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

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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.

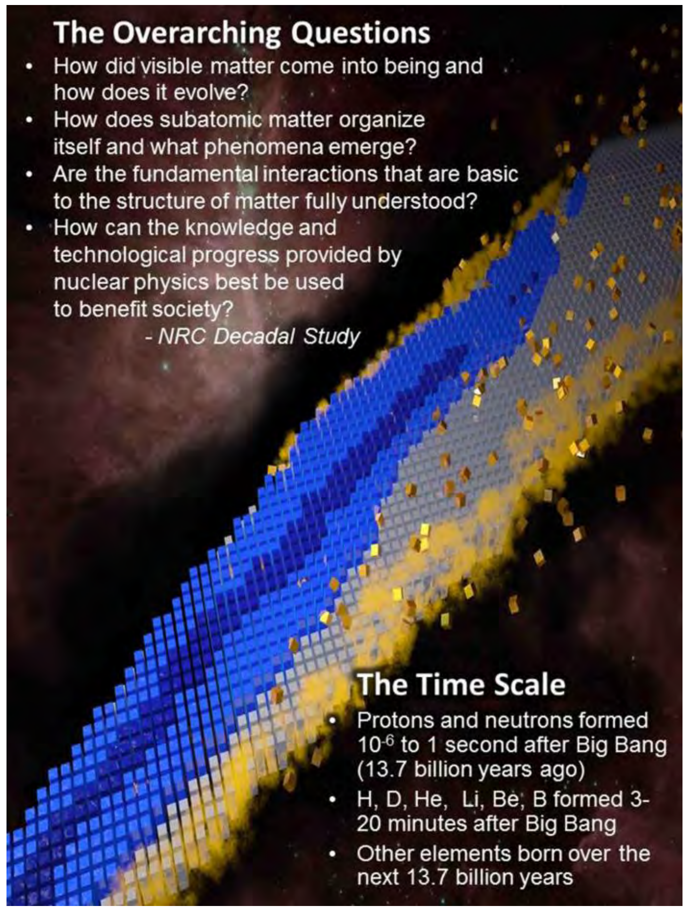

Figure 1: FRIB will yield answers to fundamental questions by exploration of the nuclear landscape and help unravel the history of the universe from the first seconds of the Big Bang to the present.

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

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."***

> "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*

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.

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."***

- 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

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.