The Rationale for the ReA12 Upgrade

20 Aug 2014

Update of the community document written for ReA12 in 2010

Rationale for Early Implementation of ReA12

1 Summary

The FRIB and NSCL user communities have strongly endorsed the early implementation of reaccelerated beams with energy up to 10 MeV/u at FRIB [FRIB09,NSCL09]. This capability would provide a world-unique set of beams from in-flight separation and gas stopping at energies sufficient to develop many of the experimental and theoretical tools necessary for the FRIB scientific program. A delay in implementation of this capability would result is a slower start-up of science at FRIB.

Specifically, the early implementation is needed to provide:

- A quantified reaction theory that will allow nuclear structure information such as spectroscopic factors, neutron and proton radii, and deformation parameters to be extracted reliably and with known theoretical error bars.
- An understanding of the influence of neutron excess and neutron skins on the processes of fusion and deeply inelastic transfer. These are potentially key reactions to be used to produce and study the heaviest elements and heaviest isotopes.
- Time to develop experimental techniques and refine methods in order to have the most efficient and fully developed experimental program for when FRIB is operational. This will allow early scientific returns from FRIB, similar to how the AGS program at BNL allowed early results from RHIC.

In addition, this early implementation would allow for a world-unique scientific program with in-flight separated and reaccelerated beams not normally available at ISOL facilities, such as S, Zr, and Ta. It will also be a necessary step to prepare the user and theoretical communities for the FRIB scientific program.

The specific rationale for why early implementation is needed at the NSCL is:

- The user community is pushing for early access to 10 MeV/u reaccelerated beams at the FRIB site [FRIB09,NSCL09]
- No other facility will have the full range of beams available from in-flight separation and gas stopping available for reacceleration up to 10 MeV/u. This makes this upgrade fully relevant to preparing for the FRIB scientific program.
- Leveraging of the investments in in-flight separation, gas stopping, charge breeding and ReA3 at the NSCL. With the implementation of the higher energy, all aspects of the FRIB program can be debugged well ahead of CD-4.
- FRIB-like intensities of radioactive beams are available for near stable isotopes, allowing tools to be developed and applied when rare isotopes are available from FRIB

2 Introduction

The availability of in-flight separated, stopped, and reaccelerated beams from the NSCL Coupled Cyclotron Facility offers a unique opportunity to the scientific community to jumpstart the scientific program of FRIB. Reaccelerated beams will be available at the NSCL for an experimental program starting in 2011. However, the

maximum energy of these beams will typically be below 5 MeV/u, which is too low for much of the envisioned FRIB experimental program.

The range of isotopes and the associated intensities available following the current NSCL reaccelerator project is shown in figure 1. These isotopes are potential candidates for acceleration to higher energy and for use in a broader scientific program. As shown in the figure, isotopes are available at intensities above 10^5/s over a wide range. This intensity is sufficient for detailed single and multiple Coulomb excitation experiments, single and two-nucleon transfer studies, sub-barrier and near-barrier fusion studies, deep-inelastic reactions, and fusion-evaporation experiments.

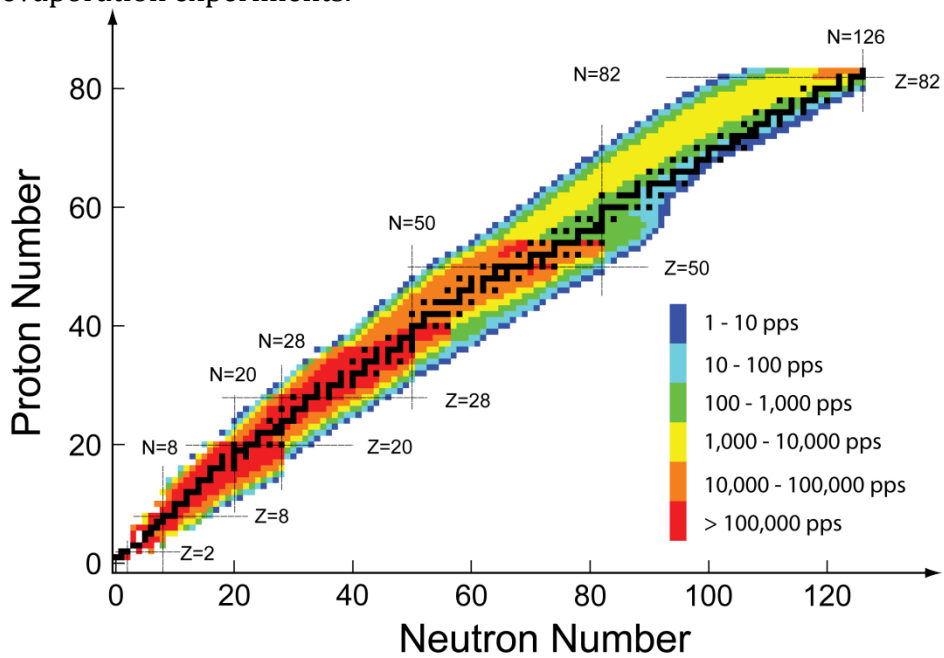

Figure 1: Reaccelerated beam rates based on the available fragment rates available at NSCL. The stopping and extraction efficiency for the gas cell was assumed to be 20%, and charge breading and acceleration 50%. The delay time in the cell was assumed to be 60 ms. For rates above $1x10^5$/s the efficiency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

With the use of fragmentation and fission of heavy-ion beams, and in-flight separation using the A1900 fragment separator a wide range of isotopes are produced. These will be stopped in an NSCL cryogenic gas cell, currently under development at the NSCL, and a linear RF-guide gas cell underdevelopment at ANL. Extract ions will be injected into an EBIT charge breeder for stripping to an N+ charge state. The use of stopping in a He-gas cell and charge breeding provide a nearly chemically independent source of ions; and hence, as shown in figure 1, the full range of elements is available. This is a unique feature of reaccelerated beams compared to beams provided by the ISOL technique. The availability of beams of elements difficult to extract from ISOL targets such as boron, zirconium, and tungsten provide the opportunity to investigate certain key nuclei not otherwise accessible.

The NSCL reaccelerated beams will be within a factor of 10^2 to 10^4 that available at FRIB, which effectively means nuclei 3 to 6 nucleons closer to stability will be

studied. Nevertheless, this upgrade will have useful (and the highest available) intensities of many nuclides until FRIB is complete.
The scientific motivation for the energy upgrade is nearly identical to the motivation for the FRIB project itself, albeit with a significantly reduced intensity for most ions. The FRIB scientific case has been described in detail in many documents including the RISAC report [RISA07], the 2007 LRP [LRP07], and the RIA Users Community document [RIAU06]. Details will be summarized in the following and subsequent sections.

3 Scientific documentation supporting the implementation of 10 MeV/u

The FRIB community (previously the RIA user community) have consistently made the case that reaccelerated beam energies of up to 10 MeV/u are necessary to achieve the scientific goals of the FRIB project. In fact the goal of reaching 10 MeV/u goes back to the initial discussion of an advance rare isotope beam facility in the early 1990s [ISF90]. In this document the argument is made that access to energies above the Coulomb barrier for all beams, and for beams used in inverse kinematics is necessary. One of the initial documents that set the specification for the reaccelerator for FRIB was the Columbus Town Meeting White Paper in which 6-10 MeV/u was specified as the desired range [COLU97]. This was chosen based on the requirements of transfer reactions studies in inverse kinematics. The RIA Users Document prepared in 2006 presents a number of example experiments that specifically require beams of near 10 MeV/u [RIAU06]. This document noted that higher than 10 MeV/u should be available for multi-nucleon transfer reactions, notably for (p,t) studies, and hence 12 MeV/u was generally accepted as the minimum energy for all ions.
The 2007 NSAC Long Range Plan [NSAC07] highlights the scientific goals of the field. This includes understanding the forces of nuclei, the origin of their often-simple structure, the nature of neutron matter, and the reactions that drive stars. As outlined in the following section, the best way to address many of these goals will require beams of approximately 10 MeV/u at FRIB.

4 Scientific case for 10 MeV/u

The simple argument for the energy of reaccelerated beams is that beams of at least 10 MeV/u for all ions provides energies above the Coulomb barrier for all beams in both normal and inverse kinematics. This opens a range of nuclear reactions that can be used to study nuclear properties and prepare nuclei in special states, such as at the highest possible spins. The detailed arguments for the higher energy are related to the nature of specific nuclear reactions and the theoretical tools used to evaluate them.
One of the most critical areas where significant work, both experimental and theoretical, is needed prior to completion of FRIB is in the area of single and multiple-nucleon transfer reactions. Further study and theoretical developments of these reactions is essential to allow them to be used to extract information on the structure of exotic nuclei. One nucleon transfer reactions to bound states A(d,p)B,

depend on the properties of the final bound state B=A+n. More specifically, these cross sections depend on the overlap function between the original state of nucleus A and the final bound state of B which tells us how the valence nucleon (here neutron n) moves relative to the core A in this complex many-body picture. The (d,p) reactions have long been one of the main tools to extract phenomenological spectroscopic factors (SF), the norm of the overlap function, a quantity related to the shell occupancy of a given state in nucleus B relative to a state in nucleus A.

It is well understood that at energies below the Coulomb barrier (such as available at ReA3), the (d,p) reactions are entirely peripheral, and thus only sensitive to the normalization of the overlap function at large distances (the ANC). By using the sub-Coulomb (d,p) reactions, the ANC can be fixed. For estimation of astrophysically interesting reaction rates, it is often only the ANC that is required.

To go beyond this information, higher energies are needed. At energies well above the Coulomb barrier, the (d,p) reactions probe deeper into the nucleus and hence become more sensitive to spectroscopic factors. The analysis of the (d,p) reaction above the barrier will enable an extraction of the SF with reduced ambiguities [MUK2005,PANG2007]. However for s-wave neutron capture (and probably a variety of resonant captures), the capture cross section is sensitive to the interior of the overlap function as well as the asymptotic region [MUK2008]. In that case, when studying neutron rich nuclei with Z=50 or larger, 3-6 MeV/u is clearly not sufficient. It is important to have the capability to reach 12-20 MeV/u.

Higher energy also has certain reaction kinematic advantages. Certainly, to investigate stripping reactions, such as (p,d) and (d,^{3}He) higher energy of closer to 20 MeV/u is required to match the higher Q-values. For (d,p) reactions higher energy, above 5 MeV/u, is needed to match higher angular momentum transfer.

Based on analysis of past data it has been argued that the interpretation of transfer data is much simpler if the reaction is done at above 10 MeV/u. For example, a survey of (d,p) and (p,d) reaction data by Lee et al [Lee07] indicated that extraction of spectroscopic data is only reliable at energies of greater than 10-15 MeV/u. Indeed, it has been argued by RC Jonson [Summ02] that energy greater than 20 MeV/u is necessary.

Developments in the theory of nucleon transfer reactions will be an important part of the developments leading up to the FRIB scientific program. The availability of beams of a range of energies will help stimulate the necessary reaction theory needed to interpret the data. Reaction studies prior to FRIB at the reaccelerator upgrade will allow the energy dependence of (p,d), (d,p) etc reactions to be explored and the reliability of reaction theory to be tested and improved.

Finally, generally the higher energy provides more favorable kinematics for particle detection since the energy of the particles are higher and segmented telescopes can be used including ΔE and E particle identification.

The same arguments also apply for (^{3}He,d), (α,t), reactions where even higher energy is necessary to be above the Coulomb barrier (≥10 MeV/u), and Q-values can be more negative. Helium-induced reactions are particularly interesting because they can probe proton-particle states and ^{3}He and α particles are well bound and remove some of the complications in using deuterium targets. The combination of

studies using (d,n) and (^{3}He,d) will be important to determine the reliability of methods used to extract proton-particle state information.
One of the advantages of the higher energy would be that it opens up new reaction mechanisms that are not available at below 5 MeV/u. Potentially interesting examples are deep inelastic reactions and/or multi-nucleon transfer reactions that are performed at around 5-15 MeV/u. These reactions can be used to transfer many neutrons onto an already neutron-rich beam. The structure of the new, exotic isotopes is probed by observation of their gamma-ray decay in beam, or by observation of isomeric decays following mass separation. An example of the possibilities is given in figure 2 taken from reference [BROD06]. It illustrates the cross section for transferring neutrons onto a beam by interaction with a neutron-rich target, in this example ^{208}Pb.
For example with a beam intensity of 10^4/s and a 4-neutron transfer cross section of only σ = 1 mb (see figure 2) the use of a 20 mg/cm^2 would yield 100 events/day. In the course of a four-day experiment, detailed level structure of very exotic nuclei can be measured.

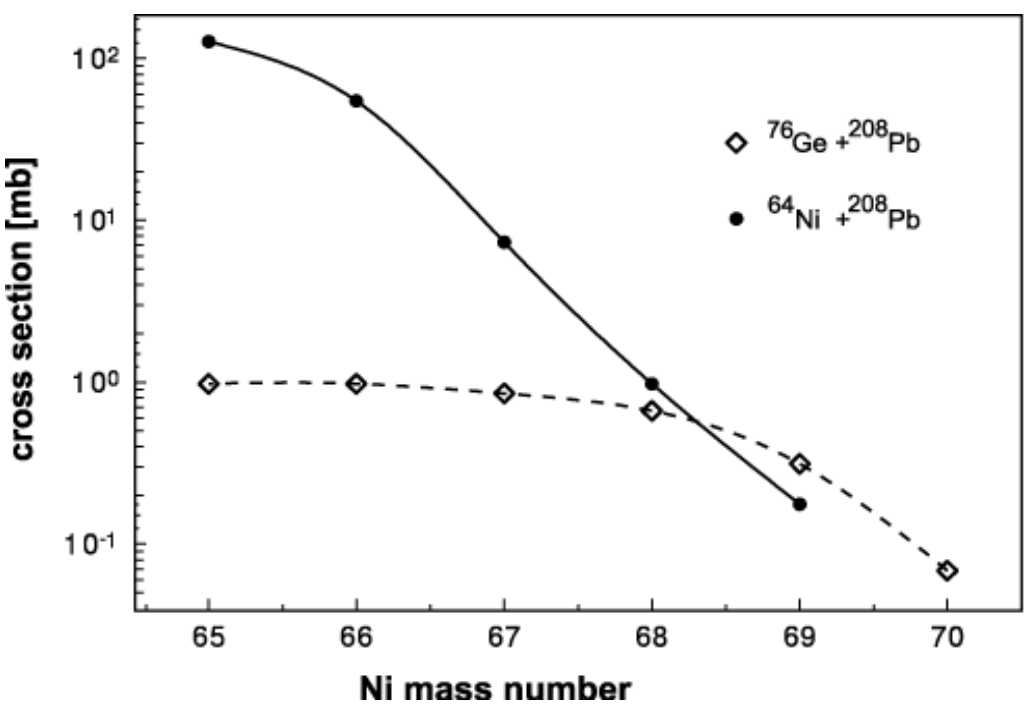

Figure 2: Illustration of the large cross sections for multi-neutron transfer possible with 5 to 10 MeV/u neutron-rich beams. The figure is taken from reference [Brod06]. It illustrates that up to 5 neutrons can be transfer to a neutron-rich projectile (in this case ^{64}Ni) by interaction with a ^{208}Pb target. This coupled with efficient gamma-ray detectors such as CAESAR could allow the study very neutron rich nuclei at or near the drip lines.

It is very likely that a workhorse of the experimental program for reaccelerated beams will be the use of Coulomb Excitation and Multiple Coulex. For this program

the energies available at ReA3 are lower than optimal. This is illustrated in figure 3, which shows the gain in cross section as a function of beam energy [CERN07]. It clearly indicates that the sensitivities for these studies could be increased by at leas an order of magnitude. Given the weak beam intensities available, this is a critical gain. A related program that would also require the higher energies (in this case to be above the Coulomb barrier) is Unsafe Coulex used to reaction studies at for example ANL [see for example WIED99].

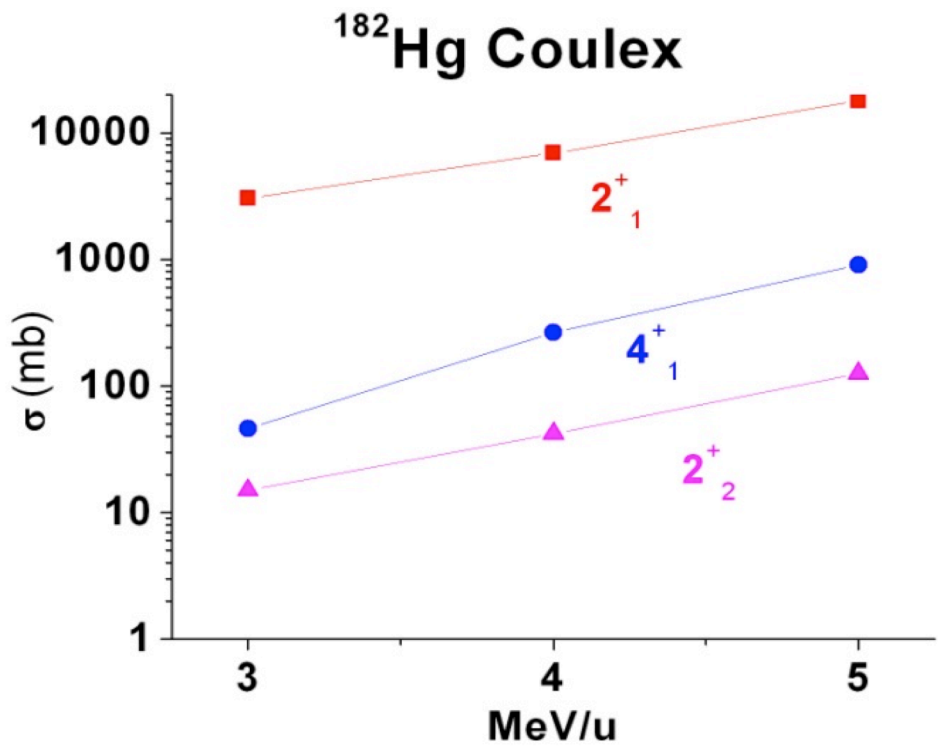

Figure 3: Illustration on the rapid increase in Coulomb excitation cross section that would be available in raising the Hg energy from 3 MeV/u at ReA3 to a higher energy. Due to thicker targets that can be used an the higher cross section, the sensitivity increase can be nearly two orders of magnitude for Coulomb excitation studies. The figure is taken from reference [CERN07].

One of the interesting topics that FRIB will address is the nature of pairing in neutron-rich matter. This has implications for neutron stars, where pairing will likely play a role in the structure of the their crust and influence observable behavior. A tool that has been identified by the user community to probe pairing is sluster transfer reactions (e.g. (p,t) and (t,p)). These reactions can have large negative Q-values, and are best done at above 12 MeV/u [RIAU06].

In the past ten years, there has been significant progress in developing indirect methods to determine important nuclear reaction rates. This is often necessary as measurement of the direct reaction is impossible due to a very small cross section,

or due to the lack of a suitable target. One example of this is the surrogate reaction program developed by the LLNL,LBL,Rutgers et al. collaboration [LESH09]. Much of this work done around 10 MeV/u equivalent in order to reach the equivalent neutron energy corresponding to neutron induced fission. The energy is important so that the assumptions of the independence of the compound nucleus on entrance channel and angular momentum is achieved.

One of the other very successful and potentially widely applicable developments has been the careful work to develop a method to extract Asymptotic Normalization Coefficients, ANCs, from transfer reactions at around 10 MeV/u. This work has been done primarily at Texas A&M [HU1994]. A critical aspect of the program is that in order to have reliable optical model parameters from the JLM formalization at approximately 10 MeV/u equivalent energy beams are needed [TRAC00].

The higher energy will allow a broad study of fission and fission barriers. For these studies a range of energies will be important. In particular for extraction of fission barriers it will be necessary to study the energy dependence of the fission cross section up to nearly 20 MeV/u [PHAI07]. In general it will be important to make detailed reaction mechanism studies including study of fusion-evaporation, and incomplete fusion near and above the barrier in order to understand the role of the extra neutrons in exotic nuclei. This in tern can be used to determine if neutron-rich beams could provide a pathway to neutron rich heavy elements.

5 Other world-unique scientific opportunities

The availability of energies near 10 MeV/u and reaccelerated beams not available elsewhere would allow a world-unique scientific program. This would include detailed study of Mg, Al, and Si nuclei in, and around, the "island of inversion" by one- and two-nucleon transfer reactions. This includes the possibility to measure proton and neutron spectroscopic factors of excited states, and study the dynamical symmetries of these nuclei by observing the low-lying spectrum of 0^+, 2^+, and 4^+ states (or their analogs in odd N and Z nuclei) by multiple Coulomb excitation. At current ISOL facilities, these studies are mostly limited to Ne, and Na isotopes. The program would also include study of the structure of phase transitional nuclei not accessible at ISOL facilities such as the predicted X(5) nucleus ^{100}Zr. A particularly important part of the program will be study of the evolution of shell structure in Ca and Ni isotopes. The higher energy will allow the use of ANC methods for indirect determination of key astrophysical reactions [HU1994] in short-lived isotopes of elements difficult to produce at ISOL facilities, such as P and S. Alternatively, the higher energy will allow proton and neutron transfer to be used for these measurements, provided improvements in transfer reaction theory can be demonstrated to provide reliable results. The unique neutron-rich beams can be used to probe nuclei at their highest spin, 10 hbar (nearly 20%) higher than previously possible. Finally, the program may make significant contributions to our understanding of nature's fundamental symmetries by allowing the study of reactions of actinide nuclei (not possible at ISOL facilities) and hence the search for octupole deformation in Pa (and similar isotopes) as a background for future atomic EDM searches.

Details of some of these possibilities are discussed in the following sections.

6 Opportunities with transfer reactions

The evolution of nuclear shell structure is one of the driving motivations for the use and study of rare isotopes. The investigation of high-lying single-particle and single-hole states. One of the driving forces that leads to the erosion of the traditional magic numbers is when particle-hole excitations across a shell gap into the next higher oscillator shell become energetically favored if stabilized by deformation and pairing correlations. Hence, the experimental identification of the resulting intruder configurations – typically high-l – at low excitation energy and ultimately in the ground state is an important part of understanding shell evolution. Direct reaction studies involving the transfer of nucleons generally require beam energies above 6 MeV/u to reduce the sensitivity to model parameters and improve the reliability of the extracted spectroscopic information; in particular, the transfer to high-l states requires higher beam energy to match in incoming and outgoing momenta. Moreover, for many of the reactions of interest energy above 15 MeV/u will be required to overcome the large negative Q-values and inverse kinematics.

a) Particle-hole study of high-l states

Figure 4 illustrates this for neutron $g_{9/2}$ intruder configurations in neutron-rich Cr isotopes approaching *N=40.* At ReA3 energies of ^{58}Cr (~ 5 MeV/u), the $9/2^+$ intruder state is hardly populated in a (d,p) transfer reaction due to linear and angular momentum mismatch, instead this beam energy is well matched to the population of states with orbital angular momentum l=1. The cross section for the population of the l=4 intruder state of interest dominates in certain angle regions starting at 15 MeV/u beam energy. At even higher beam energies and using the (α,^{3}He) reaction, the l=4 state dominates at all angles. A technique for the sensitive identification of high-l intruder states is of great interest for the study of shell evolution and the identification of new "Islands of Inversion".

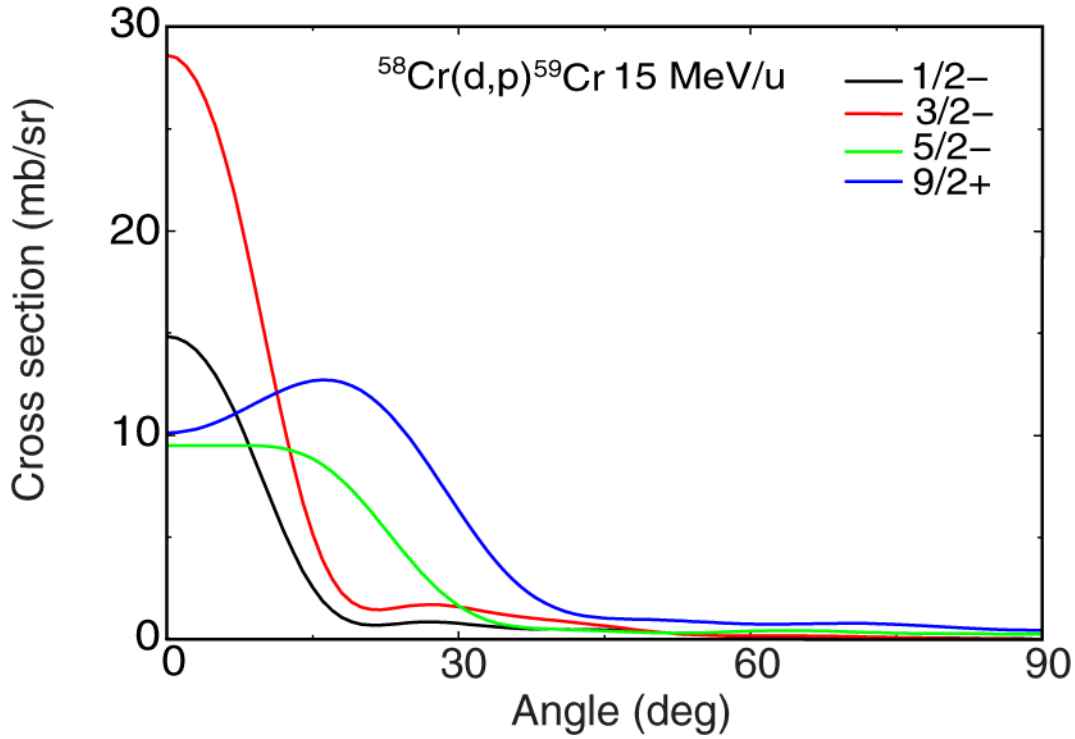

Figure 2: Calculation courtesy of Jeff Tostevin, standard potentials, unity spectroscopic factors for all states, level scheme based on PRC 69, 064301 (2004).

Single nucleon transfer reactions, with favorable cross sections of greater than 1 mb/sr can be performed with beam rates of greater than 1000 /s. For ReA12 the estimated rate ^{58}Cr rate is 2 x 10^4 /s, well above the acceptable range

b) Transfer reaction studies around regions of shell closures away from stability

One example is the region around N=16 which appears to be a closed neutron shell for neutron-rich nuclei. Surveys of neutron transfer across the N=16 line with beams of ^{26}Ne, ^{27}Na, ^{28}Mg, and ^{29}Al, all of which may be possible from ReA12 above 6 MeV/u, with intensities greater than 10^4/s. These intensities are sufficient for (d,p), (^{3}He,d) and (p,d) studies. Also, due to appreciable level densities, high-resolution measurements are essential.

c) Use of surrogate reactions to determine (n,γ) rates for basic and applied research

Measurement of data and nuclear reaction rates to allow the connection between fissile material and the long-lived daughters of fission fragments is a central issue for nuclear forensics and stockpile stewardship. If the connection can be made, the measured yields of the fission product daughters can be used to determine the differences in the uranium and plutonium isotopes in a nuclear device and the yield of the device. An example of a long-lived fission fragment of interest is ^{95}Zr which has a half-life of 64 days, and is the daughter of the prompt fission fragment ^{95}Sr,

with $t_{1/2}$ =24 s. Calculating the expected yield of ^{95}Zr requires a network of (n,γ) and (n,2n) reactions and beta decays on fission fragments with mass A≈95. The ^{95}Sr(n,γ) reaction has been identified as a key reaction, since varying this cross section can have significant effect on the measured yield of ^{95}Zr.
Given the short half-life, it will be extremely difficult to measure the ^{95}Sr(n,γ) cross section directly. The (d,pγ) reaction is a promising surrogate for (n,γ). Surrogate measurements in inverse kinematics require beam energies sufficiently high (>8 MeV/u) to populate the final nucleus at least 1 MeV above the neutron separation energy, with light reaction particle energy resolutions of at least 200 keV. Hence the ReA12 upgrade is essential for these measurements.

d) ANC for determination of (n,γ) or (p,γ) reaction rates

Of particular interest will be transfer reactions in vicinity of closed shells, for example ^{54}Ca and ^{56}Ni, and for nuclei of interest for astrophysical modeling of X-ray burst or novae energy generation. By determination of ANCs, there are a number of important astrophysical reactions that can be inferred. To determine ANCs from transfer reactions, typically, beam intensities of greater than 10,000 /s are required. A number of key rates for modeling novae and X-ray bursts can be studied by ANCs due to the high rates available at ReA12. Some examples are given in table 1.
Table 1: Important astrophysical reactions that can be studied using the ANC technique following the energy upgrade to 10 MeV/u.

Reaction	Shown Critical	Beam intensity ReA12 [pps]
^{23}Mg(p,γ)	Nova	2.8 x10^6
^{25}Al(p,γ)	Nova	1.2 x10^6
^{29}P(p,γ)	Nova	2.5 x10^6
^{30}P(p,γ)	Nova	3.6 x10^6
^{33}Cl(p,γ)	Nova	3.2 x10^6
^{34}Cl(p,γ)	Nova	2.8 x10^6
^{35}Ar(p,γ)	XRB	3.3 x10^6

e) Pair transfer 2n, 2p, or pn

Measurement of (t,p) or (p,t) on even-even cases ^{66}Ni to ^{70}Ni (rates of 6.8 x10^5 /s, 1.5 x10^5 /s, 1.5 x10^4 /s respectively) are possible. This will allow the strength of nucleon pairing to be studies as a function of neutron number. The role of pn-paring can be explored in N=Z nuclei by deuteron transfer on ^{56}Ni and ^{60}Zn. To explore the

influence of very weak binding, nn and pp pair transfer on a wide range of Na isotopes will be possible.

7 Excited-state lifetime measurements

The energy upgrade from 3 MeV/u to 12 MeV/u considerably increases the potential of excited-state lifetime measurements with reaccelerated beams, either excited by Coulex, inelastic scattering or transfer. Precision lifetime measurements with Doppler-shift techniques (see DSAM in C.4.2.3.3) require high recoil velocities to be in a regime where the stopping powers are well understood and contribute less to systematic uncertainties [E.A. McCutchan et al., Phys. Rev. Lett. 103 (2009) 192501.].
A key light nucleus that exhibits many of the aspects of shell evolution and influence of a large neutron excess is ^{12}Be. The recent lifetime data obtained for ^{12}Be with 60 MeV/u beams have a large uncertainty of around 40% [N. Imai et al., Phys. Lett. B 673 (2009) 179.] due to the low sensitivity of the Doppler-shift technique in this energy regime. High-precision lifetime data on light nuclei could provide stringent tests of ab-initio calculations that involve NN and 3N forces. With higher energy and reduced uncertainty in stopping powers, a precision lifetime measurement of the first 2+ state in ^{12}Be can be performed at ReA12 with the inverse-kinematics transfer reaction d(^{11}Be,^{12}Be)p. For this case, ReA12 beam energies also allow for the use of a thicker reaction target, increasing the yield of produced ^{12}Be.

8 Fusion-Evaporation and heavy elements

Another area where an improvement in reaction theory is needed is in attempting to understand the role of neutrons in enhancing the fusion-evaporation cross section. The hope is that a neutron-excess would lead to enhanced fusion cross sections and this would provide a path toward synthesis of long-lived, neutron-rich, superheavy elements. The progress and possibilities in this field was summarized by Loveland [LOVE07]. The paper shows the potential role for radioactive beams, but also indicates that experimental studies are needed to further investigate the fusion cross section predictions for neutron-rich beams.
Beam intensity of greater than 10^4/s is required for these studies. The reaccelerator project will deliver greater than 10^6/s over a wide range (see figure 1), and is hence well suited for exploratory studies. Particularly interesting examples are ^{22}O at 4000/s, and ^{20}O at 7×10^5/s. One of the key question to be measured is the changes in the fission barrier, for example a possible shift toward lower energy, are found when using neutron-rich nuclei. It is also possible that neutron-flow may enhance fusion cross sections [STEL88].

9 Neutron skins and interactions in asymmetric matter

One of the related phenomena to be studies is the possible role of a large neutron skin on fusion and transfer reactions. The nature of nuclei with enhanced neutron skins was one of the science drivers for FRIB, as identified by the National Academies Rare Isotope Scientific Assessment Committee [RISA07]. Understanding the role of a neutron skin is both important for reactions studies, but also in probing the interaction of neutrons in very asymmetric matter. Experiments with nuclei with enhanced skins such as ^{27}Na (see for example [GAMB01]), available at $5x10^5$/s, will allow fusion, as well as, one and two neutron transfer reactions to be studied to explore the influence of the neutron skin.

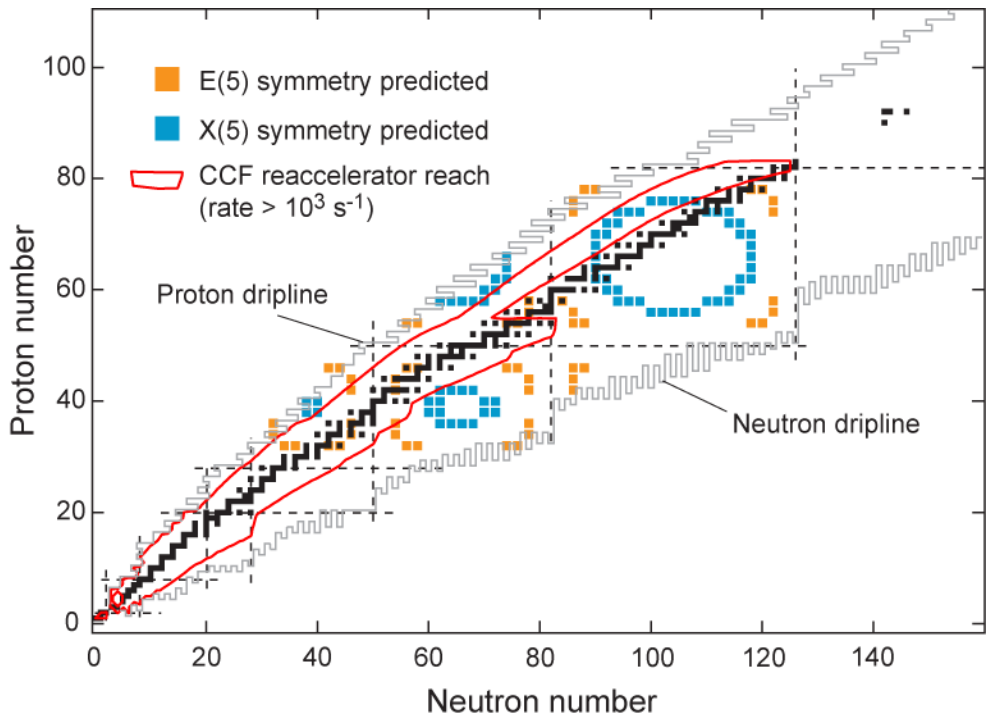

Figure 5: E(5) and X(5) symmetry candidates that could be studied using beams from the reaccelerator. The red line indicates where the projected rates are above 1000/s, where Coulomb excitation and transfer reaction studies are possible. Particularly interesting for ReA12 is the region of zirconium isotopes and in the actinide region, whose studies will unique to this facility.

10 Simple patterns in nuclei and the origin of simplicity from complex motion

The quest to understand the underlying symmetries of the nuclear many-body system requires experimental data in nuclei with unusual neutron-to-proton ratios. Figure 5 illustrates one example of nuclear symmetry studies that can be carried out with the reaccelerator energy upgrade with multiple Coulomb excitation at barrier energies. Shown in the figure are possible candidates for transitional E(5) or X(5) [MCCU05,CAST07] nuclei within reach with intensity greater than 10^3/s. Particularly interesting for ReA12 is the region of zirconium isotopes and in the actinide region, whose studies will unique to this facility.

11 Search for fundamental symmetries of nature and electric dipole moments in atoms

In addition to nuclear structure and astrophysics studies possible with an energy upgrade, there are other potential benefits for the study of fundamental symmetries using nuclei. One of the key tests is the search for an electric dipole moment (EDM) in atoms. This could be an area where FRIB will make a major contribution. We can begin this work with the reaccelerator project by starting systematic studies of static deformation in actinide nuclei by unsafe Coulomb excitation in inverse kinematics. This will be used to identify octupole vibration and/or rotational modes that may enhance the EDM signature. The nuclide ^{229}Pa, for example, is predicted to have an EDM 40 times that in ^{225}Ra, since all four T,P-odd nuclear moments (Shiff, electric dipole, quadrupole and octupole) contribute to the atomic EDM [FLAM08]. Such groundwork experiments are essential to identify the best candidate nuclei for high precision measurements when FRIB is complete.

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Document Information

This document summarize the scientific case made by the FRIB user community for the minimum top acceleration energy of the FRIB reaccelerator. This document is based on several documents prepared by the members of the FRIB user community over the past 5 years.