FRIB: Opening New Frontiers in Nuclear Science

Moving Forward with the Long Range Plan

Prepared by members of the FRIB Users Organization for the
NSAC Long Range Plan Implementation Subcommittee

August 2012

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Contents

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Introduction and Executive Summary

Low-energy nuclear science, which addresses the origin and properties of atomic nuclei, is at the very core of nuclear physics and is a central component of the DOE mission "to ensure America's security and prosperity by addressing its energy, environmental, and nuclear challenges through transformative science and technology solutions." The current and potential future discoveries from this field are compelling and important for the nation, with relevance to many branches of science, national security, energy, medicine, and technology. Opportunities to advance this field play a critical role in attracting and training the next generation of science leaders needed by our national laboratories, industry, and academe.

The Mission

The intellectual challenges for low-energy nuclear science were captured well in the four overarching questions posed in the most recent National Research Council decadal study of nuclear physics (shown in Figure 1):

- 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 science best be used to benefit society?

> "We recommend construction of the Facility for Rare Isotope Beams (FRIB), a world-leading facility for the study of nuclear structure, reactions, and astrophysics."
>
> *The Frontiers of Nuclear Science*
> *2007 NSAC Long Range Plan*
>
> "Failure to pursue a U.S. FRIB would likely lead to a forfeiture of U.S. leadership in nuclear-structure-related physics and would curtail the training of future U.S. nuclear scientists."
>
> *Scientific Opportunities with a Rare-Isotope Facility in the United States*
> *NRC RISAC report (2007)*

Answers to these questions require a deeper understanding of atomic nuclei both theoretically and experimentally than we now have. The path to a deeper understanding requires new insights from experiments on rare isotopes that will be used to guide new theoretical approaches by discovery of model deficiencies and missing physics. The ultimate goal of this effort is to develop a reliable model of nuclei and nuclear reactions with predictive power and quantified uncertainties, coupled with experimental determinations of important properties for key nuclei that will allow us to, for example, know the fusion rates of light nuclei, understand the fission patterns of heavy nuclei and properties of fission products of the actinides, trace the origin of the elements in the cosmos, provide nuclear information crucial for interpretation of experiments involving nuclei such as neutrino less double beta-decay and searchers for dark matter, improve diagnosis and treatment of disease, and contribute in a major way to the nation's stockpile stewardship mission.

Achieving this goal involves developing predictive theoretical models that allow us to understand the emergent phenomena associated with small-scale many-body quantum systems of finite size. The detailed quantum properties of nuclei depend on the intricate interplay of strong, weak, and electromagnetic interactions of nucleons and ultimately their quark and gluon constituents. A predictive theoretical description of nuclear properties requires an accurate solution of the nuclear many-body quantum problem — a formidable challenge that, even with the advent of super-computers, requires simplifying model assumptions with unknown model parameters that must be constrained by experimental observations.

Fundamental to Understanding

The importance of rare isotopes to the field of low-energy nuclear science has been demonstrated by the dramatic advancement in our understanding of nuclear matter over the past twenty years. We now recognize, for example, that long-standing tenets such as magic numbers are useful approximations for stable and near stable nuclei, but they may offer little to no predictive power for rare isotopes. Recent experiments with rare isotopes have shown other deficiencies and led to new insights for model extensions, such as multi-nucleon interactions, coupling to the continuum, and the role of the tensor force in nuclei. Our current understanding has benefited from technological improvements in experimental equipment and accelerators that have expanded the range of available isotopes and allow experiments to be performed with only a few atoms. Concurrent improvements in theoretical approaches and computational science have led to a more detailed understanding and pointed us in the direction for future advances.

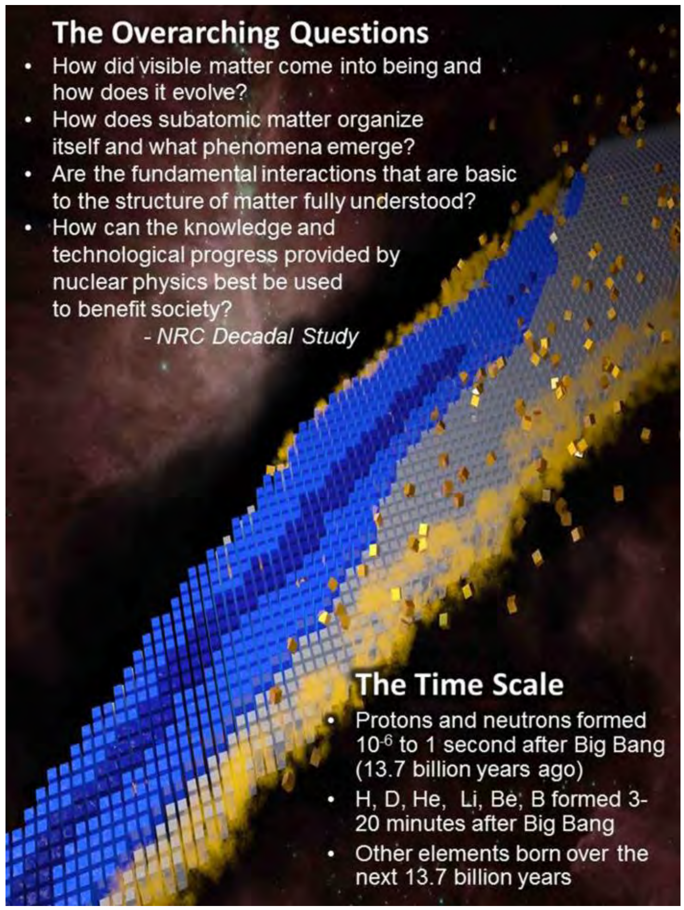

Figure 1: FRIB will yield answers to fundamental questions by exploration of the nuclear landscape and help unravel the history of the universe from the first seconds of the Big Bang to the present.

We are now positioned to take advantage of these developments, but are still lacking access to beams of the most critical rare isotopes. To advance our understanding further low-energy nuclear science needs timely completion of a new, more powerful experimental facility: the Facility for Rare Isotope Beams (FRIB). With FRIB, the field will have a clear path to achieve its overall scientific goals and answer the overarching questions stated above. Furthermore, FRIB will make possible the measurement of a majority of key nuclear reactions to produce a quantitative understanding of the nuclear properties and processes leading to the chemical history of the universe. FRIB will enable the U.S. nuclear science community to lead in this fast-evolving field.

Important for Science and the United States

> "The U.S. nuclear science program will erode without significant new capital investments. At present, this need is most acute in research programs that require intense beams of rare isotopes — essential for advancing our understanding of both the physics of atomic nuclei and nuclear astrophysics. Maintaining U.S. leadership position in this vital subfield requires the generation of significant new capabilities for rare-isotope beams on a timely basis."
>
> *The Frontiers of Nuclear Science*
> *2007 NSAC Long Range Plan*

In the 2007 LRP, FRIB was given the highest priority for new construction. Implementation of the 2007 LRP and follow-through on the last three long-range plans must include completion of FRIB. FRIB is a priority of the full U.S. nuclear science community because it is a necessary asset required to keep U.S. nuclear science at the forefront of this international field. The importance of FRIB has been documented in many expert panel reports. In 2007, the National Academies completed an independent review of the science of FRIB and stated: **"*The committee concluded that the science addressed by a rare-isotope facility, most likely based on a heavy-ion driver using a linear accelerator, should be a high priority for the United States. The facility for rare-isotope beams envisaged for the United States would provide capabilities, unmatched elsewhere, that would help to provide answers to the key science topics outlined above.*"** The committee affirmed the science of rare isotopes as **"*an essential part of the U.S. nuclear science portfolio.*"** More recently the NRC decadal study *Nuclear Physics: Exploring the Heart of Matter* (released in 2012) listed FRIB as its first recommendation and urged that **"*The Department of Energy's Office of Science, in conjunction with the State of Michigan and Michigan State University, should work toward the timely completion of the Facility for Rare Isotope Beams and the initiation of its physics program.*"**

Strategic for International Leadership

Many countries have come to recognize that the exploration of the rare isotope frontier offers great promise for important breakthroughs in fundamental nuclear science and new applications with significant societal benefits. Some of these countries have invested in planning, development, and/or implementation of rare isotope facilities, but most of these facilities have modest capabilities or are designed to deliver a few specific isotopes at high rates. None of the planned or existing facilities will have the reach of FRIB nor have the cutting-edge capability to reaccelerate in-flight separated beams, which allows experiments at the desired energy for all available isotopes of any element.

FRIB will be the world's most powerful facility, making nearly 80% of the isotopes predicted to exist for elements up to uranium. Without the ability to explore the elemental variety of reaccelerated beams at FRIB, it will not be possible to study most reactions of astrophysical importance nor conduct many classes of crucial nuclear structure experiments. With its unique capabilities, FRIB will be the world's best facility for addressing key nuclear science issues, such as:

- Delineation of the limits of existence of atomic nuclei,
- Providing the most stringent tests of nuclear models and the deepest insight into model approximations,
- Study of neutron-rich matter with unusual features such as halos, skins, and their new collective modes — these nuclei are our best laboratories for exploring neutron matter,
- Production of the greatest number of isotopes in the astrophysical r-process to allow the r-process site(s) to be determined,
- Measurement of most of the key nuclear reactions involved in explosive astrophysical environments, and
- Determination of weak interactions rates important for supernova and neutron star modeling.

Isotope production at FRIB will be based on a heavy-ion linear accelerator, an area where the United States has a special advantage due to its leadership in superconducting cavity technology. Application of this technology in the FRIB design has allowed the project to design the most powerful heavy-ion driver capable of providing yields for key isotopes often a factor of 10 to 100 times higher than any other existing or planned facility.

- FRIB will advance fundamental understanding in the core field of nuclear science
- FRIB is needed to retain U.S. leadership in nuclear physics and meet the needs of the U.S. research community
- FRIB is the top priority for new construction in the 2007 LRP; adherence with this plan and the previous two LRPs requires that FRIB be a timely component of the plan's implementation
- FRIB will have world-unique capabilities and will advance major aspects of nuclear science
- FRIB has relevance for many sciences, applications of nuclear science, medicine, and national security

Unique in the World

The uniqueness of FRIB was documented in four NSAC reports and two National Academies studies. Representative of the conclusions, the 2007 NSAC Rare Isotope Beam Task Force report stated that: **"*This unique facility will have outstanding capabilities for fast, stopped, and reaccelerated beams. It will be complementary in reach to other facilities existing and planned, worldwide.*"**

Relevant to Mesoscopic Science

The connections of the nuclear many-body problem to the physics of complex systems are as old as the field of nuclear structure physics itself. Many examples, including superfluidity, superconductivity, collective excitations, symmetry-breaking phenomena, phase-transitional behavior, and chaos have been discussed in the 2007 Long Range Plan and the two most recent National Research Council decadal studies. FRIB, with its potential to explore weakly-bound nuclei with a large proton-to-neutron imbalance, will offer many unique opportunities for interdisciplinary research. The understanding of the structure and decays of rare isotopes will lead to important progress in the general quantum science of open and marginally stable mesoscopic systems. In atomic nuclei, on a femtoscopic scale, one can also explore physics that is related to and will provide insight for nanoscale systems (complex atoms and molecules, atomic clusters, metallic grains, condensed matter devices, atoms in traps and optical lattices, and future quantum multi-qubit computers). The existence of marginally-stable many-body systems is determined by intrinsic shell structure that is a universal property of finite quantum objects and, frequently, by specific pairing-like interactions which are responsible for superfluidity and superconductivity.

Relevant to Society

A U.S.-based rare isotope facility will provide important benefits to society. Aside from FRIB's role in producing a wide range of isotopes relevant to stockpile stewardship and nuclear forensics, FRIB will provide the training required to develop the next generation of the nuclear scientists crucial to the nation. As a forefront science facility, FRIB will attract top talent into fields with critical applications such as nuclear chemistry. Beyond important contributions to nation's technology workforce, rare isotopes hold promise for new applications in a wide array of sciences including environmental science, the nuclear fuel cycle, biology, medicine, and materials science.

Document Overview

This document summarizes the scientific goals of the field of low-energy nuclear science and briefly describes the four major intellectual challenges addressed by the FRIB facility; nuclear structure and reactions, nuclear astrophysics, tests of fundamental symmetries, and applications of isotopes. The document concludes with appendices that provide details of the anticipated FRIB experimental program, the educational impact of the facility, and a selected bibliography for further reading. The first appendix describes the 17 benchmark programs that were introduced by the NSAC Rare Isotope Beam Task force in 2007 to judge the capabilities of a rare isotope facility. These benchmarks include 63 different rare isotope beams that represent what might be the focus of the early FRIB experimental program. The following sections reference the benchmarks where appropriate.

Nuclear Structure and Reactions

The relevant NRC question most related to nuclear structure and reactions is: **"How does subatomic matter organize itself and what phenomena emerge?"**

Answers to this compelling question require a comprehensive picture of the atomic nucleus, which describes quantitatively and predictably this quantum many-body system and have a grounding in the fundamental interactions at play between its constituents. Such a theoretical description can be gained from an accurate solution of the nuclear many-body quantum problem, but this is a formidable challenge that can only be attacked with experiment and nuclear theory working in concert.

Rare Isotopes: Predictive Understanding of Atomic Nuclei

To arrive at a complete understanding of nuclei will require new insights from experiments on rare isotopes that will guide new theoretical approaches by discovery of model deficiencies and potentially missing physics (see Figure 2). Although the ultimate goal of a reliable model of nuclei with predictive power has not yet been achieved, significant progress has been made. An increase in computational power and novel "*ab initio*" calculations based on bare inter-nucleon interactions have led to accurate calculations of the properties of nuclei with up to 12-16 nucleons, and of medium-mass closed-shell systems.

For open-shell medium-mass nuclei, configuration-interaction approaches utilizing data on rare isotopes to refine approximations are the methods of choice, while mean-field methods rooted in density functional theory, guided and tested by comparison to rare isotope properties, have been employed with great success to describe medium-mass and heavy nuclei, including the superheavy systems [Benchmarks 1,2]. By exploring the intersections between these theoretical strategies, it is possible to aim at nothing less than developing a comprehensive description of nuclei and their reactions — rooted in quantum chromodynamics (QCD). Promising links to QCD have already been made with chiral effective field theory and recent Lattice QCD computations.

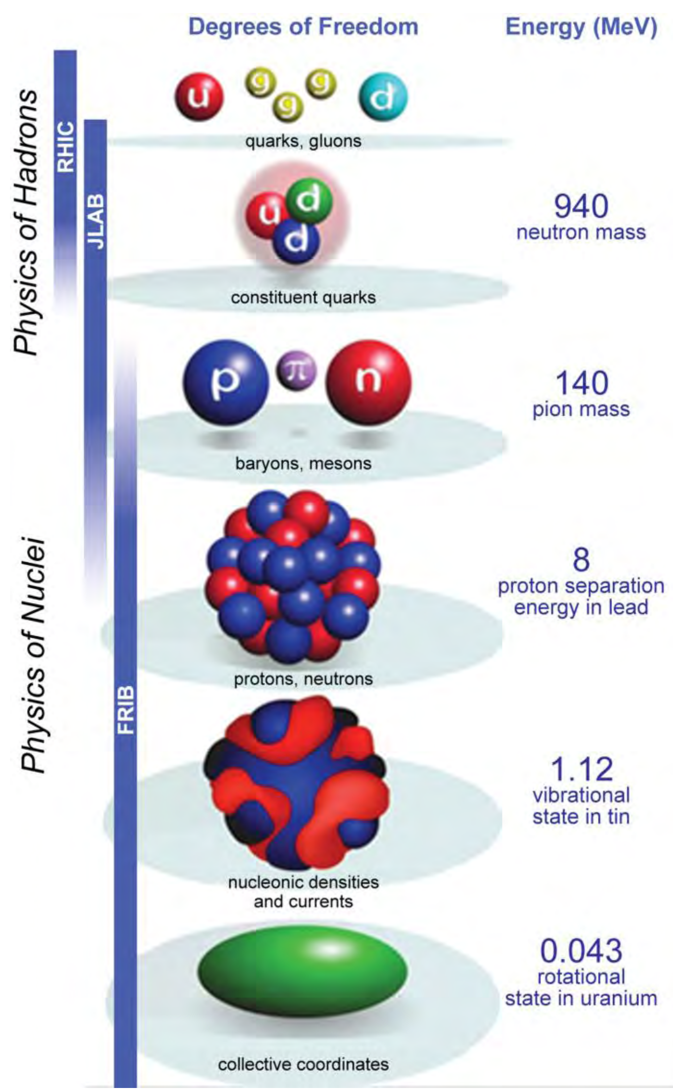

Figure 2: FRIB will open new approaches to identifying the important degrees of freedom of atomic nuclei and developing reliable models of practical use.

To tackle the challenge of obtaining a predictive model of nuclei, the properties of rare isotopes provide essential constraints for the poorly known but essential many-body potentials and quantify the role of the particle continuum — crucial for neutron-rich nuclei. Only with FRIB does one gain access to all necessary regions of the nuclear chart.

Addressing Key Questions

This research thrust directly addresses one of the key questions posed to the field by the 2007 LRP: "**What is the nature of the nuclear force that binds protons and neutrons into stable and rare isotopes?**" However, given the complexity of the nuclear many-body problem with dozens to hundreds of strongly-interacting nucleons, there are emergent phenomena that present another challenge articulated in the 2007 LRP and the NRC decadal study: "**What is the origin of simple patterns in complex nuclei?**" Nuclei display striking regularities; e.g., the emergence of shell structure [Benchmark 1], nuclear superfluidity [Benchmark 4], the occurrence of collective modes associated with rotations and vibrations, clustering phenomena, and the appearance of many-body symmetries and phase-transitional behavior [Benchmark 5].

FRIB will

- allow key measurements required to guide the development of a comprehensive understanding of atomic nuclei
- extend knowledge on the limits of nuclear existence tremendously - below uranium, 80% of all nuclei predicted to exist can be produced
- provide the most stringent tests for nuclear models through producing unusual nuclei with large halos and skins

These are common features not only in nuclei, but generally in mesoscopic and leptodermous quantum systems such as atomic clusters, quantum dots, and atomic wires, making nuclear structure physics part of a broader intellectual challenge for modern science: how to explain the properties of complex systems in terms of their underlying building blocks. In all sciences, this is a challenge that only realistically can be tackled with a synergistic interplay of advanced computational techniques and new measurements on quantum systems with a broad range of finely-tuned variables — neutron-to-proton ratios in the case of nuclear science. With rare-isotope beams one can explore unique features of mesoscopic quantum systems that result from the interplay of two types of fermions whose mixture can be precisely tuned by adjusting the proton-to-neutron ratio.

The limits of the nuclear landscape are defined by the nucleon driplines. The driplines outline the combinations of protons and neutrons that result in stable and rare isotopes — driplines represent a fundamental benchmark for nuclear models. While the proton dripline has been delineated fairly well, the neutron border is only known with certainty up to oxygen ($Z=8$). FRIB will produce dripline nuclei up to roughly $Z=40$ and perhaps higher, exploring nuclear properties over a vastly increased range [Benchmark 13]. Close to the driplines, in the regime of weak binding, FRIB will provide intensities of rare isotopes sufficient to explore the properties of halos and skins and clustering, and to discover new modes of excitation associated with the weak binding and the particle continuum, thus providing unprecedented insight into nuclear structure at the extremes of isospin [Benchmarks 3,14]. FRIB will nearly double the number of such nuclei that can be studied with sufficient detail and extend the reach from $A=40$ to $A=90$.

The spin-isospin sector of the inter-nucleon interaction remains poorly understood and constitutes a major roadblock in the development of models with predictive power applicable to the entire nuclear landscape. Progress will only be achieved by measuring properties of rare isotopes in key regions of the nuclear chart. One of these largely unexplored regions comprises very neutron-rich nuclei along the astrophysical r-process path. Nuclei in this region are unknown and their properties, at present, must be obtained from model-based extrapolations, which often have large uncertainties that limit their sensible use. FRIB's world-unique complement of fast, stopped, and reaccelerated rare-isotope beams is essential to provide the input needed to constrain nuclear models at the limits of nuclear binding [Benchmarks 1,7,15]. FRIB will offer the broadest view of isotopes for a given element. For nickel isotopes the reach is predicted to be from dripline to dripline, from ^{48}Ni to ^{84}Ni, and include three different double magic nuclei.

Exploring Structure and Interaction

Closely related to studies of nuclear structure is the challenge of describing accurately how nuclei interact with each other. Nuclear reactions represent an essential tool for the extraction of crucial information for both nuclear structure and nuclear astrophysics. With its unique capability to provide both fast and reaccelerated exotic beams across the nuclear chart, FRIB offers unprecedented opportunities to exploit nuclear reactions in various regimes. Reaction mechanisms that can be utilized for experiments range from low-energy grazing reactions that involve weakly-bound nucleons from a halo or neutron skin to intermediate-energy heavy-ion collisions or giant resonance studies that probe the nuclear matter equation of state (EOS) for neutron matter. The higher-energy reactions sensitively characterize the nuclear EOS that determines the static and dynamic behavior of (neutron) stars [Benchmark 6].

Particularly intriguing in the general context of nuclear science is the fact that weakly bound nuclei are open quantum systems that require a treatment that integrates nuclear structure and reactions in a seamless way. For the heaviest nuclei, where competition between shell effects and huge electrostatic repulsion determines nuclear survival, FRIB — with the unique high-intensity reaccelerated rare-isotope beams reacting with actinide targets, for example — may lead to neutron-rich heavy nuclei in an uncharted superheavy territory [Benchmark 2].

For nuclear structure, the unprecedented reach of FRIB will give access to unexplored regions of the nuclear chart, where new phenomena like large nucleon skins and new collective modes will guide the development of a more comprehensive picture of the atomic nucleus, likely changing known paradigms and forcing a rewrite of the textbooks on the structure of atomic nuclei. With the anticipated beam power of FRIB, the cross section that corresponds to the production of a single atom per week required for discovery experiments is as low as $3 \cdot 10^{-20}$ b, compared to the $3 \cdot 10^{-15}$ b limit achievable at present-generation facilities. This gain of 5 orders of magnitude enables the extension of the study of dripline nuclei from $Z=8$ to $Z=40$ or perhaps even higher [Benchmark 13,14] and, for the whole chart, more than doubling the number of nuclei for which excited states are known.

The huge number of new nuclei that will be made available at FRIB — proton rich, neutron rich, the heaviest elements, and long chains of isotopes for many elements — comprises a vast pool from which key isotopes, or "designer nuclei," can be chosen because they isolate or amplify specific and relevant physics. Over the last decade, tremendous progress has been made in techniques to fabricate and describe these crucial femtostructures with special properties tailored to addressing specific physics issues. FRIB will advance this capability to the next level and provide a new window for discovery.

Nuclear Astrophysics

The nuclear processes that drive stars, stellar evolution, and stellar explosions are central to understanding the cosmos. Their detailed knowledge is fundamental to answer the NRC question: "**How did visible matter come into being and how does it evolve?"** Nuclear reactions have driven the chemical evolution of the universe since the Big Bang and are responsible for the origin of the elements in nature (see Figure 3). Yet, the importance of nuclear science to astrophysics extends beyond that: Nuclear reactions power stars and are vital to how they evolve. Neutron stars are remarkable stellar size blobs of nuclear matter where aspects of nuclear physics determine their structure, size, and stability. Stellar explosions are triggered, powered, and influenced by nuclear properties and processes.

Rare Isotopes: Window on the Origin of Elements

FRIB will

- allow measurements of nuclear properties needed to understand chemical evolution in the cosmos
- provide reaction rates and nuclear structure information central to modeling stellar explosions
- measure key nuclear properties that are needed to understand neutron stars

Many of the nuclear reaction sequences important for our understanding of the cosmos occur in extreme astrophysical environments and involve short lived, rare isotopes that, in most cases, so far have been inaccessible in the laboratory (see Figure 4). As a result, stellar explosions and nucleosynthesis processes are poorly understood, and the astronomical observations that identify their signatures — including infrared, visible light, UV, X-ray and gamma-ray observations, neutrino detection, meteoritic abundances, cosmic rays, and possibly, in the near future, gravitational waves — cannot be fully exploited and, in some cases, remain unexplained. FRIB will produce a variety of short-lived isotopes with sufficient intensity to address most of the fundamental nuclear physics important for understanding stellar explosions and the origin of the elements.

The origin of elements heavier than iron is a compelling mystery that has only deepened with recent astronomical observations. On one hand, observations of old stars in the halo of the Galaxy, carried out with the largest telescopes, show a robust pattern of abundances of elements heavier than tin that agrees with that of the solar system. However, on the other hand, strong differences between the observations and solar abundances are seen for elements between iron and tin. The physical processes that lead to these abundances early in the history of the Galaxy are difficult to explain within the context of known astrophysical phenomena. Realistic, multidimensional models of core collapse supernovae fail to reproduce the hydrodynamical conditions needed to robustly create heavy "r process" elements, and neutron star mergers seem too infrequent to produce sufficient abundances of heavy elements early in the history of the Galaxy. A fundamental issue is that the great uncertainties in properties of short-lived nuclei render ambiguous a direct comparison of the wealth of new observations to realistic astrophysical simulations.

Nuclear masses and decay properties govern the abundances of isotopes produced at high temperatures in stellar explosions and during their subsequent decay back to stability. Especially important are regions of the chart of nuclides far from stability where nuclear structure effects such as rapid shape changes or the emergence of shells or subshells may lead to distinct signatures in the produced abundances. Careful comparison of observed abundances and model predictions of such signatures is a powerful diagnostic for models, provided that the nuclear physics is understood. Examples of signatures are the abundance peaks at A~130 and A~195, which probe the conditions during the main r-process phase and enable predictions of actinide synthesis as a chronometer for chemical evolution; abundance in the region immediately preceding the A=130 abundance peak are sensitive to neutrino fluencies; and, as recently pointed out, the small abundance peak around A~160 probes the late time conditions of the r-process.

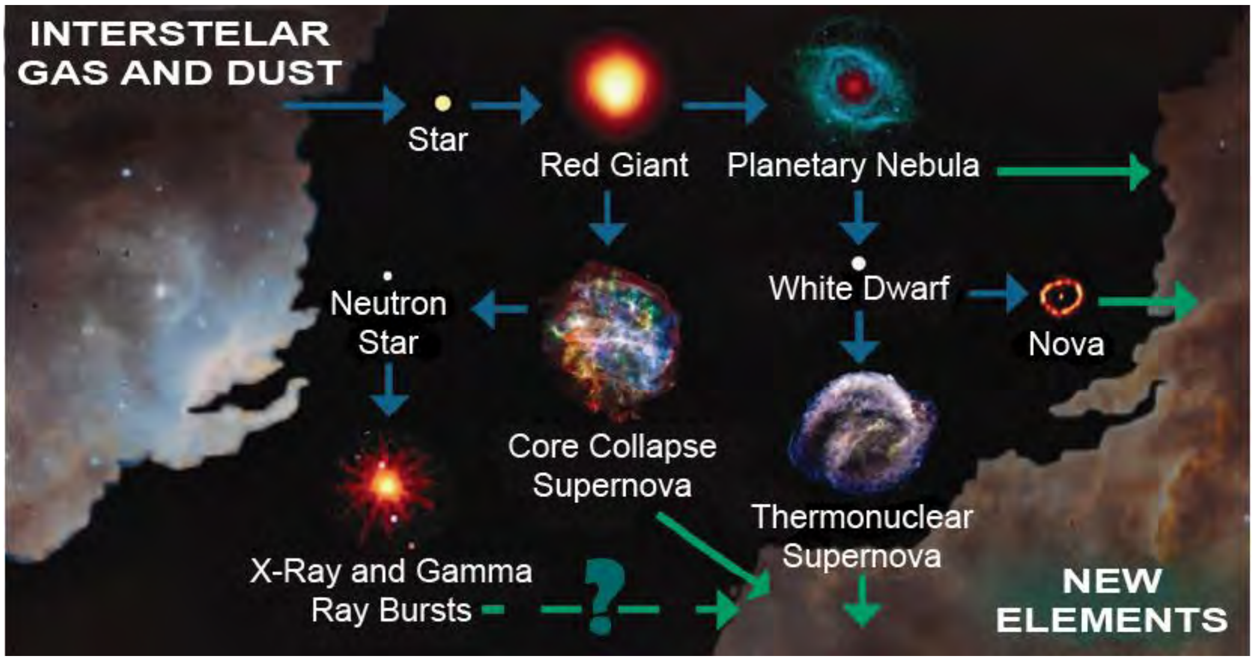

Figure 3: FRIB is critical to understanding the nuclear processes in supernovae, novae, neutron stars, and X-ray bursts.

FRIB is the only facility where most of the corresponding masses and decay properties can be measured and the different aspects of the astrophysical models constrained on the basis of experimental and observational data [Benchmark 7 and 15]. Astrophysical studies have also recently identified a few key nuclei near closed neutron shells (such as around ^{78}Ni and ^{132}Sn) where detailed nuclear structure information and nuclear reaction rates have a significant influence on the overall abundance pattern of the elements. Closed neutron-shell nuclei somewhat closer to stability influence the abundances at late times. At FRIB, these nuclei will be produced with sufficient intensities for the first time to allow detailed study of nuclear structure properties that will improve our understanding of their influence on the heavy element abundances. The combination of mass and half-life measurements over a large number of r-process nuclei, combined with detailed studies of nuclear structure and reactions closer to stability, will enable robust predictions of abundances in astrophysical models. The comparison of these abundances to improved astronomical data holds the key to deciphering the enigma of the origin of the heavy elements.

While core collapse supernova simulations are not able to reproduce the neutron-rich conditions that are conducive for an r-process, many newer models consistently predict proton-rich ejecta with a small admixture of free neutrons produced from neutrino interactions. Within these environments, the interplay of proton and neutron induced reactions enables rapid synthesis of neutron deficient unstable isotopes up to tin and might explain the varied degrees of enrichment of these elements observed in metal poor stars. FRIB with its unique reaccelerated low-energy beams will enable the first measurements of the unknown reaction rates governing this process. FRIB data will enable us to determine if the puzzling metal poor star abundances are indeed the signatures of this new process.

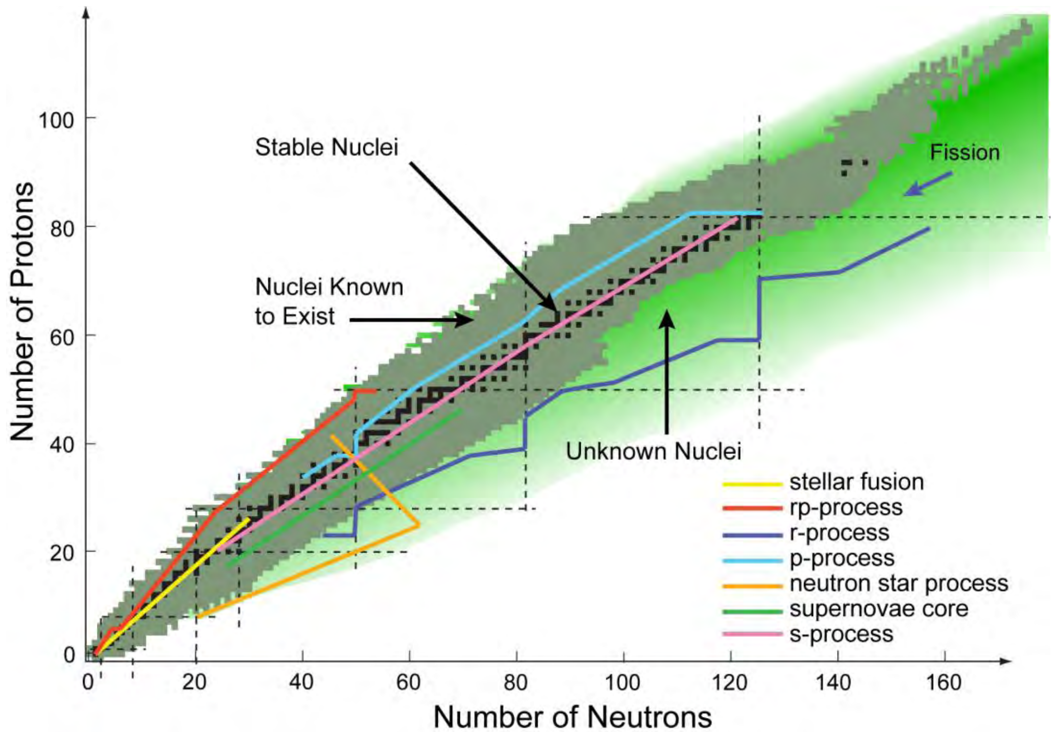

Figure 4: FRIB will produce in the laboratory the same rare isotopes that define the reaction sequences in the cosmos. Experiments at FRIB will provide data critical for the understanding of the origin of the elements, stellar explosions, and neutron stars.

Unraveling the Secrets of Neutron Stars

A similar process of rapid proton captures, further augmented by fast helium-induced reactions, is believed to be the main energy source of x-ray bursts, the most common stellar explosions in the Galaxy. The model for x-ray bursts is that they occur on accreting neutron stars. The analysis of burst light curves from repeated observations of the same system over long times scales (more than a decade) are now providing insights into the evolution of the binary star systems, accretion phenomena, and neutron star compactness. Direct measurements at FRIB of the largely unknown rates of proton and alpha particle induced reactions on unstable neutron deficient nuclei will enable a quantitative analysis of astrophysical observations. This, in turn, will open a pathway towards more precise determination of neutron star properties and an understanding of the many unexplained phenomena associated with x-ray bursts [Benchmarks 8 and 16].

Another avenue to unravel the hidden secrets of neutron stars is the observation of their cooling shortly after accretion has turned off in a binary system. Modern x-ray observatories have now followed the ensuing decline of the surface temperature over many years, in principle revealing the structure and properties of the neutron star crust including the existence of superfluid neutrons. Unfortunately, the processes heating the crust during the accretion phase, and the resulting initial temperature profile, are unknown and models give vastly different results depending on assumptions of the properties of extremely neutron-rich nuclei. Only FRIB will be able to delineate the neutron dripline, and therefore the neutron star depth where free neutrons first occur for all isobaric chains of relevance to neutron stars [Benchmark 13]. FRIB will also push mass measurements of neutron-rich nuclei further than any other facility [Benchmark 15]. Major problems are the unknown weak interaction and fusion rates of very neutron-rich nuclei. FRIB offers unique opportunities for systematic measurements of these rates as a function of neutron richness, enabling a more reliable theoretical description of these rates [Benchmark 17]. Studying collisions of neutron rich isotopes at higher energies at FRIB allows in addition to directly probe the equation of state of asymmetric nuclear matter governing neutron stars [Benchmark 6]. With such an improved understanding of the nuclear physics of neutron star crusts, astronomical observations promise to become a quantitative tool to examine the largest nuclei in nature — neutron stars.

Accelerating Discovery in Other Areas of Nuclear Astrophysics

Experimental data from FRIB will have a major impact on the understanding of many other astrophysical reaction sequences and sites. Weak interaction data from charge exchange reactions will lead to a better understanding of core collapse supernovae and the nucleosynthesis in type Ia supernovae [Benchmark 17]. Measurements of proton induced reactions of unstable heavier nuclei will allow one to clarify the origin of the so-called p-isotopes, i.e., those rare neutron deficient isotopes that exist for some elements. Experiments at FRIB will finally address the remaining nuclear deficiencies in nova models [Benchmark 16], enabling models to address some of the long standing open questions such as the origin of the factor-of-10 under-prediction of the mass of material ejected from these outbursts and resolve uncertainties in the highest masses that novae can synthesize. FRIB will also offer the capability to harvest longer-lived isotopes for studies of key neutron capture reactions on rare isotopes relevant to the s-process. Long-lived isotopes can be collected and used as targets for neutron capture rate measurements at other facilities such as LANL. The new data would enable the understanding of conditions during neutron capture processes in stars by comparison with the isotopic composition of interstellar dust grains [Benchmark 9].

Progress in nuclear astrophysics requires access to stable and rare isotope beams, a full complement of beam energies, a wide range of experimental techniques, taken together with a close interplay of theoretical, modeling, and observational efforts across disciplines. While progress has been made on many fronts, the lack of intense and varied rare isotope beams has, over the last decades, developed into one of the most critical roadblocks for progress. This issue has been recognized early on — already Nobel laureate Willy Fowler stated in 1984 "It is in my view that continued development and application of radioactive beam techniques could bring the most exciting results in laboratory astrophysics in the next decade." The synergistic approach to nuclear astrophysics to be taken at FRIB will allow us to fulfill the long-standing dream of understanding all the nuclear processes that shape the cosmos.

Test of Fundamental Symmetries

The interactions between elementary particles are successfully described by the Standard Model. The Standard Model does not, however, accommodate several recent discoveries, including neutrinos with non-zero masses, generation of an excess of matter over antimatter in the early universe, and the abundance of exotic dark-matter. The search for a New Standard Model is proceeding on two fronts: at the high-energy frontier, i.e., the LHC, where direct evidence of new particles and interactions are sought, and at the precision frontier, which exploits the fundamental symmetries of special observables as sensitive probes of the structure and interactions of matter. Specific nuclei have special properties that allow aspects of the Standard Model to be tested in ways complementary to other means. The production and study of such nuclei at FRIB addresses the NRC question **"Are the fundamental interactions that are basic to the structure of matter fully understood?"**

Rare Isotopes: Amplifying Effects

The role of FRIB in providing samples of the key isotopes is well documented. For example, in the 2007 National Research Council Report of the Rare Isotope Science Assessment Committee included a section in their report on the opportunities of studying fundamental interactions and concluded that: ***"Experiments addressing questions of the fundamental symmetries of nature will similarly be conducted at a FRIB through the creation and study of certain exotic isotopes."***

FRIB will

- produce key isotopes for which symmetry-breaking processes or potential new physics are amplified
- provide opportunities to identify and benchmark new candidate nuclei for atomic EDM searches
- be the most intense source of candidate nuclei for beta-neutrino correlation studies

Search for an Atomic Electric Dipole Moment (EDM)

The nuclei produced at FRIB will enable experiments on basic interactions because aspects of their structure greatly magnify the magnitude of the symmetry-breaking processes being probed. One application is related to a possible explanation for the observed asymmetry between matter and antimatter in the universe that can be studied by searching for a permanent electric dipole moment (EDM) in heavy rare isotopes. The dominance of matter over antimatter in the Universe is one of the most intriguing questions in physics and is related to the violation of interactions under time-reversal symmetry. The observation of a permanent electric dipole moment in a particle or a simple quantum-mechanical system, with a magnitude larger than the Standard Model prediction, would provide an unambiguous signature of a new mechanism of time reversal symmetry violation. Measurements of EDMs are considered the most sensitive to search for such signatures and provide also stringent constraints on parameters of extensions of the Standard Model such as supersymmetry. These models predict EDMs of magnitudes within reach of current experimental methods.

Specific heavy rare isotopes produced at FRIB are expected have much larger EDMs than most atoms, because their nuclear structure greatly magnifies the symmetry-breaking processes being probed.

Particularly sensitive candidates for EDM searches are diamagnetic atoms for which the EDM is induced by the interaction of the electrons with the nuclear Schiff moment. Enhancements of the Schiff moment, a factor of 100-1000 larger than in the most sensitive cases probed so far, are possible in nuclei that exhibit octupole deformation or soft octupole vibrations. Which of the many rare isotopes available will be the most sensitive case for these studies is not yet fully known. Initial experiments trying to exploit these enhancements are now being developed with the available candidates such as ^{225}Ra that are available in limited quantities. In advance of FRIB, it is critical to identify the most sensitive candidates, where evidence for octupole deformation and octupole vibrations can be identified and probed with Coulomb excitation of reaccelerated beams of, for example, ^{223}Rn and ^{225}Ra [Benchmark 12]. New candidates can be studied as they are identified. For example, based on speculation about the structure of ^{229}Pa, its EDM was calculated to exceed the EDM of ^{225}Ra by a factor of 40. If that were to be true, this nucleus may become a prime candidate for an EDM measurement in the future.

Once operational, FRIB will provide an intense source of all of the viable candidates identified thus far and may provide a source for any new examples discovered in the meantime. FRIB will be the best source for cases such as ^{229}Pa and would produce 50 times the amount of ^{225}Ra available at present generation facilities. A great advantage at FRIB is that interesting atoms for EDM studies can be collected in a commensal mode of operation, as is planned for providing isotopes for societal applications. This would provide a regular source of isotopes on a nearly continuous basis for up to four months per year for studies of systematic effects and for atom trap developments.

Precision Tests for Particles and Interactions

FRIB will contribute in other ways, such as, with searches for evidence of new interactions or new particles that leave their signature in nuclear beta decay. The standard model for beta decay involves vector and axial vector components. Deviations from this theory may be evidence for new particles, new interactions, or new symmetries such as supersymmetry. Currently, the most stringent limits for deviations from the Vector-Axial Vector (V-A) theory of beta decay such as the distribution of angles between the neutrino and the electron, which can be precisely determined by measuring the nuclear recoil.

The results of measurements performed so far put stringent constraints on possible scalar and tensor contributions to weak interaction. FRIB will provide an intense source of new candidates for beta-neutrino angular correlation studies that will greatly improve the sensitivity of such measurements. In addition, advances are also expected in characterizations of the systematic effects that limit current investigations. Such a program will complement measurements with the neutron underway or in development at NIST, LANL, and SNS. FRIB will be the most intense source of key isotopes such as ^{6}He, ^{19}Ne, ^{62}Ga, and candidate isotopes of heavier elements up to tin. It may be that the best cases for beta-correlation studies have yet to be determined. FRIB will enable a quick path to identifying and exploiting the opportunities. Once a discovery is made in one system, studies of others made possible by FRIB will be necessary for confirmation.

The Standard Model predicts that the coupling of the neutral boson, Z^0, to leptons and quarks is not constant as a function of the momentum transfer but is “running.” A measurement of the weak charge of the nucleus would provide a test of the running of $\text{Sin}^2\theta_W$ at very low momentum transfer. Measurements in nuclei will give complementary information to the measurement of the weak charge of the proton and electron at JLab and to related experiments at SLAC and Fermilab.

The presence of a weak charge in the nucleus can lead to observable effects, primarily in the form of parity violation in atomic transitions. Parity non-conserving (PNC) effects are strongly enhanced in heavy atomic systems and probe two key issues: the breaking of parity in the hadronic part of the weak interaction (which manifests itself as a spin-dependent part of the PNC effect, called the anapole moment); and the possible detection of new currents affecting the neutral weak currents (which would affect the weak charge in a spin-independent way).

The isotopes produced at FRIB will allow an improved measurement of PNC effects in atomic systems, a determination of the weak charge of the nucleus, and measurement of anapole moments. FRIB could provide more sensitive cases such as francium isotopes, with higher atomic number, than the stable cesium atoms that provide the most stringent constraints so far. Compared to existing facilities, FRIB will provide a more intense source of francium atoms by up to one order of magnitude compared to existing facilities. With the possibility to harvest francium from the FRIB beam dump at these high rates, a nearly continuous source of a wide range of francium isotopes may be available for up to four months per year. This availability would allow systematic effects to be studied in detail. The wide range of isotopes at FRIB would also allow the study of nuclear systematic effects by looking at ratios of PNC effects in isotopic chains. This method would require a precise knowledge of the isotopic dependence of the neutron skin that could be taken from theory or inferred from other experiments at FRIB.

Applications of Isotopes to Serve Society

Of major interest to the broader public is the NRC question **"How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?"** Rare isotopes are used in a wide variety of applications ranging from medical diagnostics to the tracing of groundwater migration patterns. They serve as sensitive probes in materials science studies of nano-scale devices and in the study of mechanical wear in novel materials. The use of radioisotopes in medical imaging and therapy has impacted the lives of millions of patients worldwide.

FRIB will provide access to the widest range of isotopes at a single site and minimal development time for exploratory studies. It will provide access to the full spectrum of known, important radioisotopes — including ^{7}Be, ^{8}Li, ^{11}Be, ^{32}Si, and others. Moreover, FRIB can enable future advances in the applied sciences by delivering thousands of new isotopes that may have properties better matched to a range of specific applications.

FRIB will

- produce key isotopes in research quantities for development of medical applications
- advance the U.S. national security missions in stockpile stewardship and nuclear forensics
- provide isotopes that support new research in ecology and biochemistry
- produce the relevant actinides and their fission products important for the nuclear power industry
- provide new isotopes that will serve as tools for nanoscience, material science, and engineering

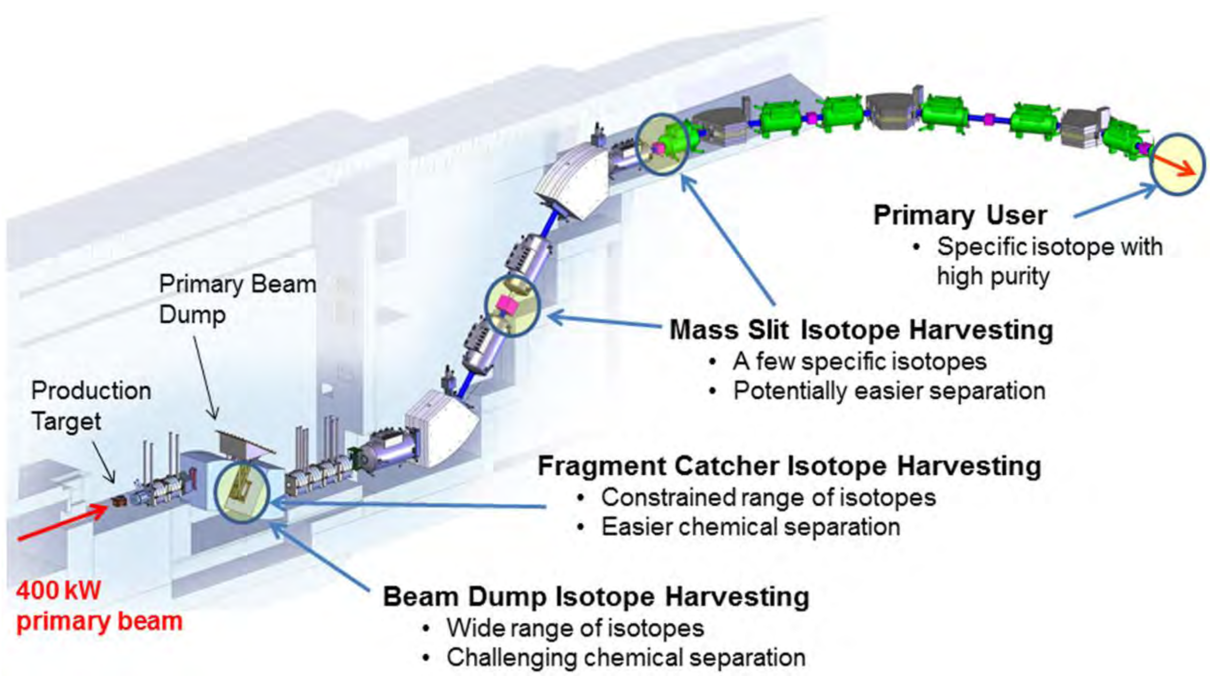

Figure 5: FRIB's design includes multiple provisions for isotope harvesting.

Rare Isotopes: Proven Benefits for Meeting Human Needs

The FRIB baseline design has provisions for delivering research quantities (μCi to Ci) of radioisotopes by on-line harvesting in parallel with the primary experiments. Isotopes may be collected from the water-filled primary beam dump and dedicated fragment catchers after the first dipole of the separator or, with increased purity, in the focal planes of the separator (see Figure 5). The collection or "harvesting" of isotopes at FRIB in commensal operation can reliably provide the nation with research quantities of isotopic material for which there currently is no comparable source. Useful quantities of longer-lived isotopes can be packaged and shipped to research facilities throughout the United States.

FRIB will produce key research isotopes for targeted cancer imaging and therapy. Nearly all isotopes noted in the recent NSAC Isotope Committee study as being in short supply would be available in research quantities. FRIB would contribute to the medical sciences and to biological research in three general categories: imaging, targeted therapy, and radiotracers. In each of these areas, radionuclides offer the capability of imaging local biological conditions such as metabolism, receptor status, and tumor microenvironment as well as delivering site-specific therapies that target cancerous cells while not affecting healthy tissue. Due to the basic research nature of FRIB, isotopes that are harvested in commensal mode would likely be available on a regular schedule compatible with medical and biological research needs. FRIB can provide sufficient quantities of many isotopes for preclinical studies and early clinical trials. In particular, potentially therapeutic isotopes such as ^{67}Cu and alpha emitters such as ^{225}Ac would be available. The isotope ^{44}Ti is also of interest as a long-lived parent generator isotope for the positron-emitting diagnostic (PET) isotope ^{44}Sc.

Isotopes for the Nation's Security

FRIB will provide isotopes for the study of important nuclear reactions related to the U.S. National Security missions in stockpile stewardship and nuclear forensics. The nation's nuclear weapons stockpile stewardship program is aimed at maintaining confidence in the nation's nuclear deterrent without testing. Therefore, increased emphasis has been placed on gaining better scientific understanding of the existing data and validity of computational tools used to evaluate the status of the stockpile. Relevant nuclear data such as cross sections, branching ratios, and transition rates are needed along with other data including radiation opacities and material equations of state to make detailed assessments of performance uncertainties.

Because of the extreme operating densities and temperatures of nuclear weapons, much of the important nuclear data involve reactions on unstable nuclei. Until now, these unstable nuclei were not available in sufficient quantities for detailed experimental studies, and much of the needed data input is taken from uncertain theoretical extrapolations. FRIB will allow measurements of new data on rare isotopes important for a basic understanding of nuclear weapons and forensics. FRIB can address many of the uncertainties with a combination of direct measurements on harvested samples of key radioisotopes as well as inverse kinematic in-beam experiments, coupled with theory. For example, samples of ^{48}V or $^{147\text{-}154}$Eu can be produced for neutron irradiations and measurements of neutron-induced cross sections. Beams of isotopes like ^{88}Y or ^{88,89}Zr can be produced for inverse kinematic reaction studies.

A Wealth of Possibilities: New Tools for Research in the Environment, Energy, Materials Science, and Engineering

FRIB will provide isotopes that support new research avenues in ecology and biochemistry. At the core of cellular metabolic pathways are enzymes and the reactive centers of many enzymes contain metal ions. For example, research is currently underway to enhance the production of H_2 gas from a variety of microorganisms for use as a biofuel. Hydrogen generating enzymes involve a number of Fe-Fe or Fe-Ni structures. The specific rates of activity, locations of these various enzymes in microbial cells, and reasons why certain enzymes are active at certain times and not others is not known. A new suite of rare metal isotopes could be applied to study the rates of enzyme activity and specific sites of activity within microbe and plant cells. Of most relevance to studies of metalloenzymes are stable or long-lived isotopes of Fe, Cu, Ni, V, W and Mo. Although stable isotopes of Fe are readily available, obtaining isotopes of V and Mo and other elements of interest remains challenging. Measurement can be based on the activities of the radioactive isotopes or based on ionization and mass spectrometric detection of stable or long-lived isotopes using ultra high resolution chemical imaging instruments such as NanoSIMS. NanoSIMS has successfully been used to identify sites of nitrogen fixation as well as the transfer of fixed nitrogen to symbiotic cells via ^{15}N tracers but studies based on heavier isotopes, however, are rare. Thus, there is abundant potential for applications of rare and stable isotopes that FRIB can provide.

FRIB will produce quantities of all the relevant actinides and their fission products that are of importance for the nuclear power industry. Relevant neutron reaction cross sections, decay data, beta-delayed neutron emission data, and fission cross sections can be accurately determined for these isotopes. The new data will allow accurate modeling of the next generation of safer nuclear reactors and nuclear waste destruction methods. New reactor designs and materials, reprocessing efforts, and transmutation of nuclear waste play key roles in the future of nuclear energy science. New or improved measurements on a number of different isotopes are needed to determine feasibility, effectiveness, and safety issues for new engineering efforts. For example, the current once-through Uranium cycle may be well understood, but modifications to this process require significant data improvements.

FRIB will provide new isotopes that serve as tools for nanoscience, materials science, and engineering. Rare isotopes from FRIB will have broad applications in condensed-matter and materials science study as they will provide a low-density, very-high-signal-to-noise in situ probe of local atomic environments. Radioactive isotopes offer the simultaneous virtues of chemical specificity with the emission of decay products (γ, β) whose angular and spectral data can carry an imprint of local field gradients and crystalline properties. Examples include varieties of photoluminescence of implanted ions, perturbed angular correlation γ-decays, emission channeling, Mössbauer spectroscopy, and beta-nuclear magnetic resonance.

The results will aid in the understanding and design of new materials, for example high-temperature superconductors, thin-film magnetic materials, or semiconductors. Radioactive probes can give an improvement in sensitivity. beta-NMR, for example, provides more than 10-orders-of-magnitude improvement in signal over conventional NMR. At FRIB, beams of ^{8}Li, ^{11}Be, ^{15}O, ^{17}Ne would be obtained from beam stopping and then polarized by laser optical pumping techniques to study magnetic thin film or superconducting materials. The study of semiconductors has been a key application of radionuclides, where their potential for detecting low-density crystalline defects, impurities, and weak doping gradients is proving very important in the development of higher performance materials.

There are broader implications of FRIB to the accelerator physics community and related applications. Rare isotopes will likely continue to gain importance as an engineering tool. Implanted isotopes (mainly ^{7}Be) have been used in sensitive wear studies but new developments aim at lower doses and shorter testing times which require shorter-lived isotopes. An industrial example is wear studies of inserts for knee prostheses with 3-day half-life ^{97}Ru. FRIB will produce many suitable isotopes with optimum half-lives in large quantities. Moreover, FRIB expertise represents a component of the accelerator physics community that has the knowledge to accelerate heavy ions to industrially relevant energies and to construct and handle high-power targets. The accelerator technologies being developed and experience gained in realizing the world's highest power heavy-ion linac will benefit future heavy ion accelerator projects. Advances in extreme material research will enable construction and operation of high-power targets required for the production of intense rare ion beams.

FRIB: Unique in the International Context

The discovery potential offered by experiments with rare isotopes is so compelling that they have spurred major new investments by all G8 countries and many others. These investments include new facilities in Europe (FAIR, SPIRAL2, and HIE-ISOLDE), Asia (RIBF and RISP), and North America (TRIUMF-ISAC, CARIBU). Additional, smaller-scale facilities are operational, under construction, or planned in India, Brazil, China, Russia, and Italy. Most of these worldwide efforts are targeted at answering specific science questions and serve various subsets of the international nuclear science community.

FRIB will

- be the highest-power in-flight rare isotope production facility
- produce at least one order of magnitude higher yield for most isotopes compared to any other facility
- have unique reacceleration capability
- meet a specific U.S. national need

FRIB's uniqueness is a consequence of its use of a 200 MeV/u, 400 kW heavy-ion driver linac, which is unmatched in power by existing designs of other facilities. FRIB's complementarity to other facilities relies on in-flight rare-isotope production and separation, with the option of stopping ions in gas, and reacceleration. The combination of high power and highly developed, chemistry-independent rare-isotope beam production, purification, and manipulation techniques guarantees world-leading programs with fast, stopped, and reaccelerated beams at FRIB. Isotope harvesting will provide important societal and national benefits to the host country. FRIB ensures that the U.S. nuclear science community can rely confidently on developing the world-leading capabilities required to achieve the scientific goals laid out in the NRC RISAC report (2007), the NSAC RIB Task Force (2007), and the recent National Research Council decadal study of nuclear physics (2012).

Complementary to Other Facilities

Lower-power, in-flight separation facilities that have minor overlap with FRIB's scope include FAIR in Germany, RISP in Korea, and RIBF in Japan. RISP is in the early stages of conceptual development and does not yet have a fully defined scope. Early considerations for that the facility have had an ISOL focus (ISOL production is discussed below) to provide it with a unique role. The Radioactive Ion Beam Factory, RIBF, is operational and is projected to provide primary beams with a power of up to 10 kW. This will make it world unique until FRIB becomes operational. Due to the cyclotron-acceleration scheme, rare- isotope production rates at RIBF will remain a factor of 10-100 below that at FRIB. This restricts the exploration of the driplines to lighter elements only and limits the study of key nuclei far from stability. The Facility for Anti-protons and Ion Research, FAIR, at GSI in Germany is a multipurpose laboratory the uses a multiple synchrotron acceleration scheme. The space charge limits mean FAIR will have a rare-isotope beam intensity 10-100 times lower than FRIB and similar limitations in science reach as RIBF. By the use of synchrotrons, FAIR benefits from higher beam energies (1.5 GeV/u) than available at FRIB. This is of interest for some specific high-energy experiments and which simplifies achieving high beam purity for the heaviest beams. In contrast to FRIB, both RIBF and FAIR will have storage rings for atomic physics experiments and mass measurements. Such capabilities are also planned at IMP Lanzhou/China, so there will be three facilities with high-energy storage rings worldwide. Given its superior rare-isotope production rates, FRIB will transcend existing fast-beam facilities or those under development with respect to science reach. At the same time, the FRIB reaccelerated-beam science program will be complementary to those of other facilities. FRIB will have reaccelerated beams of elements that are impossible to produce at ISOL facilities either due to chemistry, half-life, or both. The importance of these capabilities is illustrated in Figure 6, where the wider reach of FRIB is highlighted along with it ability to perform experiments with reaccelerated beams of dripline nuclei that will not be possible at other facilities.

Several rare-isotope facilities make use of production at rest (Isotope Separation On Line, or ISOL) with subsequent acceleration of the rare isotopes. These facilities include TRIUMF-ISAC in Canada, SPES in Italy, HIE-ISOLDE at CERN, and SPIRAL2 in France, which plan to operate with primary beam power in the range 10 to 50 kW. A design study for EURISOL, a MW ISOL facility in Europe, has been completed, but a start date for this ambitious project does not appear to be on the immediate horizon. The ISOL technique has an advantage over in-flight production in that it provides the highest production yields for isotopes that can be easily extracted from the production target. The disadvantages are the chemistry dependence of the extraction capability (providing access to isotopes of only certain elements) and the relatively long extraction times that in general limits experiments with the shortest half-life isotopes. This limitation means that ISOL facilities cannot meet most of the benchmarks (see Appendix) and resulted in both the 1999 NSAC Grunder Committee and the 2007 NSAC Rare Isotope Beam Task Force reports to endorsing in-flight separation as the correct approach for the U.S. to follow. A high-power (400 kW) ISOL production capability can be implemented at FRIB at a later stage, with gains over one to two orders of magnitude for favorable isotopes over the baseline FRIB facility. Prior to the upgrade, for stopped and reaccelerated beams, FRIB achieves uniqueness by focusing on experiments with rare isotopes that cannot be produced by ISOL methods and thus provides complementary and unique science opportunities to ISOL facilities worldwide.

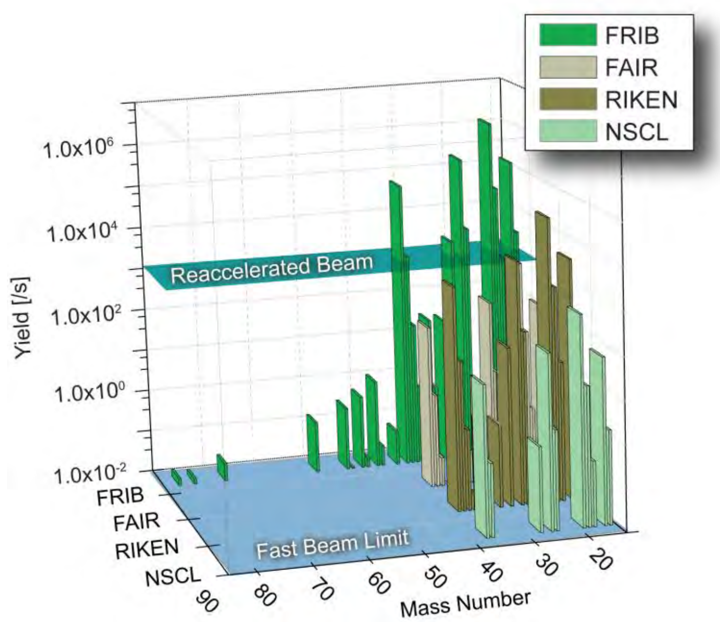

Figure 6: FRIB will be the most powerful rare isotope facility in the world. It will have sufficient intensity (about .01/s) to allow a broad range of nuclei along the driplines up to *A=90* to be studied. FRIB will also have reaccelerated beams of nuclei with large halos and skins at sufficient intensity, greater than 1000/s, for detailed reaccelerated beam studies. Such research is now limited to essentially one case, ^{11}Li.

Critical to Meeting the Benchmarks

The uniqueness of FRIB compared with other international efforts can be judged using the science benchmarks articulated in the 2007 NSAC Rare Isotope Beam Task Force report (see Appendix A). Two-thirds of the experiments corresponding to these benchmarks require fast rare-isotope beams at intensities only available at FRIB. The same holds for the one-third of experiments that require reaccelerated beams that can only be performed at FRIB because ISOL facilities do not readily deliver beams of those elements. Moreover, a large fraction of the experimental equipment required to perform these experiments will be available and commissioned at the start of FRIB operations since the U.S. nuclear science community is already using these tools to perform world-leading experiments at ATLAS, NSCL, and other institutions.

For FRIB's role in providing rare isotopes to the benefit of health, security, energy, and applied science it is important that researchers have ready access to isotopes collected in commensal mode. Other facilities have not built this into their planning or do not use water beam dumps where this is possible. FRIB is the only facility where multiple provisions are incorporated in the baseline design for delivering research quantities (μCi to Ci) of radioisotopes by on-line harvesting. In a commensal mode of facility operation, these isotopes can be made available for research and applications, for example in the areas of medicine, materials science and engineering, nuclear power, stockpile stewardship, and nuclear forensic. Isotopes may be collected from the water-filled primary beam dump and dedicated fragment catchers after the first dipole of the separator or with increased purity in the focal planes of the separator. This unique approach of carefully integrating harvesting capabilities in FRIB's rare-isotope beam production provides additional return of the national investment made into FRIB, supporting both fundamental research and applications with isotopes produced in the US.

Appendix A: FRIB Benchmark Programs

The report to NSAC from the Rare-Isotope Beam Task Force (NSAC RIB Task Force report; July, 2007) introduced a methodology to quantify objectively the capability of any rare-isotope program/facility to meet the NSAC 2007 LRP goals and the scientific opportunities identified in the National Research Council Rare Isotope Science Assessment Committee report from 2007 (NRC RISAC report). This methodology used 17 benchmark scientific programs (referred to as "benchmarks" in this document) that were based on programs presented in the Rare Isotope Accelerator Users Brochure and augmented with further examples from the NRC RISAC report. Listed below are the 17 benchmarks as they address the overarching questions posed by the 2007 LRP, see Figure 7 and Figure 8. The examples are representative of the type of the physics that can be pursued at FRIB — they represent world-class programs spanning numerous experiments — but do not fully capture all of the program or all aspects of the science that will be performed. The goal was rather to identify representative programs whose requirements would illustrate the power of a certain approach.

Intellectual challenges from NRC Decadal Study			
How does subatomic matter organize itself and what phenomena emerge?	How did visible matter come into being and how does it evolve?	Are fundamental interactions that are basic to the structure of matter fully understood?	How can the knowledge and technological progress provided by nuclear physics best be used to benefit society?
Overarching questions from NSAC Long Range Plan			
What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the universe?	What are new applications of isotopes to meet the needs of society?
Science drivers (thrusts) from NRC RISAC			
Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Overarching questions are answered by rare isotope research			
17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research			
1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 13. Limits of stability 14. Weakly bound nuclei 15. Mass surface	6. Equation of State (EOS) 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe s-process 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment 15. Mass surface 17. Weak interactions	10. Medical 11. Stewardship

Figure 7: FRIB will allow the low-energy nuclear physics community to answer the overarching questions from the NSAC 2007 LRP, thereby addressing the NRC RISAC and NRC Decadal Study scientific thrusts. The NSAC RIB TF developed 17 benchmarks to test facility capability to address the questions. FRIB has been designed to contribute to all four science drivers and address all 17 benchmarks.

Benchmark	Unique Capability of FRIB	Unique Science Impact of FRIB	Necessary Capability
Shell structure 1	Only facility with yields above 0.01/s to allow study of ^{60}Ca	New doubly magic nuclei are key benchmarks for nuclear theory	Fast beams for experiments at 0.01/s
Super-heavies 2	Facility with the most intense ^{24}O beams	Intensity critical for fastest and most comprehensive exploration	Reaccelerated beams at 4-6 MeV/u
Skins 3	Only facility to allow study of extreme >0.5 fm skins	Exploration of asymmetric matter over a much wider range of shells and mass number	Fast beams for experiments with intensity of 0.01/s
Pairing 4	Furthest reach and only facility to study pairing in near dripline nuclei with A>34	Key insight into pairing in asymmetric matter	Reaccelerated beams of short-lived nuclei
Symmetry 5	Access to the widest range of transitional nuclei	Deeper insight into the origin of symmetries	Fast beams for rates below 100/s Reaccelerated for rates above 10^4/s
EOS 6	Use of probes, such as intermediate-energy heavy ion reactions with beams at the extremes of isospin	Cleanest and most distinctive tests of different neutron matter EOS	Fast beams of 100 to 200 MeV/u
r-Process 7	Constraints on the largest number of astronomical observables	Most complete data to connect models with observations of elemental abundances	Fast for half-life studies Stopped for masses Reaccelerated for (d,p)
$^{15}O(\alpha,\gamma)$ 8	FRIB may have the highest ^{15}O intensity	First possibility to directly measure this key rate	Low-energy reaccelerated beam
^{59}Fe 9	Provide the largest samples of this key isotope by 10 times	Measurement of (n,γ) on key radioactive isotopes	Isotope harvesting capabilities
Medical 10	Provide a source of material for the U.S. research community	A close proximity of medical and veterinary schools is a benefit	Isotope harvesting capabilities
Steward-ship 11	Wide range of isotopes available to the U.S. community	Access to isotopes involved in reaction networks for nuclear forensics	Harvesting Fast Reaccelerated for indirect studies
Dipole moment 12	Widest search for favorable octupole deformation	FRIB will contribute by exploration of favorable candidates	Fast beams Reaccelerated beams
Limits of stability 13	Will determine the limits of stability to near mass 100	Limits of stability are a key benchmark for nuclear models	3-stage separator and sensitive single isotope identification
New nuclei 14	3x more dripline nuclei having a range of mass and shells	Cases where collective and single-particle degrees compete	Fast experiments with less than 0.01/s
Mass surface 15	More masses available for study than any other facility	Key constraints for nuclear models	Penning trap with stopped beams Fast for some TOF measurements
rp-Process 16	Only facility where sufficient intensity of key nuclides will be available	Only facility where all rates in the rp-process can be determined	Reaccelerated for direct measurements Fast for indirect study
Weak inter-action 17	Ability to determine full range of key electron-capture rates via charge-exchange reactions	The ability to reliably model supernovae core evolution	Fast beams at 100 to 200 MeV/u

Figure 8: FRIB will make unique contributions to the benchmarks. Fast and reaccelerated beams each contribute about half of the short-term unique capabilities.

Appendix B: Educational Aspects of FRIB

Research and education in low-energy nuclear science continue to be the major contributors to developing the future nuclear science workforce. Over the last eight years, 35% of all nuclear physics PhDs in the United States were earned in nuclear structure/nuclear astrophysics (experiment and theory). A majority of these PhDs moved on to careers at National Laboratories.

The field of low-energy nuclear science offers graduate programs in experimental and theoretical nuclear physics, nuclear chemistry, and accelerator physics. The field includes about half of the programs in the U.S. that grant nuclear chemistry degrees — an important national need as articulated in the 2012 National Academy report "Assuring a Future U.S. Based Nuclear and Radiochemistry Expertise." The nature of experiments in low-energy nuclear science assures an exceptional all-around hands-on education to ensure experimental nuclear science graduate students excel at skills relevant to the workforce needs of the nation.

> "The growing use of nuclear medicine, the potential expansion of nuclear power generation, and the urgent needs to protect the nation against external nuclear threats, to maintain our nuclear weapons stockpile, and to manage the nuclear wastes generated in past decades, require a substantial, highly trained, and exceptionally talented workforce."
>
> *Assuring a Future U.S.-Based Nuclear and Radiochemistry Expertise NRC Report (2012)*

Graduate students in experimental nuclear science, including physics and chemistry, typically oversee an experiment from its conception through the proposal process to the preparation and setup and throughout the execution, data analysis, interpretation, and publication of the results. Due to the nature of the various fields, this is different from graduate student education in high-energy physics where, for example, students are part of >1000 member strong collaborations centered around established large-scale detectors and previously planned campaigns. The hands-on training in low-energy nuclear science typically includes apparatus development, nuclear electronics, γ-ray, electron, neutron and charged-particle detection, vacuum systems, data acquisition, digital signal processing, and data analysis. This rigorous, experiential training is what makes low-energy nuclear science graduates highly sought-after candidates for careers in national laboratories.

As a representative statistic, the U.S. careers of MSU-educated/NSCL-trained nuclear science graduates, (who represent about 10% of all nuclear physics PhDs granted in the U.S. or 1/3 of the nation's PhDs in low-energy nuclear physics), were analyzed by professional discipline. All students who left MSU and NSCL between 2004 and 2011 were considered (88% graduated with a PhD and 12% with a M.Sc). About 73% of these recent graduates pursued careers in the U.S. For the graduates who remained in the U.S., 49% of them joined National Laboratories. NNSA-sponsored laboratories alone recruited about 17% from the total of the MSU graduates that pursued careers in the U.S., directly contributing to the nuclear and homeland security missions mission of the nation (see Figure 9). A total of 37% of the graduates are working in the medical field, for the government or nonprofits, or in one of the NNSA-sponsored laboratories, directly addressing a significant and increasing demand of the nation's nuclear workforce needs in these critical sectors. Many of these positions are typically open only to U.S. citizens. Notably, 75% of the students presently enrolled at MSU/NSCL are U.S. citizens.

A Superior Nuclear Science Workforce for the Future

Low-energy nuclear science has become a core part of the NNSA workforce development program. Presently, two major centers are funded with a total investment of around $20M. Michigan State University is part of the SUCCESS PIPELINE, an NNSA-funded center aimed at educating the workforce for the nation's stockpile stewardship mission. The other NNSA center is The Center for Radioactive Ion Beam Studies for Stewardship Science led by Rutgers University and includes Oak Ridge National Laboratory, Michigan State University, Louisiana State University, the University of Tennessee, and the Colorado School of Mines.

MSU postdoctoral researchers in the field, who receive a hands-on training as comprehensive as outlined for the low-energy nuclear science graduate students, have been exceptionally successful over the years, with more than 50% of them moving on to permanent positions in academia and National Laboratories (combined 86%) and industry (14%) (numbers drawn from MSU statistics).

At FRIB, the education and training of MSU nuclear science graduate students and research associates will be pursued in a similar fashion, with active mentoring to ensure the nation's increasing demand will be met with an exceptionally skilled and well-trained nuclear physics and chemistry workforce.

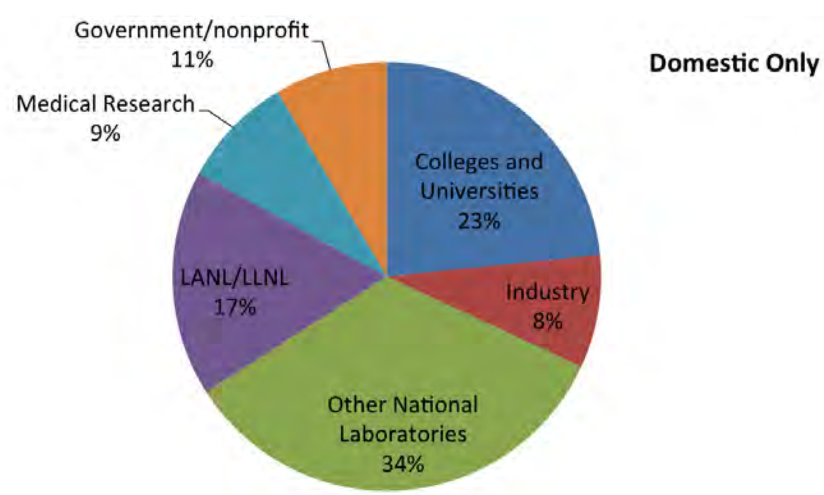

Figure 9: Representative statistics for expectations of FRIB-educated graduate students based on actual employment of MSU-trained nuclear scientists in critical U.S. sectors. Most of these careers are open only to U.S. citizens. Of significance, 75% of the nuclear science graduate students presently enrolled at MSU are U.S. citizens.

Appendix C: Bibliography

Overview Documents:

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