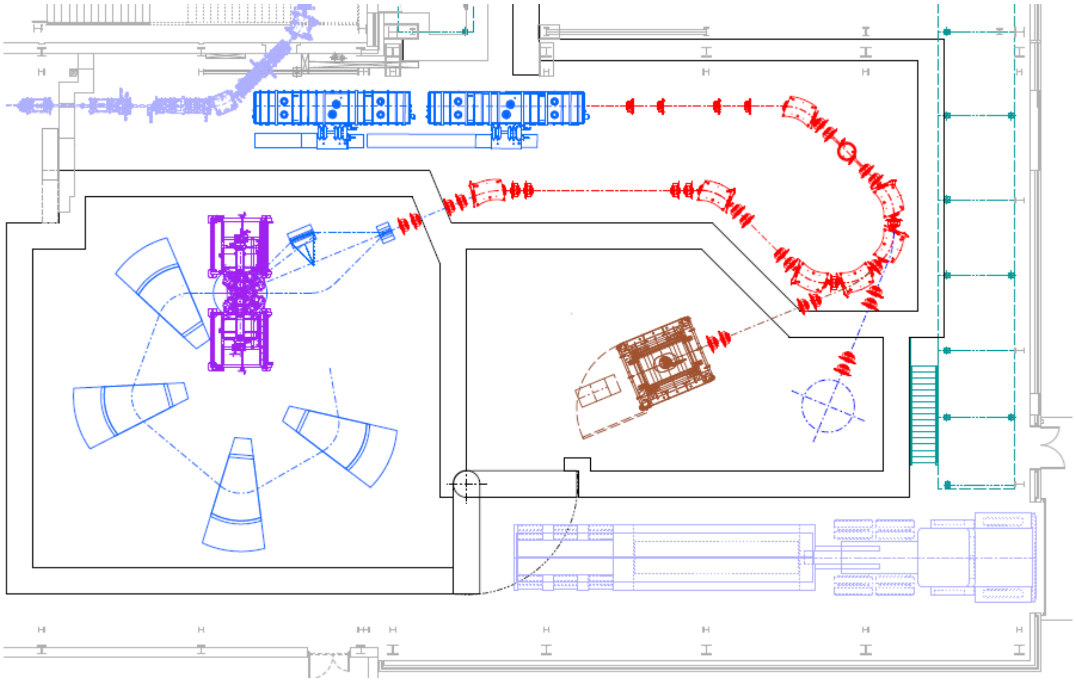


*Fig.9.2: Staging options of the ReA energy upgrade. Possible layout plans are shown for (a) ReA6 (top) and (b) ReA9 (bottom), respectively***.**

ReA3 upgrade workshop

ReA3 upgrade workshop held in August, 2015 on campus of Michigan State University

A one-day workshop to discuss science opportunities with the energy upgrade to NSCL's ReA3 accelerator was held on August 20, 2015, on the campus of Michigan State University, preceding the 2015 Low Energy Community Meeting (LECM). The event was very well attended with more than 70 registered participants. A high energy upgrade to ReA6 and eventually to ReA12 in the future is one of the flagship projects at NSCL and in the future at FRIB. A timely construction of ReA12 has been strongly endorsed in the 2014 Low-Energy Nuclear Physics DNP town meeting and the long-standing interest of the community was reaffirmed by the large number of participants in the workshop and again articulated in the close-out of the 2015 LECM. Following the opening and overview talks on the ReA facility, 14 speakers presented science opportunities that will open up with energy upgrades to ReA6−12.

Reference

[Abu02] K. Abu Saleem, Ph.D Dissertation, Illinois Institute of Technology (2002)

[Amt08] A.M.Amthor, Ph.D. Dissertation, Michigan State University (2008)

[Axe96] L.Axelsson et al., Phys. Rev. C 54, R1511 (1996)

[Bar13] D.W.Bardayan, Nucl. Instr. Meth. A 711, 160 (2013)

[Bar15] D.W.Bardayan, Physics Procedia 66, 451 (2015)

[Ber81] A.M.Bernstein, V.R.Brown, and V.A.Madsen, Phys. Lett. B103 (1981) 255

[Bro73] R.A.Broglia et al., Adv. Nucl. Phys. Vol 6 (1973)

[Bro13] K.Brown et al., Phys. Rev. C 87, 061601(R) (2013)

[Chi14] K.A.Chipps et al., Nucl. Instr. Meth. A 763, 553 (2014)

[Cow06] J.J.Cowan and C.Sneden, Nature 440, 1151 (2006)

[Cyb16] R.Cyburt et al., to be published.

[Czo83] T.Czosnyka et al., Am. Phys. Soc. 28, 745 (1983), and the user manual http://www.pas.rochester.edu/~cline/Gosia/Gosia.Manual.20120510.pdf

[Dew12] A.Dewald, O.Moller, P.Petkov, Prog. Part. Nucl. Phys. 67, 786 (2012)

[Dob07] J.Dobaczewski et al., Prog. Part. Nucl. Phys. 59, 432 (2007)

[Fis04] J.L.Fisker et al., Astrophys. J. Lett. 608, L61 (2004)

[For03] N.Forston, P.Sanders, S.Barr, Physics Today 56, 33 (2003)

[For13] C.Forssen et al., Phys. Scr. T152, 014022 (2013)

[Fos16] K.Fossez et al., Phys. Rev. C93, 011305(R) (2016)

[Fra14] S.Frauendorf and A.O.Macchiavelli, Prog. Part. Nucl. Phys. 78, 24 (2014)

[FRIB09] "FRIB Users Workshop Consensus Statements" Argonne, IL, May (2009)

[Gaf13] L.P.Gaffney et al., Nature 497, 199 (2013)

[Gar16] R.F.Garcia Ruiz, Nature Physics 12, 594 (2016)

[Gav80] A.Gavron, Phys. Rev. C21, 230 (1980)

[Gez11] A.Gezerlis, G.F.Bertsch, and Y.L.Luo, Phys. Rev. Lett. 106, 252502 (2011)

[Gol10] V.Z.Goldberg et al., Phys. Lett. B 692, 307 (2010)

[Gol12] V.Z.Goldberg et al., J. of Physics, Conference Series 337, 012008 (2012)

[Gor07] S.Goriely and J.P.Delaroche, Phys. Lett. B 653, 178 (2007)

[GRE14] The Gamma-ray Energy Tracking Array GRETA, whitepaper submitted to Astrophysics and Low Energy Nuclear Physics Town Meeting August 2014

[Gri09] W. C. Griffith, et al., Phys. Rev. Lett. 102, 101601 (2009)

[Hag13] G.Hagen et al., Phys. Rev. Lett. 111, 132501 (2013)

[Hat10] R.Hatarik et al., Phys. Rev. C 81. 011602(R) (2010)

[Hau52] W.Hauser and H.Feshbach, Phys. Rev. 87, 366 (1952)

[Hax83] W.C.Haxon and E.M.Henley, Phys. Rev. Lett. 51, 1937 (1983)

[Hof14] C.Hoffman et al., Phys. Rev. C 89, 061305(R) (2014)

[Hud12] S.Hudan et al., Phys. Rev. C 86. 021603(R) (2012)

[Ili02] C.Iliadis et al., Astrophys. J. Suppl. 142, 105 (2002)

[ISLA15] M.Amthor and D.Bazin, Isochronous Separator with Large Acceptances, Recoil Separator for ReA12, white paper on the science case and proposed technical solution (2015)

[Iwa16] H.Iwasaki et al., Nucl. Instr. Meth. A 806, 123 (2016)

[Jed16] A.Jedele et al., in preparation (2016)

[Jon16] K.L.Jones, private communication and to be published.

[Koz12] R.L.Kozub et al., Phys. Rev. Lett. 109, 172501 (2012)

[Lan14] C.Langer et al., Phys. Rev. Lett. 113, 032502 (2014)

[Lia03] J.F.Liang et al., Phys. Rev. Lett. 91. 152701 (2003)

[LECM15] Consensus Statements from 2015 Low Energy Community Meeting, East Lansing, Michigan, http://2015.lecm.org/

[Lig10] J.C.Lighthall et al., Nucl. Instr. Meth. A 622, 97 (2010)

[Lin12] L.Linhardt, et al., J. Phys. Conf. Ser. 403, 012306 (2012)

[Lov06] W.Loveland et al., Phys. Rev. C 74, 044607 (2006)

[Lov07] W.Loveland et al., Phys. Rev. C 76, 014612 (2007)

[LRP15] "Reaching for the horizon" The 2015 Long Range Plan for Nuclear Science, the Nuclear Science Advisory Committee (2015)

[LRPI15] "Meeting isotope needs and capturing opportunities for the future" The 2015 Long Range Plan for the DOE-NP Isotope Program, Nuclear Science Advisory Committee Isotopes Subcommittee (2015)

[Mac00] A.O.Macchiavelli et al., Phys. Lett. B480, 1 (2000)

[Mac02] A.O.Macchiavelli et al., ANL Physics Division 2002 Annual Report, ANL-03/23, page 21.

[Mar16] D.Martin et al., Phys. Rev. Lett. 116, 121101 (2016)

[May14] D.A.Mayorov et al., Phys. Rev. C 90, 024602 (2014)

[May15] L.W.May, Thesis, TAMU (2015)

[McC09] E.A.McCutchan et al., Phys. Rev. Lett. 103, 192501 (2009)

[McI14] A.B.McIntosh et al., Eur. Phys. J. A 50, 35 (2014)

[Nom10] K.Nomura, N.Shimizu, T.Otsuka, Phys. Rev. C81, 044307 (2010)

[NRC13] "Nuclear Physics: Exploring the Heart of Matter", The national academies press 2013, National Research Council (2013)

[NRV] Nuclear Reactions Video, Low Energy Nuclear Knowledge Base, Near and sub-barrier fusion reactions of atomic nuclei; http://nrv.jinr.ru/nrv/webnrv/fusion/

[NSAC07] 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

[NSCL09] "Letter from the NSCL Users Executive Committee following the 2009 NSCL Users Workshop", East Lansing, MI, August (2009)

[Oga15] Yu.Ts.Oganessian and V.K.Utyonkov, Rep. Prog. Phys. 78, 036301 (2015)

[Ots05] T.Otsuka et al., Phys. Rev. Lett. 95, 232502 (2005)

[Oza00] A.Ozawa et al., Phys. Rev. Lett. 84, 5493 (2000)

[Pai07] S.D.Pain et al., Nucl. Instr. Meth. B 261, 1122 (2007)

[Pai08] S.D.Pain et al., Proceedings of Nuclei in the Cosmos X, Proceedings of Science 142 (2008)

[Par08] A.Parikh et al., Astrophys. J. Suppl. 178, 110 (2008)

[Par11] A.Parikh et al., Phys. Rev. C 83, 045806 (2011)

[Par15] R.H.Parker et al., Phys. Rev. Lett. 114, 233002 (2015)

[Pas13] S.Paschalis, et al., Nucl. Instr. Meth. A 709, 44 (2013)

[Rat13] A.Ratkiewicz et al., AIP Conf. Proc. 1525, 487 (2013)

[ReA12] The Rationale for the ReA12 Upgrade, the ReA12 upgrade whitepaper, (2014)

[ReA3] A list of ReA3 beams at NSCL, http://www.nscl.msu.edu/users/beams.html

[Rii94] K.Riisager, Rev. Mod. Phys. 66, 1105 (1994)

[Ril14] L.A.Riley, et al., Phys. Rev. C90, 011304(R) (2014)

[RISAC07] "Scientific opportunities with a rare-isotope facility in the United States" Rare-Isotope Science Assessment Committee, Board on Physics and Astronomy, Division on Engineering and Physical Sciences, National Research Council, the National Academies Press, (2007)

[Rog03] G.V.Rogachev et al., Phys. Rev. C 67, 041603 (2003)

[Rog04] G.V.Rogachev et al., Phys. Rev. Lett. 92, 232502 (2004)

[Rui06] C.Ruiz et al., Phys. Rev. Lett. 96, 252501 (2006)

[Sak13] S.Sakaguchi et al., Phys. Rev. C87, 021601(R) (2013)

[Sch00] A.Schiller et al., Nucl. Instr. Meth. A 447, 498 (2000)

[Sch06] H.Schatz and K.E.Rehm, Nucl. Phys. A 777, 601 (2006)

[Siw08] K.Siwek-Wilcznska et al., Intl. J. Mod. Phys. E 17, 12 (2008)

[Smi12] A.G.Smith et al., Phys. Rev. C 86, 014321 (2012)

[Sne08] C.Sneden et al., Ann. Rev. Astro. Astrophys. 46. 241 (2008)

[Sny13] J.B.Snyder et al., Phys. Lett. B 723, 61 (2013)

[Sor13] O.Sorlin and M.-G.Porquet, Phys. Scr. 2013, 014003 (2013)

[Sou14] G.A.Souliotis et al., Phys. Rev. C 90, 064612 (2014)

[Sou89] R.T.de Souza et al., Phys. Rev. C 39, 114 (1989)

[Spe97] V. Spevak, N. Auerbach, and V. V. Flambaum, Phys. Rev. C 56, 1357 (1997)

[Ste13] D.Steppenbeck et al., Nature 502, 207 (2013)

[Sur09] R.Surman et al., Phys. Rev. C 79, 045809 (2009)

[Sur14] R.Surman et al., AIP Advances 4, 041008 (2014)

[Suz12] D.Suzuki et al., Nucl. Instr. Meth. A 691, 39 (2012)

[Suz13] D.Suzuki et al., Phys. Rev. C 87, 054301 (2013)

[Tan08] I.Tanihata et al., Phys. Rev. Lett. 100, 192502 (2008)

[Tar03] O.B.Tarasov and D.Bazin, Nucl. Instr. And Meth. B 204, 174 (2003)

[Tel71] H.Tellier and C.M.Newstead, in Proc. Conf. Neutron Cross Sections and Technol., 3rd, Knoxville, Tenn., edited by R.L.Macklin (1971), vol. 2 of CONF-710301, p680.

[Ube16] E.Uberseder et al., Phys. Lett. B 754, 323 (2016)

[Ull14] J.Ullmann et al., Phys. Rev. C 89, 034603 (2014)

[Wak16] A.Wakhle et al., in preparation (2016)

[Wer15] T.A.Werke et al., Phys. Rev. C 92, 034613 (2015)

[Wie13] F.Wienholts et al., Nature 498, 346 (2013)

[Wim10] K.Wimmer et al., Phys. Rev. Lett. 105, 252501 (2010)

[Wou87] J.M.Wouters et al., Nucl Instr. Meth. B 26, 286 (1987)

[Wre14] C.Wrede, AIP Advances 4, 041004 (2014)

[Wu06] C.Y.Wu et al., Phys. Rev. C 73, 034312 (2006)

[Wu16] C.Y.Wu et al., Nucl. Instr. Meth. A 814, 6 (2016)

[Wuo07] A.H.Wuosmaa et al., Nucl. Instr. Meth. A 580, 1290 (2007)

[Yan13] R.Yanez et al., Phys. Rev. C 88, 014606 (2013)

[Yan14] R.Tanez et al., Phys. Rev. Lett. 112, 152702 (2014)

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