The Science of FRIB

Prepared by Michigan State University 2008 in response to the DOE FOA DE-PS02-08ER41535 and revised for release 2009.

Contents

1. The Scientific and Technical Merit of FRIB

FRIB will be a critical component of the DOE mission to understand the fundamental forces and particles of nature as manifested in nuclear matter, and provide the necessary expertise and tools from nuclear science to meet national needs. FRIB will enable the nuclear science research community to make major advances in our understanding of nature by accessing key rare isotopes that previously only existed in the most violent conditions in the universe. This facility will:

- Enable users to answer compelling questions about the structure of nuclei and the origin and evolution of elements in the cosmos
- Permit sensitive tests of the fundamental symmetries of nature to address basic questions on the character of the universe
- Serve as a center to draw the most talented scientists and students into nuclear science
- Provide the U.S. community a source of rare isotopes to develop new applications for medicine, stockpile stewardship, and national security, and improve applications that benefit from the use of radioisotopes

The basis of FRIB's technical scope is founded upon and supported by DOE reference material listed in the FOA (**Figure 1-1**), plus additional nuclear scientific user community documentation (**Figure 1-2**).

Title	Description of Focus Areas	Reference Name
The Frontiers of Nuclear Science, DOE/NSF Nuclear Science Advisory Committee, December 2007 [LRP07]	Expert panel advice based on input from the nuclear scientific user community on the priorities for nuclear science for the next 5-10 years	NSAC 2007 LRP
Scientific Opportunities with a FRIB in the United States, December 2006 [RIS06]	National Research Council Rare Isotope Science Assessment Committee review of FRIB science–identified science drivers of FRIB	NRC RISAC
Report to NSAC of the Rare-Isotope Beam Task Force, July 2007 [RTF07]	Expert panel advice on technical options for FRIB–introduced the 17 benchmarks	NSAC RIB TF
Four years later: An Interim Report on Facilities for the Future of Science: A Twenty-Year Outlook, August 2007 [TYO07]	Internal DOE report updating the 20-year facility plan published in 2003–FRIB is tied for third in priority out of 28 facilities	DOE-SC Twenty-year Outlook

Figure 1-1. DOE FOA-referenced Documents. The primary DOE-referenced documents that the MSU team used as the basis for our FRIB proposed concept and that are referenced often.

Title	Description of Focus Areas	Reference Name
The 2007 Nuclear Structure Town Meeting Report, January 2007 [NTM07]	Research goals of the U.S. rare-isotope research community–provides guidance for FRIB scope	DNP Town Meeting
The Science of the Rare Isotope Accelerator (RIA): A Brochure from the RIA Users Community, 2006 [RIA06]	Position paper produced by the RIA Users Organization with input from future FRIB users–introduced benchmark examples	RIA Users Brochure
RIA Theory Bluebook: A Road Map–A Report from the RIA Theory Group September 2005 [TBB05]	Position paper produced by the RIA Theory Group–laid out a theory road map for achieving a unified description of nuclei	RIA Theory Bluebook

Figure 1-2. Science Community-generated Documents. The primary science-community documents that the MSU team used as the basis for our FRIB proposed concept.

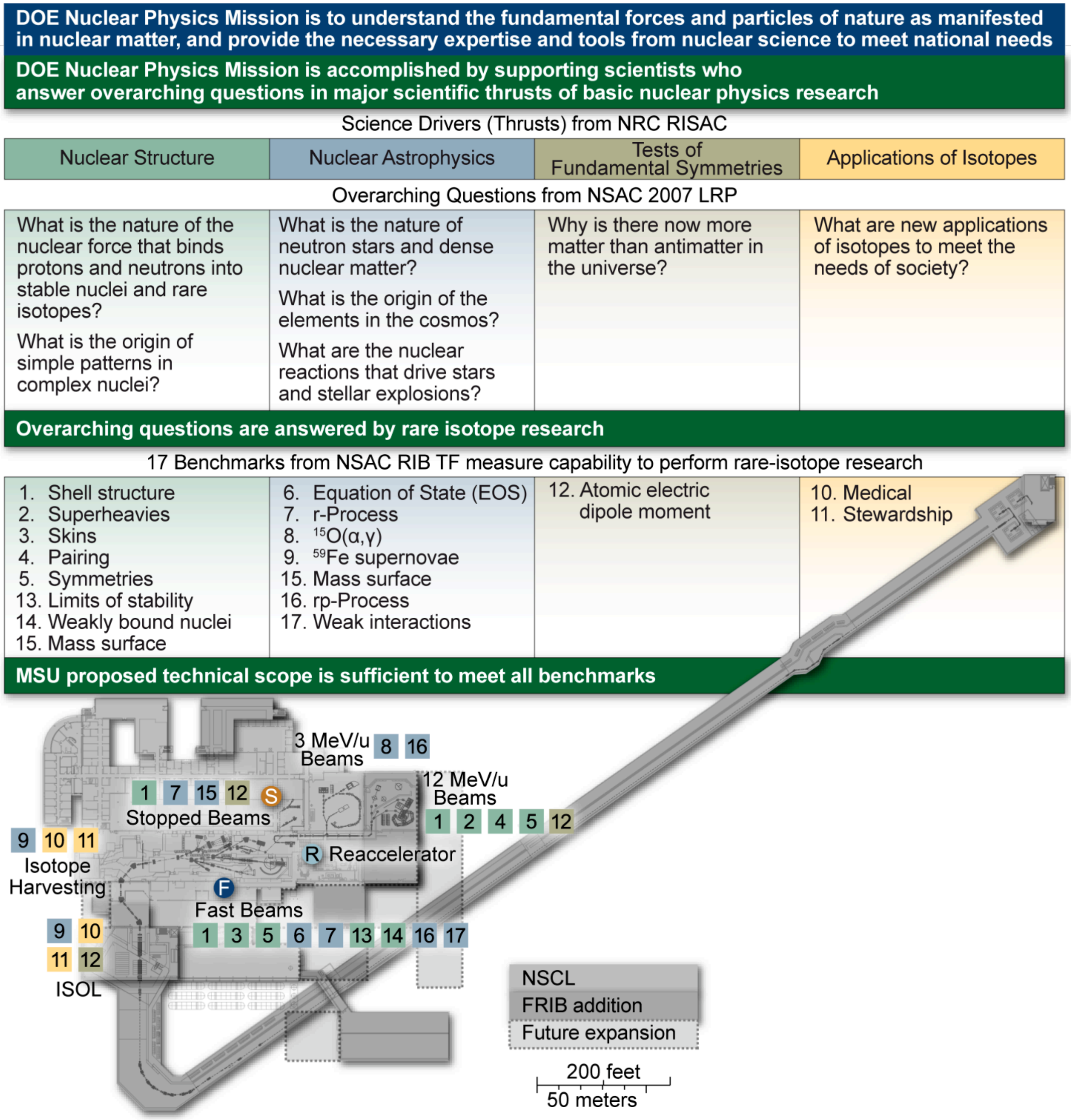
The MSU team's technical solution reflects all of these documents in a comprehensive plan that addresses:

- FRIB objectives and performance requirements and how they support the DOE Nuclear Physics Program (discussed in Section 1.a)
- The means to work collaboratively within the scientific user community to ensure that FRIB will meet the requirements of the community (discussed in Section 1.b)
- The technical merit of equipment (discussed in Section 1.c)

MSU proposes a facility based on a heavy-ion linac with a minimum energy of 200 MeV/u for all ions at beam power of 400 kW. The facility will have a production area, three-stage fragment separator, three ion-stopping stations, and post accelerator (reaccelerator) to reach at least 12 MeV/u for all ions. Experimental equipment for a full program of fast, stopped and reaccelerated beam research is included. Infrastructure and office space will accommodate the anticipated user demand.

The MSU team uses a benchmarked approach to validate our technical specifications. The NSAC RIB TF report [RTF07] introduced a methodology to judge the capability of any facility to meet the NSAC 2007 LRP [LRP07] and NRC RISAC [RIS06] goals. This methodology is based on 17 benchmark scientific programs (referred to hereafter as benchmarks) that were based on example programs presented in the RIA Users Brochure [RIA06] and augmented with further examples from the NRC RISAC report.

The DOE nuclear physics mission, its relation to the FRIB science drivers, their reflection in the NSAC 2007 LRP key questions, and corresponding benchmarks are illustrated in **Figure 1-3**. The figure demonstrates how the scientific goals (answering the NSAC 2007 LRP questions) drive the scope. The bottom of the figure illustrates the tools required for each of the benchmarks. To achieve the goals, we recognize the need for a broad-approach technical scope that provides fast, stopped, and reaccelerated beams of rare isotopes on day one of operations. Our approach provides a facility that is flexible and responsive to DOE expert panel advice and expressed user community needs.



DOE Nuclear Physics Mission is to understand the fundamental forces and particles of nature as manifested in nuclear matter, and provide the necessary expertise and tools from nuclear science to meet national needs

DOE Nuclear Physics Mission is accomplished by supporting scientists who answer overarching questions in major scientific thrusts of basic nuclear physics research

Science Drivers (Thrusts) from NRC RISAC

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes

Overarching Questions from NSAC 2007 LRP

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
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?

Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare-isotope research

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
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 supernovae 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment	10. Medical 11. Stewardship

MSU proposed technical scope is sufficient to meet all benchmarks

Figure 1-3. Approach to FRIB. *The goal of FRIB is to allow users to answer the overarching questions from the NSAC 2007 LRP, thereby addressing the NRC RISAC scientific thrusts and accomplishing the DOE Nuclear Physics Mission. NSAC RIB TF developed 17 benchmarks to test facility capability to address the questions. Meeting these benchmarks has driven the technical scope and specifications for FRIB.*

The scientific reach of a 400 kW, 200 MeV/u heavy-ion linac with capabilities for fast, stopped, and reaccelerated beam experiments exceeds that of any facility in the world. The power of the linac approach and reach of such a facility was acknowledged by the NRC RISAC report: "*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 ...*"

1.a. FRIB Nuclear Physics Mission

Our approach is aligned with the FRIB mission and the DOE nuclear physics mission as captured in **Figure 1-3**.

Additionally, pre-, short-, mid-, and long-term goals take advantage of NSCL's existing capabilities and provide a low-risk approach (because the techniques can be shaken down prior to CD-4) and a best-value approach.

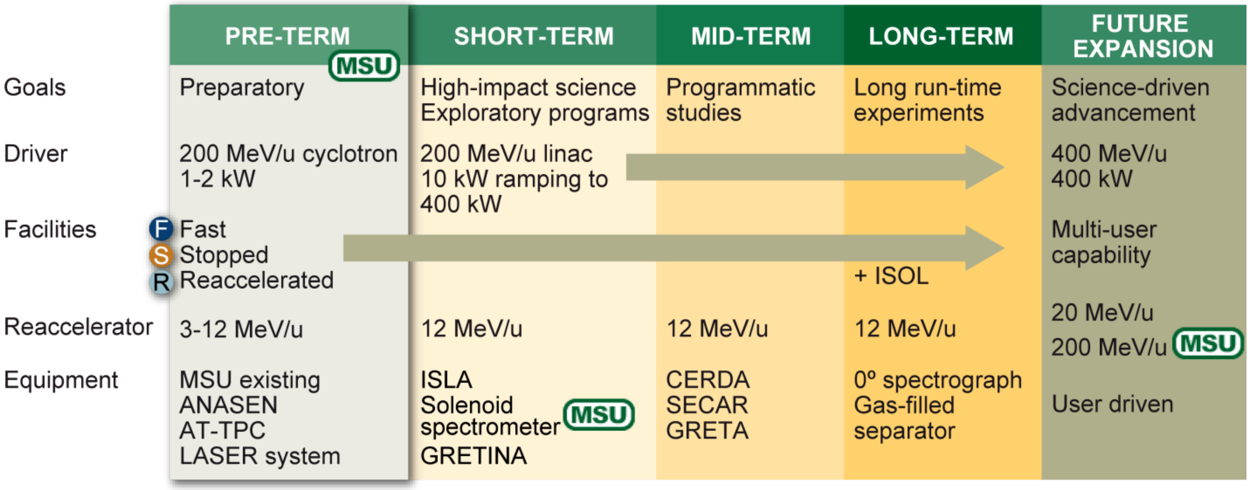
1.a.1 Short-, Mid- and Long-term Scientific Goals that Drive Facility Specifications

MSU's FRIB technical design and construction specifications were driven by scientific goals developed in collaboration with the U.S. scientific user community. To fulfill the facility scope specifications and produce world-leading science, MSU will capitalize on NSCL assets and capabilities. The Government will benefit by having a facility able to do the best science, by having a strong user community, and by FRIB having a wide-ranging set of research tools that will allow the U.S. to remain a world leader in nuclear science.

The scientific goals for FRIB map directly onto the NRC-RISAC science drivers, the overarching questions of the NSAC 2007 LRP, and the representative benchmarks. The 17 benchmarks will be used to validate that at each term of operation, the technical scope is appropriate to achieve the relevant scientific goals. Ground-breaking studies of rare isotopes, performed in the short-term FRIB program, will lead to programmatic studies, enhanced by more sensitive equipment in the mid-term. The long-term science program will move to more beamtime-intensive experimentation that can lead to important new discoveries, such as, superheavy elements or an atomic electric dipole moment. MSU will manage the program following the lessons learned in the earlier terms. A key requirement emphasized by the users is the availability of fast, stopped, and reaccelerated beams [NTM07].

MSU's extensive scope provides users the ability to conduct experiments related to all 17 benchmarks in all terms of FRIB operation. This feature provides leadership opportunities for the U.S. community and hence is the most effective way to grow the community. It meets the expressed user needs and allows the best science to be done in the short term, leading to new opportunities in the mid- and long-terms. Prior to FRIB start-up, a pre-term science program using beams from NSCL will be available to maintain world leadership, cultivate a strong community of users, commission scientific instrumentation, and optimize operating procedures.

Figure 1-4 shows the programmatic science goals and their relationship to the technical scope of FRIB and related major experimental equipment. We envision that each phase has a time frame of about five years, with future expansions extending the life of the facility beyond twenty years. The phases are roughly defined by the nature of the science, preparatory in the FRIB pre-term, highlight driven in the short term, programmatic in the mid-term, and user and science driven in the long term, when long beamtime experiments will be performed.



	PRE-TERM	SHORT-TERM	MID-TERM	LONG-TERM	FUTURE EXPANSION
Goals	Preparatory MSU	High-impact science Exploratory programs	Programmatic studies	Long run-time experiments	Science-driven advancement
Driver	200 MeV/u cyclotron 1-2 kW	200 MeV/u linac 10 kW ramping to 400 kW			400 MeV/u 400 kW
Facilities	F Fast S Stopped R Reaccelerated			+ ISOL	Multi-user capability
Reaccelerator	3-12 MeV/u	12 MeV/u	12 MeV/u	12 MeV/u	20 MeV/u 200 MeV/u MSU
Equipment	MSU existing ANASEN AT-TPC LASER system	ISLA Solenoid spectrometer MSU GRETINA	CERDA SECAR GRETA	0° spectrograph Gas-filled separator	User driven

Figure 1-4. The Approach to FRIB Technical Scope. *The phased technical scope through each term is listed. The existing MSU and other planned equipment is described in Section 1.c.*

In the long term, it may become desirable to add Isotope Separation On-Line (ISOL) as an experimental capability. ISOL is not included in the base facility in light of the overlap this program would have with existing and planned ISOL facilities worldwide. However, as recommended by the NSAC RIB TF, the base facility includes infrastructure for ISOL. Two ISOL targets can be added at any time at low cost and minimal impact on facility operation.

Other future FRIB expansions or upgrades can be considered at any time as driven by scientific and user needs. The MSU approach has identified three likely and important future upgrades. One upgrade is to increase the rare-isotope yield by at least one order of magnitude for the most exotic isotopes by increasing the driver energy to 400 MeV/u. This upgrade would provide a particular benefit for the production of very neutron-rich nuclei near the driplines in the mass 100 region, and for the study of heavy r-process nuclei. The second upgrade is to boost the reacceleration energy to 200 MeV/u and take advantage of all the fast-beam tools for reaccelerated beams, including fragmentation of ISOL-produced beams to expand the facility reach. The third upgrade would add multi-user capability by catching unused isotopes in the separator and delivering them to the reaccelerator.

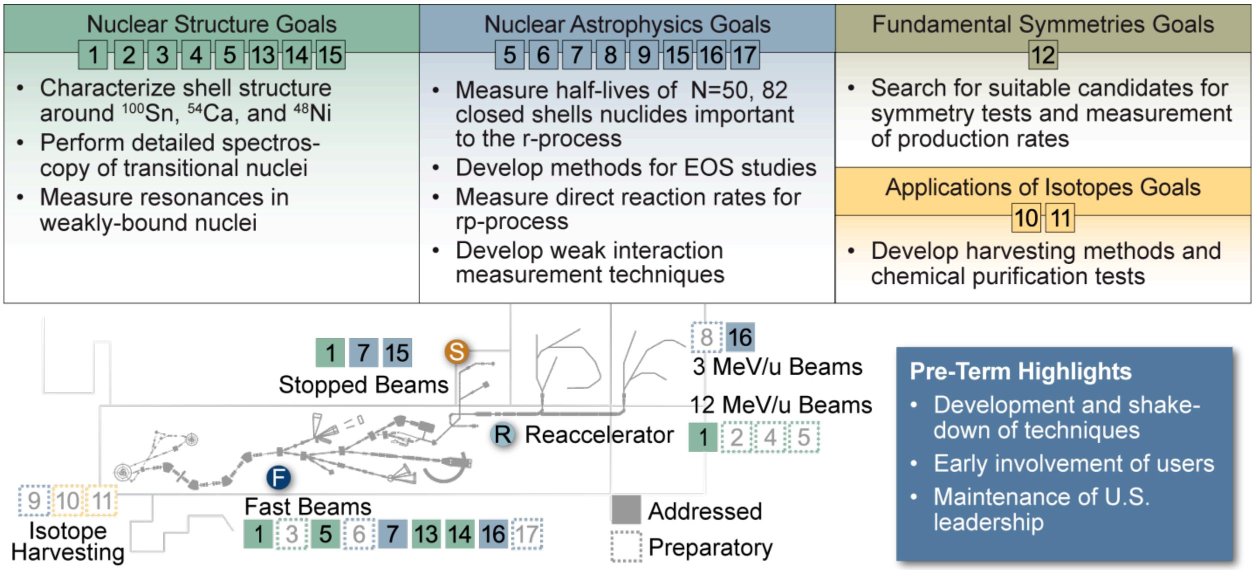
The sections below will address the five phases of the approach identified in Figure 1-4. The ability to meet a benchmark using a given research tool (for example, nucleon knockout with fast beams) was described in the RIA Users Brochure and is dependent on obtaining a sufficient rate of the isotope of interest. The science goals can be met when the corresponding technical scope is sufficient to achieve the experiments in the benchmark programs.

1.a.1.1 Scientific Goals of the Facility in the FRIB Pre-term

The pre-term science goals, listed in **Figure 1-5**, will make full use of existing NSCL capabilities to address some of the benchmarks and to allow preparatory studies on others. A pre-term science program will:

- Provide a seven-year head start on performing experiments with fast, stopped, and reaccelerated beams
- Establish a community of users and theorists that will invest in the science of FRIB, including the development of scientific instrumentation and data analysis methods
- Increase training, and increase experience related to key scientific programs
- Maintain and augment world leadership in rare-isotope science in the period leading up to FRIB start-up

Data obtained during pre-FRIB operations will make important contributions to *ab initio*, configuration interaction, and density functional theories. Preparatory studies on near-barrier fusion, one and two-nucleon transfer, quasi-free scattering, and other reactions will stimulate the necessary developments in reaction theory that will be important for the success of the FRIB science program. Experimental programs will benefit from the additional experience from performing experiments with rare-isotope beams. Operational experiences at present-day rare-isotope facilities, including NSCL, TRIUMF-ISAC, and ORNL-HRIBF have demonstrated that experiments with rare-isotope beams are inherently different from those executed with stable beams due to low intensity, background radiation, and contaminant beams.



Nuclear Structure Goals

1 2 3 4 5 13 14 15

- Characterize shell structure around ^{100}Sn, ^{54}Ca, and ^{48}Ni
- Perform detailed spectroscopy of transitional nuclei
- Measure resonances in weakly-bound nuclei

Nuclear Astrophysics Goals

5 6 7 8 9 15 16 17

- Measure half-lives of N=50, 82 closed shells nuclides important to the r-process
- Develop methods for EOS studies
- Measure direct reaction rates for rp-process
- Develop weak interaction measurement techniques

Fundamental Symmetries Goals

12

- Search for suitable candidates for symmetry tests and measurement of production rates

Applications of Isotopes Goals

10 11

- Develop harvesting methods and chemical purification tests

Pre-Term Highlights

- Development and shake-down of techniques
- Early involvement of users
- Maintenance of U.S. leadership

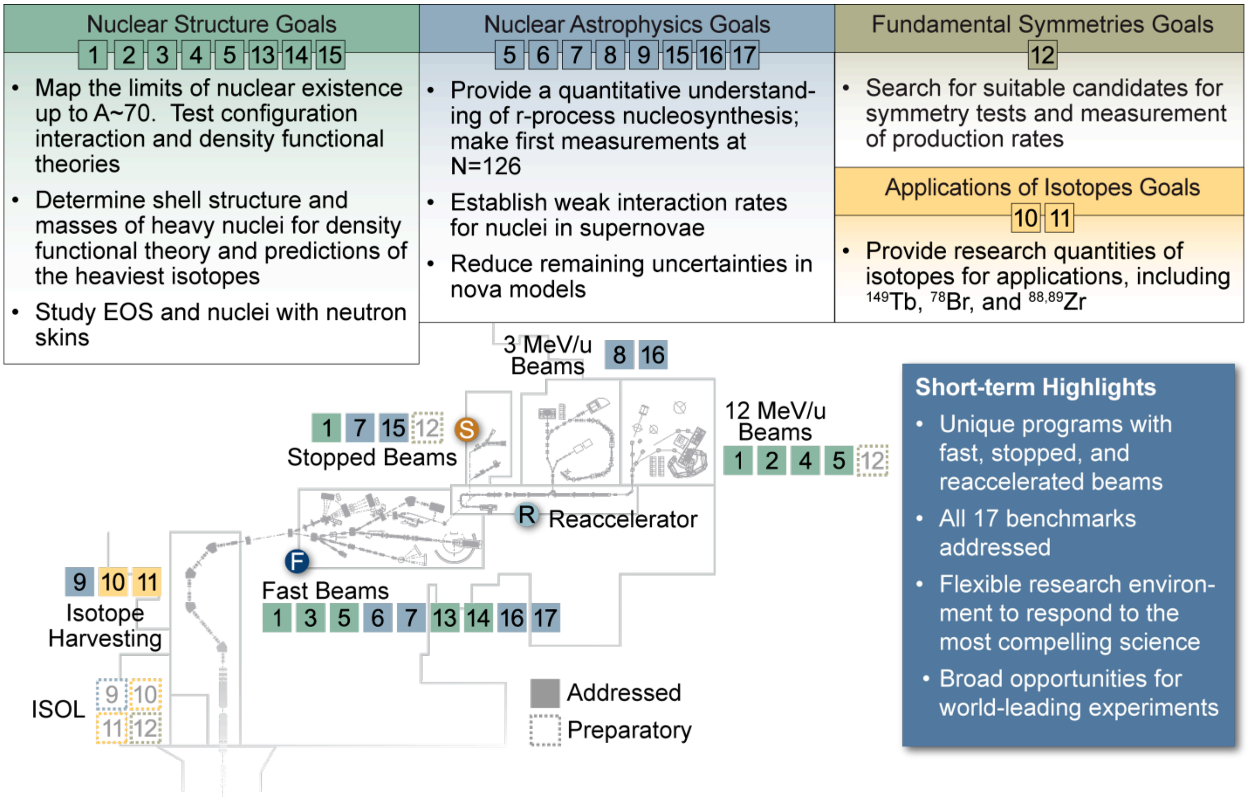
Figure 1-5. Scientific Goals and Corresponding Technical Scope for Pre-term FRIB Operations. *The numbered benchmarks of the science goals (listed in Figure 1-3) are located near the required technical scope element. The pre-term takes advantage of the NSCL cyclotrons to provide a shake-down period prior to FRIB CD-4, when the user community can be engaged and U.S. leadership in rare-isotope science is maintained and augmented.*

The pre-FRIB operations will test harvesting options for isotopes produced by fast fragmentation, and will include collection, purification, and specific-activity analysis. Such efforts will involve cross-disciplinary interactions across the MSU community and with other universities and national laboratories. It will allow users to develop techniques for using harvested isotopes, paving the way for later applications.

Rare-isotope beams will be produced in-flight with the present NSCL accelerator and fragment separator complex. The rare-isotope reaccelerator, ReA3, funded by MSU to be operational in 2010, will initially provide beams to a maximum energy of 3 MeV/u for uranium, increasing to 12 MeV/u early in the FRIB project. The pre-FRIB science program will use much of the scientific instrumentation already available at NSCL (see section 1.c) and will take advantage of user equipment, such as GRETINA and its auxiliary equipment. Major experimental equipment within FRIB's scope will be completed in the early stages of FRIB construction, so that scientific instruments are fully commissioned and producing science prior to FRIB start-up. Details of the technical scope are described at *http://frib.msu.edu/*, new scientific instrumentation is described in Section 1.c.

1.a.1.2 Scientific Goals of the Facility in the FRIB Short-term

The short-term science goals, listed in **Figure 1-6**, will make full use of rare isotopes at fast, stopped, and reaccelerated energies to capitalize on the most compelling science opportunities across the benchmarks. For example, FRIB will allow the first study of the predicted doubly-magic nucleus ^{60}Ca that will serve as a benchmark for nuclear models far from stability. FRIB will define and map the limits of nuclear existence up to A~70, provide key data, such as masses, half-lives, and deformations to test density functionals. The program will measure reaction rates and properties of relevant nuclear states to provide a quantitative understanding of stellar nucleosynthesis to be realized (up to A~195 for the r-process and A~70 for the rp-process). Research quantities of isotopes such as ^{149}Tb and ^{211}At for localized tumor therapy, ^{88,89}Zr for stockpile stewardship, and ^{86}Y, ^{89}Zr, and ^{124}I for imaging will be available for applications.



Nuclear Structure Goals

1 2 3 4 5 13 14 15

- Map the limits of nuclear existence up to A~70. Test configuration interaction and density functional theories
- Determine shell structure and masses of heavy nuclei for density functional theory and predictions of the heaviest isotopes
- Study EOS and nuclei with neutron skins

Nuclear Astrophysics Goals

5 6 7 8 9 15 16 17

- Provide a quantitative understanding of r-process nucleosynthesis; make first measurements at N=126
- Establish weak interaction rates for nuclei in supernovae
- Reduce remaining uncertainties in nova models

Fundamental Symmetries Goals

12

- Search for suitable candidates for symmetry tests and measurement of production rates

Applications of Isotopes Goals

10 11

- Provide research quantities of isotopes for applications, including ^{149}Tb, ^{78}Br, and ^{88,89}Zr

Short-term Highlights

- Unique programs with fast, stopped, and reaccelerated beams
- All 17 benchmarks addressed
- Flexible research environment to respond to the most compelling science
- Broad opportunities for world-leading experiments

Figure 1-6. Scientific Goals and Corresponding Technical Scope for Short-term FRIB Operations. *The numbered benchmarks of the science goals (both listed in Figure 1-3) are located near the required technical scope element. The short term provides a flexible research environment that addresses all 17 benchmarks immediately by offering fast, stopped, and reaccelerated beam programs.*

To meet the scientific goals outlined for the short term, the MSU team's technical scope for FRIB includes production of rare isotopes in-flight, with a wide range of primary beams with energy of 200 MeV/u for uranium, and with intensities up to 400 kW. By the end of the fourth year, we anticipate operation at the full performance goal of 400 kW.

The rationale for the primary performance specifications for FRIB of 200 MeV/u and 400 kW is illustrated in **Figure 1-7** for calcium isotopes (similar considerations apply to most other elements). The figure shows the estimated FRIB beam rates, which are a factor of nearly 100 higher than at any other facility planned in the world. This factor of 100 allows the key benchmark nuclei ^{54}Ca and ^{60}Ca to be studied. The performance goals (200 MeV/u, 400 kW) also allow studies of nuclei near the dripline and study of very heavy calcium isotopes with extreme neutron skins greater than 0.5 fm.

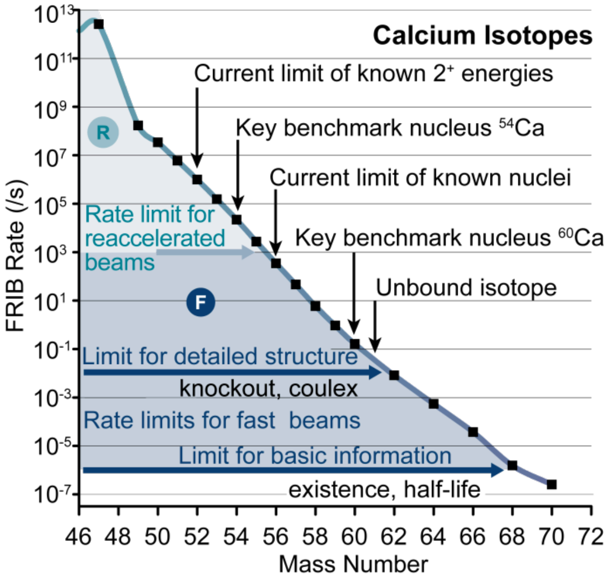


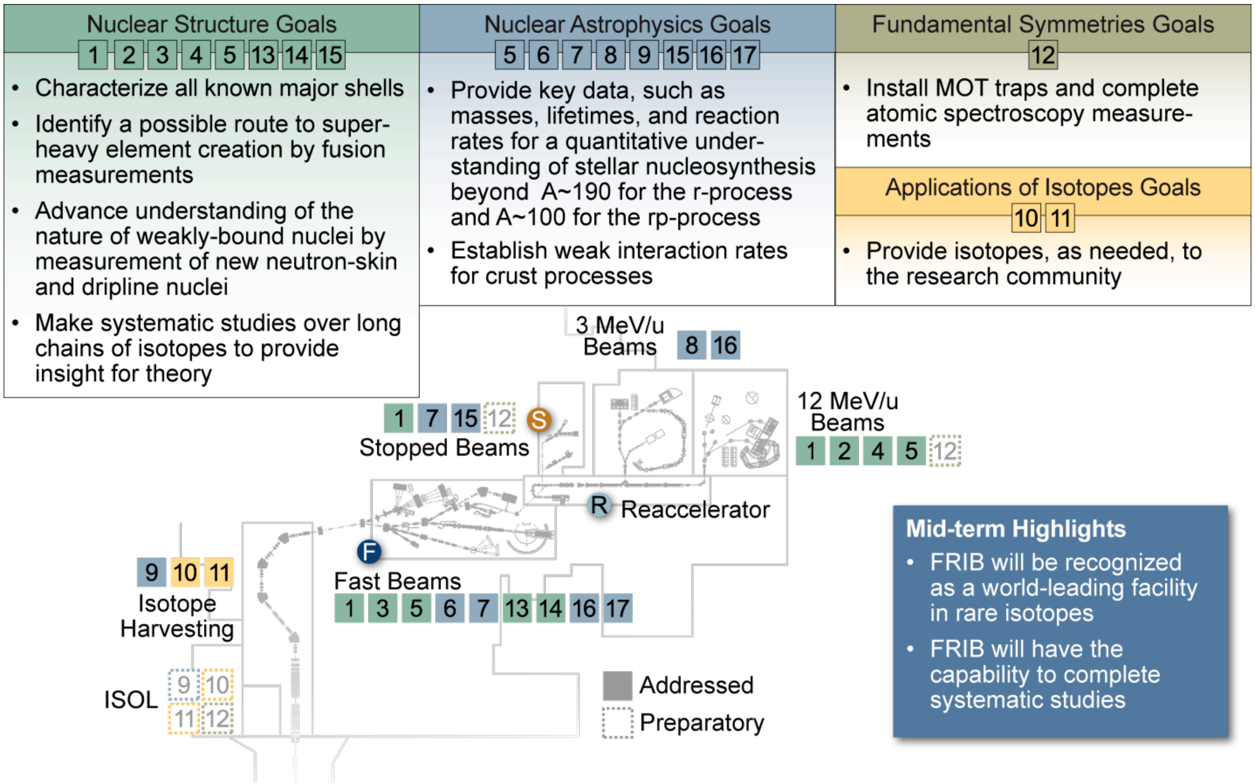
Figure 1-7. FRIB Short-term Scientific Reach with 400 kW. *Simulated rates for calcium isotopes showing the reach offered by 400 kW. Power of 400 kW for all beams provides calcium rates nearly 100 times those as other facilities. The figure shows that this factor of 100 is critical to reach key isotopes.*

An initial performance specification of 10 kW beam power is chosen to allow a world-unique program on day one of operations. The reaccelerated beam rates will be more than ten times the 1 kW-based NSCL rates, and the fast-beam capability for A<100 beams may exceed that of RIKEN and GSI by at least a factor of two.

The in-flight fragment separator will have three separation stages to reduce background when searching for the limits of stability. This feature is based upon insight gained during a series of experiments that culminated in the recent discovery of ^{40}Mg [Bau07]. The reaccelerator, installed in the early time line for FRIB construction with reacceleration energies of 12 MeV/u for uranium and greater than 20 MeV/u for ions with A<50, will exceed technical specifications required for the proposed transfer, fusion/evaporation, and inelastic scattering experiments. New scientific instrumentation is described in Section 1.c.

1.a.1.3 Scientific Goals of the Facility in the FRIB Mid-term

Figure 1-8 highlights science goals associated with the mid-term phase. The expertise gained by users in the short-term operations of FRIB will play a key role in defining the course of the mid-term science program. The science program will evolve towards programmatic measurements in key regions of the chart of nuclides, such as study of the evolution of structure from ^{48}Ni to the very exotic ^{80}Ni (predicted to have an extreme neutron-skin thickness greater than 0.5 fm). Development and implementation of new scientific instrumentation will be needed to meet the sensitivity requirements of these more difficult measurements. The GRETA gamma-ray device, a high-sensitivity recoil separator for nuclear astrophysical measurements (SECAR), and a high collection efficiency beta- and gamma-ray detector for decay studies (CERDA) are examples.



Nuclear Structure Goals 1 2 3 4 5 13 14 15

- Characterize all known major shells
- Identify a possible route to superheavy element creation by fusion measurements
- Advance understanding of the nature of weakly-bound nuclei by measurement of new neutron-skin and dripline nuclei
- Make systematic studies over long chains of isotopes to provide insight for theory

Nuclear Astrophysics Goals 5 6 7 8 9 15 16 17

- Provide key data, such as masses, lifetimes, and reaction rates for a quantitative understanding of stellar nucleosynthesis beyond A~190 for the r-process and A~100 for the rp-process
- Establish weak interaction rates for crust processes

Fundamental Symmetries Goals 12

- Install MOT traps and complete atomic spectroscopy measurements

Applications of Isotopes Goals 10 11

- Provide isotopes, as needed, to the research community

Mid-term Highlights

- FRIB will be recognized as a world-leading facility in rare isotopes
- FRIB will have the capability to complete systematic studies

Figure 1-8. Scientific Goals and Corresponding Technical Scope for Mid-term FRIB Operations. *The numbered benchmarks of the science goals (both listed in Figure 1-3) are located near the required technical scope element. The mid-term provides capabilities to execute programmatic studies that will be facilitated by additional sensitive experimental equipment.*

The scientific outcomes from the proposed program in the mid-term will be significant. Detailed characterization of nuclei near all known doubly-magic nuclei will be completed. The systematic development of neutron skins and their impact on nuclear structure for closed-shell tin and nickel will be completed. Nucleosynthesis processes, such as those important for modeling neutron stars and those that occur in novae, will be on a fully quantitative basis, with uncertainties reduced to a level that allows reliable comparison of astronomical observations to models. The hardware requirements for atomic electric dipole moment (EDM) measurements, and other fundamental symmetry tests, will be fully defined in the mid-term, and the necessary atomic spectroscopy measurements for the high-Z EDM candidates will be completed. Details of new scientific instrumentation are described in Section 1.c.

1.a.1.4 Scientific Goals of the Facility in the FRIB Long-term

The long-term science goals of FRIB (see **Figure 1-9**) will result in more time-intensive experimentation to complete important science quests, again relying on the base technical scope of the FRIB accelerator complex that provides heavy-ion primary beams of energy 200 MeV/u with 400 kW beam power, in-flight production, and gas stopping. Depending on the outcome of measurements in the short- and mid-terms, it may be desirable to implement a capability for ISOL in the long term as an experiment. This would allow long-beamtime experiments to synthesize superheavy elements and searches for rare processes, such as an atomic EDM, to be completed. Our base design includes shielding and target handling facilities to allow ISOL to be added at low cost and with minimal downtime (because components can be added during normal maintenance periods).

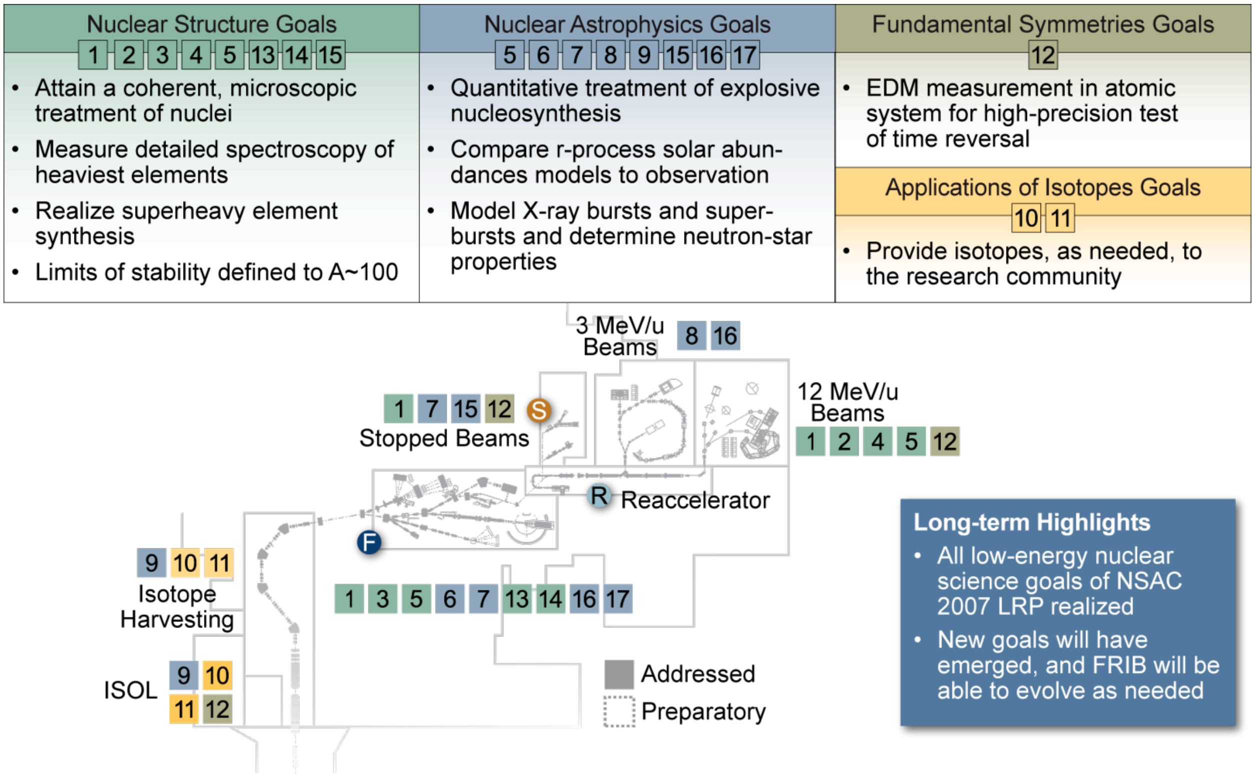


Figure 1-9. Scientific Goals and Corresponding Technical Scope for Long-Term FRIB Operations. *The numbered benchmarks of the science goals (listed in Figure 1-4) are located near the required technical scope element. MSU is flexible to add ISOL capability if this is supported by scientific demand. The baseline scope of the facility can accommodate a low-cost, low-operational impact addition of ISOL.*

At the conclusion of long-term FRIB operations, a comprehensive and coherent picture of the nature of nucleonic matter will have been attained, with bridges between the three model approaches: *ab initio*, configuration space, and density functional theory. Attempts to synthesize heavy elements will have provided data to define the limits of nuclear existence at the very reaches of the nuclear chart, while the neutron dripline will have been established up to A~100. A quantitative understanding of stellar nucleosynthesis will have been achieved, including a majority of the nuclear physics data required to quantify the r-process. New opportunities will have been realized for time-reversal symmetry tests, including an atomic EDM measurement. Details of new scientific instrumentation are described in Section 1.c.

1.a.1.5 Future Expansion

As the science goals are realized and new opportunities identified, we expect the community to identify evolutionary changes for FRIB. An important aspect of the MSU approach is to allow for the most probable enhancements by modification to the baseline design, so they can be implemented in a cost-effective manner. Accommodation of these expansions has driven the technical specifications of the base facility. Because we cannot anticipate all of these directions, flexibility of the expansion paths is essential, and the MSU site is fully able to accommodate doubling of the driver energy, doubling of the experimental areas, and increase of the reacceleator energy by an order of magnitude. We describe potential expansions that have impacted base facility specifications below.

Increase of the Maximum Energy of the Heavy-ion Linac Driver to 400 MeV/u for Uranium. An increase in the primary beam energy from the heavy-ion linac driver would give an increase in the production rates of many rare isotopes by up to a factor of 10, thus enabling new science and extension of our reach to the driplines to mass 120 nuclei. The corresponding higher proton driver energy would also make the implementation of ISOL more desirable, as the enhanced production with 400 kW of 1 GeV protons would clearly outpace other facilities. The approach to an energy upgrade of the primary driver is to build the base facility with space provided in the linac for the gradual addition of cryomodules to reach 400 MeV/u.

Reacceleration of Rare Isotopes to 200 MeV/u Using the Existing K1200 Cyclotron. A future upgrade of the energies of reaccelerated rare-isotope beams to 200 MeV/u could be realized by the addition of a gas stopper after the second stage of the fragment separator, and/or by use of beams from the ISOL target, and an injection line into the K1200 cyclotron. The beams would feed into the third stage of the fragment separator and use existing equipment. The availability of high-energy rare-isotope beams with high brightness would be world unique. The fragmentation of high-energy rare-isotope beams and the third stage of the fragment separator would make it possible to extend the limits of stability for neutron-rich nuclei to A~150.

Increase of the Maximum Energy of the Linear Reaccelerator to 20 MeV/u for Uranium and 39 MeV/u for Ions with A<50. An increase in the reaccelerator energy to about 20 MeV/u for uranium and up to 39 MeV/u for ions with A<50 would provide rare isotopes with sufficient energy to study transfer reactions that have large positive Q values, including (p,t) reactions in inverse kinematics. The characterization of nuclear pairing for nuclei near N=Z is an important contribution to the development of a coherent treatment of nucleonic matter, and multi-nucleon transfer reactions would provide key data on like and unlike nucleon interaction strengths.

Add Multi-user Capability for Simultaneous Fast and Reaccelerated Beams. Multi-user capability would expand the user base of FRIB and increase scientific output. This could be accomplished by a catch-and-release scheme for interesting isotopes that would otherwise be stopped in the mass slits of the fragment separator.

A compact isotope catcher/ion source system would be installed in the focal plane of the pre-separator or second-stage separator. Unused secondary beams could be stopped in a high-temperature solid catcher. The released rare-isotope atoms would be ionized in a suitable ion source. The system would be remotely positioned inside the focal-plane chamber to allow beams with different rigidity to be intercepted. Depending on the chemistry of the catching material and the ion of interest, efficiency of 10% or higher could be achieved [Qin03]. After mass separation, the beams would be transported to the stopped-beam area and the reaccelerator by a low-energy beam transport system shared with the ISOL system.

1.a.2 Plans to Fulfill Scientific Thrust Areas of NSAC 2007 Long-range Plan

The scientific thrusts for FRIB have been articulated repeatedly [RIA02,TBB05,RIA06, RIS06, RTF07] and most recently in the NSAC 2007 LRP. The MSU team also considers the Nuclear Physics Performance Measures [OMB03] developed by NSAC and used to benchmark progress in the field. The 2015 measure reads: "*Investigate new regions of nuclear structure, study interactions in nuclear matter like those occurring in neutron stars, and determine the reactions that create the nuclei of atomic elements inside stars and supernovae.*" Although this milestone will have been superseded prior to CD-4, it nevertheless captures the frontier of the field and indicates the areas where FRIB should have a focus. The MSU team's focus encompasses both the use of fast beams to study new regions of nuclei near the limits of stability and intense reaccelerated beams for laboratory measurements of important nuclear reactions for astrophysics.

The goal of FRIB is to allow users to perform experiments with rare isotopes that answer the overarching questions presented in the NSAC 2007 LRP, which also describes the required experimental programs are described in the NSAC 2007 LRP. These programs include study of nuclei at the driplines, study of nuclei with thick neutron skins, study of the structure of the heaviest nuclei, and the determination of the equation-of-state of neutron matter. A central theme of the NSAC 2007 LRP is the role FRIB will play in guidance for the nuclear science theory roadmap that will lead to a comprehensive description of atomic nuclei.

The NSAC 2007 LRP provides a decadal outlook. Correspondingly, the pre- and short-term operation of FRIB should address all LRP goals. In the following subsections, one for each goal, we describe how the pre-, short-, mid-, and long-term goals address each of these opportunities in turn. The specific experiments, taken from the benchmarks, are intended to illustrate the scientific reach provided by the technical scope described in Section 1.a.1 and demonstrate that the corresponding goals can be reached.

We recognize that the actual experimental program will be driven by the user community, prioritized by an external program advisory committee, and guided by a collaborative process discussed in Section 1.b.2. Discoveries will likely lead to quick evolution of the program, where again, flexibility and broad capability will be important for meeting future demands.

1.a.2.1 The Force that Binds Neutrons and Protons into Stable and Rare Nuclei

FRIB will provide the key experimental input needed for developing a more complete understanding of the nuclear force that binds protons and neutrons into stable and rare isotopes. The RIA Theory Bluebook [TBB05] outlines the path towards a comprehensive description of the nuclear many-body problem across the nuclear chart that merges three approaches: *ab initio*, configuration-interaction, and density functional theories (DFT). The road map for this effort involves extension of *ab initio* approaches to the description of medium-heavy nuclei, the development of configuration-interactions in a variety of model spaces, and the quest for a universal density functional to describe all nuclei up to the heaviest elements. Special, related challenges are the description of the role of the continuum in weakly-bound nuclei, realistic models for pairing, and the development of microscopic reaction theory that is integrated with improved structure models. **Figure 1-10** summarizes how FRIB can fulfill the LRP goal.

LRP Question: What is the nature of the force that binds protons and neutrons? Science Benchmark Examples: 1, 2, 3, 13, 14, 15		
Scientific Thrusts	**Experimental Input from FRIB**	**Importance**
Ab initio models	Pre-Term: Resonance measurements in weakly-bound and unbound nuclei provide stringent test of *ab initio* methods	Coupled-cluster calculations around neutron- and proton-rich, doubly magic nuclei are constrained for extending *ab initio* to odd-mass neighbors; nuclear properties at the extremes, including beyond the neutron dripline up to A<30 provide benchmarks for the testing of this theoretical approach
	Short-Term: Detailed study of regions near new doubly magic mid-mass nuclei for connection of *ab initio* to configuration-interaction models; resonance measurements in nuclei beyond the neutron dripline over a range of orbits and shells	
	Mid–Term: Systematic study of nuclei at the boundary between *ab initio* and configuration-interaction models	
	Long-Term: Tests of new approaches and interactions as required by future developments	
Configuration-interaction theory	Pre-Term: Study of shell structure, level schemes, beta-decay properties, GT-strength distributions, single-particle spectroscopic strength, and collectivity around ^{100}Sn, ^{54}Ca, and ^{48}Ni	Experimental information is necessary input for configuration-interaction theories, which are largely constrained by data; data on the extremes of isospin provide most rigorous tests of the predictive power of fully developed microscopic models
	Short-Term: Extended program to ^{60}Ca	
	Mid-Term: Extend program to long chains of isotopes from, for example, ^{48}Ni to ^{84}Ni and ^{80}Zr to ^{120}Zr, with emphasis on cross-shell interactions	
	Long-Term: Extend program in heavier nuclei from, for example, ^{100}Sn to ^{148}Sn	
The universal energy density functional (DFT)	Pre-Term: Preparatory measurements on masses, moments, and shapes by Coulex and beta-decay studies; exploration of fusion reactions with neutron-rich beams as a path to superheavy elements	Masses, radii, moments, and deformations are testing grounds for DFT; the location of the driplines presents a benchmark for all theories; the symmetry energy connects to the isoscalar and isovector mean fields that enter DFT; spectroscopy of heavy
	Short-Term: Measure mass surface, moments, and deformations (up to A~130) and the limits of existence (A~70); continue exploration of fusion reactions with neutron-rich beams as a path to superheavy elements; measurements of the structure of heavy elements	

	Mid-Term: Constrain the symmetry energy in the EOS from neutron-skin thickness and observables in nucleus-nucleus collisions; possible first structure studies of superheavy elements	elements provides the means to extrapolate towards superheavy elements
	Long-Term: Produce and study superheavy elements with a range of neutron number; measure limits of stability up to A=100	
The role of the continuum	Pre-Term: Characterization of resonances in n-rich helium, and exotic nuclei such as ^{19}B, and ^{22}C; study reaction mechanisms involving weakly-bound systems	Necessary constraints for models that treat the particle continuum and that combine structure and reactions
	Short-Term: Studies of weakly-bound nuclei advanced significantly with new neutron skin and dripline measurements over a range of mass numbers and shells; study of resonances and low-lying structure of exotic nuclei such ^{33}F.	
	Mid-Term: Dripline studies up to A=70	
	Long-Term: Dripline studies extended to A=100	

Figure 1-10. Approach to Achieve an LRP Goal. This chart captures the importance of the experimental input (by term) from FRIB to address a scientific thrust and achieve the designated LRP goal to develop a comprehensive description of atomic nuclei.

1.a.2.1.1 Ab initio Models

The crucial observables that serve as tests for *ab initio* models will be provided by experiments performed at FRIB. An *ab initio* description of the atomic nucleus that solves the many-body problem for realistic nuclear forces is expected to have unmatched predictive power for nuclei where it is applicable [Pie01]. Coupled-cluster calculations are an *ab initio* approach to the structure of medium-heavy nuclei [Hag07a,Hor07]. Their test beds are doubly magic nuclei, and in the future, possibly their odd-mass neighbors. The relevant frontier of doubly magic nuclei opened by FRIB will include ^{60}Ca and ^{48,78}Ni, where the available beam intensity will require the use of fast-beam techniques, including ion-by-ion identified stopped beams. The other key testing ground for *ab initio* theory will be light nuclei near the driplines, where specific tests can be made to study isospin-dependent terms [Pie01,San06,Mue07].

1.a.2.1.2 Configuration-interaction Theory

Access to key new isotopes will provide the nuclear-structure input needed to develop state-of-the-art configuration-interaction theories across the nuclear shells. Typical large-scale shell-model calculations–which have provided some of the most successful, detailed microscopic descriptions of the atomic nucleus–are based on an effective interaction derived for a given model space [Bro01,Dea04,Cau05, Cau07]. Doubly magic nuclei are the cornerstones of these calculations as they define model spaces and serve as inert cores. Nearby nuclei provide some of the best tests of the validity of the effective interactions, often (and perhaps ideally) derived from a fundamental microscopic theory used in the calculations. For nuclei over the entire model space, a variety of data, particularly at the extremes of isospin, are necessary to test the model assumptions and validity of the model space.

Development of accurate configuration-interaction models for neutron-rich nuclei is of particular interest because they often provide the most accurate predictions for nuclei of importance in other applications. In astrophysical models in particular, crucial nuclear-structure input is routinely provided by configuration-interaction based shell-model calculations. Improved predictive power by the shell model translates into improved accuracy of the nucleosynthesis models.

Experimental nuclear structure data, such as binding energies, excitation level schemes, locations of single-particle and single-hole states, nuclear moments, Gamow-Teller (GT) strengths, and spectroscopic factors, are important for tests of configuration-interaction models. FRIB will provide the widest range of such studies, spanning the whole nuclear chart. Particularly important is the identification and characterization of doubly magic nuclei and the mapping of the shell structure along chains of magic nuclei to provide the most sensitive information for configuration-interaction theory. For example, detailed studies of the shell structure of the extreme neutron-rich nuclei ^{60}Ca and ^{78}Ni will be possible with knockout reactions and with event-by-event decay correlation measurements, both requiring the fast-beam capability of FRIB. Transfer reactions in inverse kinematics will be possible with reaccelerated beams on nuclei in the region of ^{132}Sn, ^{52}Ca, and ^{78}Ni, and provide more detailed information on the single-particle structure, two-, and three-body matrix elements than is now possible.

1.a.2.1.3 Universal Energy-density Functional

Nuclear data in new regions of the nuclear landscape, far from the known extent, will provide necessary data to constrain the universal energy-density functional. The goal of energy-density functional theory (DFT) is to provide a global description of the properties of nuclei across the nuclear chart [Ber07]. In condensed matter physics and computational chemistry, functionals have been developed for the Coulomb interaction and describe a variety of systems. The challenge for DFT in nuclear science is a unified description of spherical and deformed nuclei and the transition between symmetry phases. Data for the low-lying states of nuclei and binding energies over a range of N, A, and Z are necessary. In particular, those nuclei furthest from stability are the most interesting, as they constrain isospin-dependent functionals. With the fast-beam capability of FRIB, the neutron dripline can be studied up to the mass region of A~100 using the three-stage separator, which is mandatory in the regime of the smallest cross sections to efficiently suppress background events. Hundreds of precise new binding energies could be measured with stopped beams and Penning traps. Beyond the ground-state mass surface, the fission barrier mass surface will be studied by fusion and inelastic excitation over a range of fast and reaccelerated beam energies.

Ultimately, FRIB will provide the key experimental input needed to reliably extend theoretical models to the heaviest nuclei and to approach the synthesis of superheavy elements. In transactinide nuclei ($Z \geq 103$), the liquid drop fission barrier disappears, and only stabilizing shell effects explain their existence. Hence, the study of shell effects provides a fascinating window into the stability of the heaviest elements, as shown by recent first experiments (see the reviews [Hee02,Her04,Lei04]). With the reacceleration capability of FRIB and the large acceptance (ISLA) spectrometer (see Section 1.b.3), the alpha-decays and gamma-ray spectroscopy of heavy elements can be studied up to at least Z=106 by fusion-evaporation reactions induced by neutron-rich, reaccelerated beams of oxygen and fluorine on plutonium, curium, or californium targets.

Nuclear structure information for heavy elements will constrain theoretical models of the heaviest nuclei and improve their predictive power. These data will be needed in the quest for the next proton magic number, and ultimately for determining the limit of the elements. Cross sections for the fusion induced by reaccelerated neutron-rich beams will map the route toward the potential synthesis of superheavy elements.

1.a.2.1.4 The Role of the Continuum

Availability of nuclei along the neutron dripline will allow experiments that explore the effects of the particle continuum on nuclear structure and reactions, and the role of nuclei as open quantum systems. A nucleus is connected to neighboring nuclei by decays and captures; a consistent description of the interplay between scattering states, resonances, and bound states in the proximity of the nucleon separation threshold requires the atomic nucleus to be treated as an open quantum system. Shell-model approaches that incorporate the particle continuum are being developed, e.g., [Mic02,Oko03,Vol05,Vol06] and recent coupled-cluster and Greens Function Monte Carlo (GFMC) calculations have demonstrated that the continuum can be included in an *ab initio* framework [Hag07b,Nol07].

Pairing at the dripline in low-density nuclear matter and the related physics of neutron stars can be explored by total reaction cross section measurements, nucleon transfer, and di-neutron decay studies. Experiments at FRIB will provide energies, decay widths, and excitation strengths for states at and above the nucleon separation energies for light and medium-heavy nuclei to test models of the continuum in weakly-bound systems. Transfer reactions and resonant scattering induced by reaccelerated beams of weakly-bound projectiles, ^{8}He and ^{19}B, for example, will reveal the effect of the particle continuum on reaction mechanisms.

1.a.2.2 The Origin of Simple Patterns in Complex Nuclei

FRIB will extend the quest for the origin of simple patterns in complex nuclei to rare isotopes out to the limits of existence. With FRIB it will be possible to investigate how regular excitation patterns, unusual shapes and shape transitions, and pairing occur in finite systems, and how these phenomena are influenced by extreme neutron-to-proton ratios. **Figure 1-11** summarizes how FRIB can approach the scientific thrusts.

LRP Question: What is the origin of simple patterns in complex nuclei? Science Benchmark Examples: 4, 5, 14		
Scientific Thrusts	**Experimental Input from FRIB**	**Importance**
Phase-transitional behavior and exotic shapes	Pre-term: Level and decay schemes of nuclei in phase transitional regions (^{96}Kr)	Tests the persistence of critical-point symmetries for extreme N/Z and probes the emergence of exotic shapes
	Short-term: Wide range of transitional examples available for study (for example ^{156}Ba)	
	Mid-term: Systematic study of long chains of isotopes, from ^{48}Ni to ^{84}Ni and ^{80}Zr to ^{120}Zr	
	Long-term: Extension of systematic studies to heavier nuclei, e.g., tin isotopes from ^{100}Sn to ^{140}Sn	
The proton-neutron degree of freedom	Pre-term: Exploratory studies of means to measure pygmy modes and determine skin thickness in neutron-rich nuclei	Elucidates the proton-neutron degree of freedom in asymmetric nuclei to the extreme of core-skin decoupled collectivity
	Short-term: Location and decay strength of mixed-symmetry states in rare isotopes and search for pygmy-like excitation modes	
	Mid-term: Neutron-skin determination in nuclei with extreme skins	
	Long-term: Further study of skins over a range of mass number and shell structure	
Pairing	Pre-term: Cross sections of two-nucleon transfer reactions from N=Z nuclei (above ^{60}Zn) towards the neutron dripline (^{14}Be), and study of (p,t) reaction for later use	Characterizes T=0 and T=1 pairing in N=Z nuclei; quantification of pairing in low-density matter in weakly-bound nuclei; study of the role of the continuum in pairing
	Short-term: Initial study of pairing using (p,t) reactions for neutron-rich rare isotopes	
	Mid-term: Extensive mapping of pairing strength by use of two-nucleon transfer reactions	
	Long-term: Pairing in tin isotopes studied out to ^{140}Sn and for N=Z nuclei up to ^{100}Sn	

Figure 1-11. Approach to Achieve an LRP Goal. This chart captures the importance of the experimental

input (by term) from FRIB to address a scientific thrust and achieve the designated LRP goal of understanding the origin of simple patterns in complex nuclei.

1.a.2.2.1 Phase-transitional Behavior and Exotic Shapes

A much broader view of nuclear properties over a range of neutron numbers for selected elements will allow tracking the occurrence of shape phase transitions and the development of unusual shapes in nuclei far from stability. The occurrence of simple patterns (e.g., the regular sequence of single-particle levels, nuclear shapes, vibrational and rotational structures, and phase-transitional behavior), seems at first surprising in the context of the complexity of the nuclear many-body problem. However, these simple patterns are common features of mesoscopic quantum systems that include atomic clusters, quantum dots, and atomic wires [MTC07].

Nuclei have additional, unique mesoscopic features associated with the interplay of two types of fermions whose mixture can be tuned by proton-to-neutron ratio and adjusted in proximity to the continuum. Very regular excitation modes related to a specific symmetry, for example, rotation or vibration, can be isolated in one nucleus, while other observables show a smooth variation across isotopic or isotonic chains.

The quest to understand the underlying symmetries of the nuclear many-body system requires experimental data for very asymmetric neutron-to-proton ratios. The relevant energy-level schemes and excitation patterns of the spherical-to-deformed phase-transition candidates [McC05,Cas06,Cas07], ^{134}Sm and krypton isotopes with N>60, can be completed with Coulomb excitation at barrier energies using the reacceleration capability of FRIB. The level and decay scheme of the heavier spherical-to-deformed phase-transition candidate ^{156}Ba will be accessible via beta decay using the fast-beam capability at FRIB.

1.a.2.2.2 The Proton-neutron Degree of Freedom and Isovector Excitations

One of the unique features of nuclei is that they are composed of two strongly interacting, yet distinct quantum objects (protons and neutrons), unlike most other mesoscopic systems. Hence, the interplay of protons and neutrons, measured by isovector excitations, is of high interest. Isovector quadrupole and dipole excitations in the valence shell–referred to as mixed-symmetry states–emerge naturally in nuclear structure models that consider the proton-neutron degree of freedom [Pie08]. The existence of isovector-like modes is a general phenomenon in two-component systems [Hey86].

In the most neutron-rich nuclei at the fringes of the nuclear chart, neutron skins develop that lead to new, collective excitations, for example, pygmy resonances, characterized by the motion of the skin against the remainder of the nucleus. There is also the possibility of a partial decoupling of the proton and neutron fluids and resulting collective modes. For example, one may expect low-lying isovector vibrational modes of the skin neutrons.

The isovector quadrupole excitations in the valence shell, the 2^+ mixed-symmetry states, can be identified and characterized by Coulomb excitation of reaccelerated beams at barrier energies, for example, out to the heavy cerium nuclei, such as ^{156}Ce. The isovector magnetic dipole excitation in the valence shell, the 1^+ mixed-symmetry state–referred to as scissors mode in deformed nuclei–can, for example, be studied out to ^{170}Gd with Coulomb excitation at fast-beam energies where the excitation cross section for magnetic dipole modes is increased. In the FRIB short-term science program, collective properties, including the pygmy resonances, of near-dripline nuclei [Paa07] such as ^{31}F, $^{41\text{-}43}$Al, and ^{40}Mg can be probed; the neutron-skin nucleus ^{80}Ni will be in reach for fast-beam Coulomb excitation and proton scattering experiments.

1.a.2.2.3 Pairing

Study of nuclei near the driplines, neutron-rich nuclei of mid- to heavy mass, and nuclei along the N=Z line approaching ^{100}Sn will provide the necessary experimental input to gain a quantitative understanding of pairing. Generally, at low temperatures, any attractive interaction between fermions leads to pairing and superfluidity, in analogy to the Cooper pairing in superconductors. Indeed, pairing exists in finite nuclei as well. Nuclear pairing is believed to occur in the exotic nuclear matter in neutron stars and in the quark-gluon plasma in the form of color superconductivity [Dea03,Ris04,Bri05]. In nuclei, pairing correlations determine the low-lying level schemes and contribute to binding energies (odd-even staggering). In loosely-bound nuclei, pairing might serve as the decisive factor for particle stability.

The role of neutron-neutron pairing in the proximity of the particle continuum can be probed, for example, via the transfer of the two halo neutrons of ^{14}Be using reaccelerated beams and the Active Target Time Projection Chamber (AT-TPC) (see Section 1.c).

Along the N=Z line, deuteron-like proton-neutron pairing correlations (isospin T=0) are expected. The large spatial overlap of single-particle orbitals occupied by protons and neutrons in N=Z nuclei provides a unique opportunity for studying the proton-neutron interaction, and in particular proton-neutron pairing correlations. The analog T=1 pairing is well established in systems such as the stable tin isotopes where the degeneracy of the neutron orbits is high. The corresponding region for T=0 pairing along the N=Z line is from ^{56}Ni to ^{100}Sn. For T=0 pairing, (^{3}He,p) transfer reactions may provide valuable new information from proton-neutron pair transfer cross sections, in analogy to (p,t) studies for T=1 pairing. With FRIB, the proton-neutron pair transfer reactions will be possible with reaccelerated beams of ^{56}Ni to ^{72}Kr.

The persistence of nuclear T=1 pairing with increasing proton/neutron asymmetry can be studied by (p,t) reactions with reaccelerated beams in long chains of isotopes ranging from ^{104}Sn to ^{146}Sn, and similarly in calcium and nickel isotopes.

1.a.2.3 The Nature of Neutron Stars and Dense Matter

Study of key rare isotopes will help clarify the nature of neutron stars and dense matter by providing nuclear data for the development of reliable models connecting neutron-star observations to neutron-star properties. Astrophysical models make the connection between astronomical observatories, such as CHANDRA, and neutron-star properties (mass, radius, and interior composition). Reliable models require, in turn, accurate knowledge of the nuclear reactions that occur in the neutron-star crust, and the equation of state of neutron-rich matter. A key goal of FRIB is to experimentally constrain nuclear input for astrophysical models and hence provide insights into neutron-star properties. A related goal is to find explanations for phenomena such as puzzling variations in the frequency of X-ray bursts, X-ray superbursts, apparent non-standard cooling behavior, oscillations occurring during X-ray bursts and soft gamma-ray repeaters, and quiescent X-ray emission from transiently accreting neutron stars (see [Pag06] for a review). **Figure 1-12** summarizes how FRIB can fulfill this LRP goal.

LRP Question: What is the nature of neutron stars and dense matter?
Science Benchmark Examples: 3, 6, 13

Scientific Thrusts	**Experimental Input from FRIB**	**Importance**
EOS and symmetry energy	Pre-term: Development of tools to study EOS in supra-nuclear densities, including pion production, particle emission and flow	The EOS, in particular the symmetry energy, determines the relation between mass and radius, interior composition, and neutron star seismology, as well as cooling behavior
	Short-term: First constraints on EOS and symmetry energy term at various densities and temperatures from nucleus-nucleus collisions and from measurements of neutron-skin thicknesses	
	Mid-term: Systematic studies over a range of collisions and asymmetries to develop firm constraints on EOS and symmetry energy term; skin thickness determined in a nucleus with extreme skins greater than 0.5 fm	
	Long-term: Complete measurements on a range of nuclei with extreme skins; connect EOS measurements to measurements at relativistic energies	
Nuclear processes in the crust	Pre-term: Develop tools for mass and charge-exchange measurements with first data available	Nuclear processes in the crust set the thermal structure and directly affect observables (superbursts, thermal
	Short-term: Measure GT-strengths and determine the location of the	

	neutron dripline up to A~70	luminosities, cooling behavior in transients); dripline is crucial as it limits the EC chains
	Mid-term: Map mass surface and complete representative series of GT measurements to constrain relevant nuclear-structure models	
	Long-term: Determine the location of the dripline up to A~100	

Figure 1-12. Approach to Achieve an LRP Goal. This chart captures the importance of the experimental input (by term) from FRIB to address a scientific thrust and achieve the designated LRP goal of understanding neutron stars.

1.a.2.3.1 EOS and Symmetry Energy

The structure and evolution of neutron stars is largely determined by the equation of state (EOS) at high densities and low temperatures [Lat01,Ste05,Pag06], which is a fundamental property of nuclear matter. Access to key isotopes will enable experiments that directly probe terms in the nuclear-matter equation of state that depend on neutron-proton asymmetry. These terms create a symmetry energy that governs the relationship between mass and radius. It also determines the proton fraction in the core.

With neutron- and proton-rich beams, the density and momentum dependence of the symmetry energy can be mapped at various densities and temperatures using the AT-TPC by studying high-energy nucleus-nucleus (NN) collisions–^{35,52}Ca and ^{102,132}Sn beams on stable calcium and tin targets at energies up to 200MeV/u. Ratios of charged pions measured with the AT-TPC will reveal features of the symmetry energy at high density. Measured spectral ratios of mirror pairs–e.g., ^{3}H to ^{3}He, or neutrons to protons–probe the proton and neutron effective masses in asymmetric matter. The neutron-skin thickness of heavy, neutron-rich nuclei poses a unique observable to constrain the stiffness of the symmetry energy of the EOS (see, for example, [Yos04a,Bro00]). With FRIB, charge radii in neutron-rich calcium and nickel isotopes (out to perhaps ^{58}Ca and ^{80}Ni) can be measured with laser spectroscopy, and the RMS-neutron radius of heavy neutron-rich nickel isotopes can be quantified out to ^{82}Ni from interaction cross-section measurements. Proton scattering experiments for the extraction of matter and charge radii [Amo06] require only one particle/s intensity at 100-200 MeV/u. Fast-beam charge-exchange reactions, which allow for a measurement of the neutron-skin thickness [Kra99,Vre03,Yak06,Paa07], will be possible at FRIB out to ^{216}Pb and can be calibrated with the neutron-skin measurement of ^{208}Pb [Hor01] proposed at JLab [PRX08].

1.a.2.3.2 Nuclear Processes in the Crust

Experiments at FRIB will provide an understanding of the nuclear processes in the crust of accreting neutron stars. Nuclear processes involving very neutron-rich nuclei are the heat sources that set the thermal structure of the crust. They therefore directly affect a number of observables, for example, X-ray burst light curves of superbursts, thermal luminosity, and the cooling behavior in transients, once accretion turns off. The critical nuclear physics data for models of the crust processes are masses, electron capture (EC) rates, and transition schemes for nuclei with $20 \leq A \leq 104$ ranging from stability to the neutron dripline [Gup07]. The location of the neutron dripline is of particular importance as it sets the depth where neutrons are released. Highly sensitive measurements with fast beams and three-stage separation will delineate the location of the neutron dripline up to A~100, essentially covering the relevant mass range for neutron-star crust processes. At FRIB, fast-beam, inverse kinematics charge-exchange reactions–(p,n), (^{7}Li, ^{7}Be) and (d, ^{2}He)–induced on neutron-rich nuclei will provide the crucial information on electron capture strengths out to ^{82}Ge and ^{102}Zr, for example. Further away from stability, measurements of the low-lying level structure with beta-decay spectroscopy will further constrain electron capture rates predicted by theory.

1.a.2.4 The Origin of the Elements in the Cosmos

Measurement of key nuclear properties of nuclei that are involved in nucleosynthesis will help clarify the origin of the elements in the cosmos by aiding in the development of reliable (and quantifiable) astrophysical models. Nuclear reactions in stars and stellar explosions are responsible for the ongoing synthesis of the elements;

nuclear physics determines the signatures of isotopic and elemental abundances found in the spectra of stars, novae, supernovae, and X-ray bursts, in characteristic gamma-ray radiation from nuclear decay, or in the composition of meteorites and presolar grains (see [Gra07] for a review of the nuclear structure input to nuclear astrophysics). FRIB, along with advances in observational astronomy and astrophysical modeling, will be necessary to determine the origin and evolution of chemical abundances in the universe. **Figure 1-13** summarizes how FRIB can fulfill the LRP goal.

LRP Question: What is the origin of the elements in the cosmos?
Science Benchmark Examples: 1, 7, 9, 15

Scientific Thrusts	**Experimental Input from FRIB**	**Importance**
r–Process and its Site	Pre-term: Half-lives of nuclides along the N=50 and N=82 closed shells important to the r-process	Masses and beta decay properties determine path, time scale and abundance pattern of the r-process. Fission rates and fragment distributions are important for the termination of the r-process, and for the abundance of long-lived actinides; may impact A~90 and A~130 abundances via fission cycling.
	Short-term: Key data for a quantitative understanding of r-process nucleosynthesis up to A~195; first measurements at N=126; begin fission barrier measurements in near-stability nuclei	
	Mid-term: Complete data, such as masses, half-lives, and reaction rates for a quantitative understanding of stellar nucleosynthesis up to A~195 for the r-process; systematic measurement of fission barriers to constrain models of fission barriers for r-process nuclei	
	Long-term: Quantitative understanding of the r-process beyond A~195	
p–Process	Pre-term: Locate resonances, direct and indirect measurement of capture rates	Resonance energies and capture rates constrain the p-process so that nuances like seed abundances and additional sites can be explored.
	Short-term: Determine key reaction rates	
s–Process	Pre-term: Develop techniques for harvesting isotopes, e.g., ^{59}Fe, for offsite direct neutron-capture measurements	Constrain s-process models to separate s- and r-process contributions from observed abundances; understand mixing in AGB stars; determine seed of the p-process.
	Short-term: Many examples of key s-process branch-point nuclei available for study; ^{59}Fe if it remains unknown	
Nova nucleosynthesis	Pre-term: Mapping the resonances important for proton-capture reactions; direct measurements of some capture rates, e.g., ^{30}P	Put nucleosynthesis modeling in novae on a solid footing; shed light on the galactic inventory of gamma-ray nuclides.
	Short-term: Address remaining uncertainties in nuclear data for models by measurement of important rates, including ones difficult to do at ISOL facilities, $^{27}\text{Si}(p,\gamma)$, $^{29,30}\text{P}(p,\gamma)$, and $^{31}\text{S}(p,\gamma)$	

Figure 1-13. Approach to Achieve an LRP Goal. Importance of the experimental input (by term) from FRIB to address a scientific thrust and achieve the designated LRP goal of finding the origin of elements.

1.a.2.4.1 r–Process and its Site

The ability to produce, for the first time in the laboratory, many of the nuclei that are thought to be involved in the r-process, will provide the experimental input needed to quantitatively model the r-process. This will lead, ultimately, to the identification of the site of the r-process and to interpretation of the accumulating astronomical observations on the chemical history of the galaxy [Cow91, Qia03]. Because of the linac's power and associated reach, FRIB will be the best facility in the world for creating and studying r-process nuclei. At present, parameterized models cannot be tested rigorously against observational data due to the lack of understanding of the physics of extremely neutron-rich nuclei.

Measurements at FRIB can fill most of the gaps. Masses and beta-decay properties of critical neutron-rich nuclei beyond A~195, in particular near the key waiting-points at N=82 and N=126 will be measured. At FRIB, the beta-decay studies are possible with the fast-beam event-by-event correlation capability of the beta counting system (BCS). High-precision Penning-trap and sensitive time-of-flight (TOF) mass measurements (e.g., out to ^{124}Mo) will provide the needed neutron-separation energies. r-process capture rates will be indirectly inferred from (d,p) transfer reactions with reaccelerated beams or decelerated fast beams, for example, approaching ^{130}Cd, using the AT-TPC or HiRA and S800 spectrograph, respectively. Fission likely influences the termination of the r-process, and might modify the abundances of long-lived actinides. Fission cycling can also impact the abundances of nuclei in the regions near A~90 and 130. Although the fissile nuclei directly involved in the r-process cannot be accessed, measurements of fission barriers using fast beams and the AT-TPC in nuclei closer to stability will provide an empirical basis for improved extrapolations of ground state and fission saddle-point binding energies for the heavy r-process nuclei that remain out of reach even at FRIB.

1.a.2.4.2 p–Process

It will be possible to produce all key isotopes and provide the experimental input needed to model the p-process [Rap06]. The p-process, thought of as a process involving (γ,n), (γ,p), and (γ,α) reactions, is responsible for the origin of the most proton-rich stable nuclei in nature from selenium to mercury [Arn03]. Many of the important reaction rates, in particular the (γ,α) chains that drive matter from heavy nuclei towards lighter species, involve unstable nuclei. With FRIB, reaccelerated beams at astrophysical energies become available for most of the p-process path.

1.a.2.4.3 s–Process

Although the s-process proceeds near stability, many capture reactions occur on long-lived radioactive isotopes with radioactive decay rates comparable to (n,γ) rates (see [Her05] for a review). Some of the relevant rates for s-process modeling will likely remain unmeasured at the time FRIB becomes operational.

The benchmark related to the s-process is the determination of the ^{59}Fe(n,γ)^{60}Fe reaction rate. This rate is also important as a diagnostic of supernovae, because ^{60}Fe is one of the three detected gamma-ray nuclides in astronomy [Die06]. For all s-process nuclei, the key is to measure the relevant neutron-capture processes by (n,γ) measurements on radioactive samples. The isotope ^{59}Fe will be produced at quantities higher than at any other rare-isotope facility, and pure samples can be obtained from the harvesting station attached to the three-stage separator. If it is still of interest at that time, FRIB will produce the largest samples of ^{59}Fe and the direct neutron capture can then be measured at a neutron-beam facility elsewhere.

1.a.2.4.4 Nova Nucleosynthesis

High intensities of all key nuclei involved in novae nucleosynthesis will enable an interpretation of observed elemental abundance patterns, and permit a search for signatures of the astrophysical processes that drive nova explosions on the surface of accreting white dwarfs. A better understanding of novae and accreting white dwarf systems in general also relates to the problem of the progenitors of type Ia supernova and their reliability as standard candles. Novae are possible contributors to the galactic inventory of ^{26}Al, which–once its sources are understood–can be used as an indicator of the galactic supernova rate, a fundamental parameter for the understanding of the chemical evolution of the galaxy. Novae are the likely producers of copious amounts of the gamma-ray emitters ^{18}F and ^{22}Na, and may host a weak rp-process (see [Ale04,Cha92,Wie98,Ili02]).

Many of the nuclear reactions important for understanding novae nucleosynthesis will be studied at ISOL facilities prior to FRIB operation. However, there may likely be key reactions that can only be studied using the reaccelerated beam techniques available at FRIB. Completion of the full reaction network will be the step leading to significant discoveries. Possible remaining examples are: ^{27}Si(p,γ), ^{29,30}P(p,γ), and ^{31}S(p,γ).

1.a.2.5 How Stars Generate Energy and Explode

Astrophysically important nuclear processes, studied in the laboratory, will enable scientists to answer the question of how energy is generated in stars and stellar explosions. Laboratory experiments provide the nuclear physics input needed to understand the driving forces behind X-ray bursts, superbursts, and explosive scenarios. X-ray bursts provide a unique window into the physics of neutron stars. They are the most frequent thermonuclear explosions known. The brightness, frequency, and opportunity to be observed with different telescopes make them a unique laboratory for explosive nuclear burning at extreme temperatures and densities [Str03,Sch06a]. **Figure 1-14** shows how FRIB will fulfill the LRP goal.

LRP Question: How do stars generate energy and explode? Science Benchmark Examples: 8, 9, 16, 17		
Scientific Thrusts	**Experimental Input from FRIB**	**Importance**
rp- and αp-process in X-ray bursts, superbursts, and explosive scenarios	Pre-term: Measure first direct reaction rates for rp-process	Reliable models of the rp- and αp-process are needed to understand the variety of observed X-ray burst light curves, and to reliably calculate the composition of burst ashes (prerequisite to understand any processes occurring deeper in the crust of neutron stars)
	Short-term: Measure masses, half-lives, location of resonance states and direct and indirect (α,γ), (p,γ), (p,α), (γ,p) reaction-rates; add significant constraints on ^{15}O(α,γ) from indirect studies	
	Mid-term: Determine all relevant nuclear physics data, including a direct measurement of ^{15}O(α,γ)	
	Long-term: Model X-ray bursts and superbursts	
Nuclear processes driving supernovae	Pre-term: Develop weak interaction program in inverse kinematics	Provides crucial Electron Capture (EC) rates and benchmarks predictive power of models for weak-interaction rates (shell model calculations with predictive power are necessary input)
	Short-term: Measure GT strengths with charge-exchange reactions in the fp- and gds-shells	
	Mid-term: Establish weak interaction rates for nuclei relevant to supernovae	
	Long-term: Complete long-duration measurements on the cases furthest from stability to provide tests of newly developed models	

Figure 1-14. Approach to Achieve an LRP Goal. This chart captures the importance of the experimental input (by term) from FRIB to address a scientific thrust and achieve the designated LRP goal of building astrophysical models based on firm nuclear data.

1.a.2.5.1 rp- and αp-Process in X-ray Bursts, Superbursts and Explosive Scenarios

The reaction sequence during an X-ray burst proceeds through nuclei at or close to the proton dripline mainly by (p,γ) and (α,p) reactions and by beta decays (rp- and αp-process) [Wal81]. It was recently proposed that neutrino-driven winds off forming neutron stars provide another proton-rich environment favorable for an rp-process. Resulting neutrino interactions generate neutrons, and the associated neutron-induced reactions can bridge the major nucleosynthesis waiting points [Fro05]. This so-called νp-process is an alternative explanation for the unexpected observations of neutron-deficient molybdenum and ruthenium nuclei in the solar system.

Most rp-process reaction rates are still based exclusively on theory. Masses, half-lives and reaction rates for (p,α)) and (α,p) reactions on proton-rich nuclei are important [Sch06b]. With FRIB, nearly all rp-process nuclei will be within reach for precision Penning-trap mass measurements. This includes the heaviest relevant neutron-deficient nuclei around and just below ^{100}Sn, which are also relevant for the νp-process. Direct reaction-rate measurements at astrophysical energies using reaccelerated rare-isotope beams will be possible at FRIB for most of the relevant reaction rates in X-ray bursts. For example, the proton capture rates on ^{64}Ge, ^{65}As, ^{68}Se, and

^{72}Kr can be determined. FRIB can deliver beams of elements not readily available at ISOL-only facilities, and therefore study the full range of important reactions.

In particular, an experimental verification of low-energy resonance parameters in the ^{15}O(α,γ) reaction is urgently needed [Fis06,Coo06]. This reaction has been shown to be of fundamental importance in shaping the burst behavior of accreting neutron stars. With FRIB, ^{15}O(α,α') inverse-kinematics resonant scattering experiments can be performed with a reaccelerated beam of ^{15}O. Using an efficient solid catching and release scheme, the projected intensity of ^{15}O is greater than 10^{10}/s . This level is sufficient for a direct measurement of ^{15}O(α,γ).

1.a.2.5.2 Nuclear Processes Driving Supernovae

Study of rare isotopes can provide the nuclear physics input for supernova models. Core-collapse supernovae play a crucial role in the understanding of the universe; they are the major source of nucleosynthesis and possibly of cosmic rays. The majority of elements in the universe–likely including the heavy elements made in the r-process–originate from core-collapse supernovae [Woo05].

Thermonuclear supernovae (type Ia) are powered by explosive carbon and oxygen burning of an accreting white dwarf that has reached the Chandrasekhar mass limit. They produce half of the iron-group elements in the universe, and are crucial standard candles for determining the equation of state of dark energy [Lei01].

The driving processes for both types of supernovae are poorly understood, but weak interaction processes play a key role. Temperatures and densities are so high that EC and beta decay involving unstable nuclei become crucial. Hundreds of EC rates in the *fp*- and *gds*- shells are important physics ingredients in supernova models and are largely provided by shell model [Heg01,Hix03] and quasiparticle random phase approximations (QRPA) [Mol90] calculations. Practically, no experimental data exist for weak interaction rates on unstable nuclei to validate the predictive power of the theoretical approaches with respect to weak interaction strengths [Ost92,Col06]. With the fast-beam capability and the high-resolution S800 spectrograph at FRIB, important Gamow-Teller strengths over the full range of relevant nuclei will be measured by charge-exchange reactions. These measurements will complement studies at FAIR, where nuclei closer to stability can be studied by measurements in storage rings.

1.a.2.6 Fundamental Symmetries and Search for the Ingredients of the New Standard Model

Rare isotopes can be used to test the fundamental symmetries and search for the ingredients of the New Standard Model [INT07]. Use of isotopes from FRIB will allow tests of parity and time reversal symmetries.

The charge conjugation parity inversion time reversal (CPT) theorem requires invariance under the combined application of three independent operations: charge conjugation (C), parity inversion (P), and time reversal (T). CP violation is thought to have played a crucial role in producing the excess of matter over antimatter in the universe [Din04]. The determination of electric dipole moments (EDM), which violate parity and time-reversal invariance, is one of the crucial steps to pinpoint physics beyond the Standard Model [Pos05]. The EDM of diamagnetic atoms is induced by the interaction of the electrons with the nuclear Schiff moment. An enhancement of order 100-1000 is possible in nuclei with octupole deformation [Aue96, Spe97] or soft octupole vibrations [Eng00, Fla03]. Prior to the long-term program required for a measurement program, it is critical to identify the best candidates. At FRIB, octupole deformation and octupole vibrations can be identified and probed with Coulomb excitation of reaccelerated beams of ^{223}Ra, ^{225}Ra, and ^{229}Pa, for example. The EDM of ^{229}Pa is calculated to exceed the EDM of ^{225}Ra by a factor of 40 [Fla08], and may become a prime candidate for an EDM measurement in the future.

Parity non-conservation (PNC) in atomic systems provides a powerful constraint on extensions to the Standard Model. The isotopes produced at FRIB would allow an improved measurement of PNC effects in atomic systems and a determination of the weak charge, Q_w, of the nucleus. In atoms, PNC observables are proportional to Q_w times an atomic structure function that depends upon the rms radius of neutrons in the nucleus. Determination of this structure function limits the accuracy of the determination of Q_w. The uncertainty from atomic calculations can be greatly reduced by using ratios of PNC observables in a series of isotopes–but this method requires a precise knowledge of the isotopic dependence of the neutron skin [Dzu86]. Experiments at FRIB will be able to measure the isotopic dependence of the neutron skin that will test energy density functional model predictions [Bro08]. PNC ratios with isotopes of cesium, barium, and dysprosium in atomic traps will be an order of magnitude more sensitive to new physics than the current measurements of the proton Q_w [You07].

1.a.2.7 Isotopes for Applications for Societal Needs

FRIB will provide isotopes for application in a variety of fields, ranging from human health to stockpile stewardship. The harvesting station attached to the three-stage separator at FRIB will allow for the harvesting of separated isotopes for applications either in a parasitic mode or as a dedicated experiment. For example, ^{149}Tb, which has been proposed for targeted alpha therapy in the battle against many metastatic cancers [All96,All99,Bey04,Bre07], can be harvested at FRIB for research studies. This isotope, ^{149}Tb, and perhaps likewise ^{211}At, are of interest because their low alpha-decay energy allows only nearby cells to be targeted. Research quantities of isotopes such as ^{86}Y, ^{89}Zr, and ^{124}I will be available for imaging studies and development of applications.

A strong U.S. stockpile stewardship program is important for the determination of the safety of the U.S. nuclear weapons inventory without a resumption of nuclear testing. The rare isotopes ^{88,89}Zr and ^{78}Br, for example, can be harvested at FRIB. Samples can be post-processed for high purity using existing shielded facilities on the MSU campus (Radiology Department).

The MSU campus infrastructure and the proximity to radiology, veterinary medicine, and agricultural departments that routinely use radioisotopes for research are a particular benefit to FRIB users and will result in interdisciplinary synergies from day one.

1.b User Research Community and Collaborations

FRIB will support DOE's Strategic Plan and the *Scientific Discovery and Innovation Strategic Goals* by providing broad opportunities for world-leading scientific research. This allows the nation's scientific user community to "achieve the major scientific discoveries that will drive U.S. competitiveness, inspire America, and revolutionize approaches to the Nation's energy, national security, and environmental quality challenges" [DSP06]. Leveraging NSCL's wide range of equipment enables experimental opportunities which encourage and support user research projects and lead to a broad research program.

For more than 40 years, MSU has been fully committed to nuclear physics research as a significant component of our role as a major research university. MSU and NSCL have a proven track record of collaboration and integration with the national and international user community and are recognized for providing superb facility and user services. Users conducting rare-isotope research at NSCL have rated their satisfaction above 94%. By extending our track record of attracting the best and most relevant research projects and users, MSU will continue to encourage and support a strong user community.

MSU will leverage an already strong relationship with the global nuclear science user community to further develop a broad national and international program. MSU capitalizes on its international prominence as evidenced by users from 203 institutions within 30 countries. We will develop a strong relationship with the current RIA Users Organization, facilitate its transformation to the FRIB Users Organization, and support their activities.

Locating FRIB on the university campus will provide an open and stimulating environment for collaboration, both within and across disciplines, that extends well beyond the campus through an expanding network of relationships. This will be particularly beneficial to the international community of users, with its open access to MSU and MSU's demonstrated support and infrastructure for international visitors.

1.b.1 Plans for External Input and Guidance for the Scientific and Technical Development of FRIB

MSU recognizes the importance of user input for FRIB project definition. Upon award, MSU will capitalize on existing user groups to facilitate involvement that ensures that the optimum facility will be built for enabling world-leading science on day one of operations.

MSU has a tradition of engaging the science and user communities in the planning of future facilities. The conceptual ideas that are the foundation of the MSU approach to FRIB were developed in collaboration with national and international scientists. As mentioned at the beginning of Section 1, the "Isotope Science Facility at Michigan State University" document [ISF06] had over 120 external contributors and was widely supported by the nuclear science community.

Figure 1-15 presents an overview of external input and guidance for the scientific development of FRIB at MSU. The role of each office or group represented in the figure is discussed in the identified subsections.

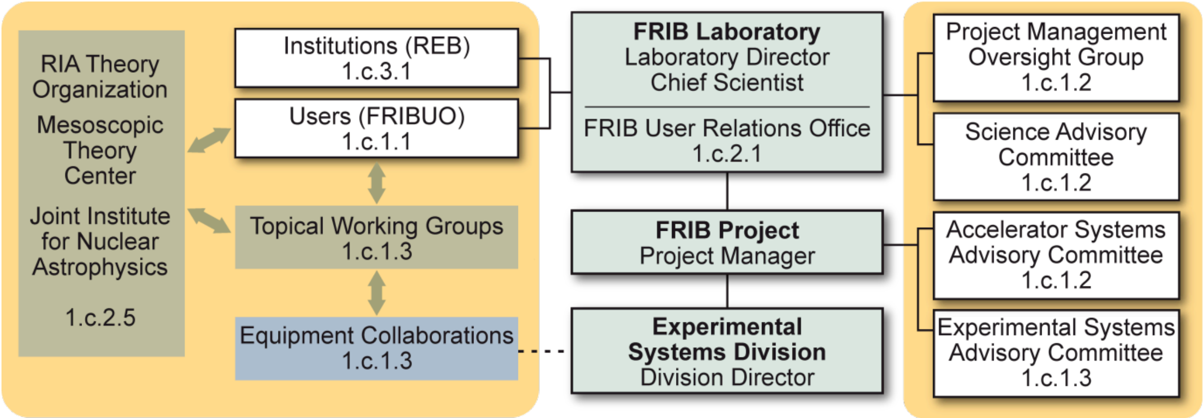


Figure 1-15. The User-integrated Approach to FRIB. *MSU will use a simple process for collaborations. The process encourages input from the external scientific community (represented in the highlighted background area) to the FRIB Director's Office and the Project Manager. In the above example, after considering advice from the SAC, the equipment input flows logically down to the FRIB Project Office and is implemented by the Experimental Systems Division. Feedback is provided at all stages.*

1.b.1.1 Facility for Rare Isotope Beams Users Organization (FRIBUO)

MSU will support the transition of the existing RIAUO into the new FRIB Users Organization (FRIBUO). A vibrant and independent FRIBUO is essential to realizing the FRIB vision of a world-leading center for rare-isotope science. FRIBUO will be comprised of individual scientists from around the world who have a scientific stake in FRIB. MSU will work with the FRIBUO to keep the user community informed and engaged, which includes seeking input and guidance on the scientific and technical development of FRIB. MSU will support and maintain FRIBUO by:

- Organizing and supporting annual meetings and funding topical workshops
- Fund yearly travel of the FRIBUO executive committee members to the FRIB site
- Arranging monthly phone conferences (and occasional video conferences) with the FRIBUO executive committee and FRIB management
- Supporting FRIBUO elections
- Supporting the dissemination of information to users

MSU's experience in growing and supporting an active user group at NSCL (which has more than 700 members) is a key component for effective relationship support and communication with FRIBUO. MSU is in the unique position to build on the valuable relationships that are established within the large NSCL user group. Members of FRIBUO will be able to perform experiments at NSCL and become NSCL users. As discussed in Section 1.a.1.1 and 1.c, the users can start in the pre-term to develop new equipment and work with NSCL's extant suite of equipment to perform world-class experiments with fast, stopped, and reaccelerated beams. The continuous improvements and the new addition of the reacceleration capabilities at NSCL will further enhance the experience of the users. At the beginning of operations, the NSCL user group will merge with the FRIBUO.

NSCL's unique pre-term features benefit users by offering:

- User-vetted input for consideration during FRIB construction, fostering community buy-in
- Cost savings related to equipment and facilities
- A growing suite of cutting-edge equipment that enables users to do excellent science and generates broad user community interest early in the program

The FRIB Laboratory Director and Chief Scientist make it a priority to actively interact with the user community. The Chief Scientist will take an active role in engaging the different user groups identified in Figure 1-15. Especially noteworthy is the Chief Scientist's dedicated interaction with FRIBUO to solicit user input that can be acted upon to improve FRIB science opportunities and FRIBUO relations.

1.b.1.2 Science and Technical Advisory Committees

The Science Advisory Committee (SAC) consists of external advisors who provide guidance and advice to the FRIB Director and Chief Scientist on scientific choices, scientific vision, and balance to optimally realize the discovery potential of FRIB. The SAC also advises on matters related to user access, support, and integration (Figure 1-15). A FRIBUO representative (normally the chair of the FRIBUO Executive Committee) will be an ex-officio member of the SAC. The SAC fulfills the role of the Program Advisory Committee (PAC) identified in the NSAC RIB TF Report.

External guidance and oversight of technical issues will be provided by the Project Management Oversight Group who will advise the FRIB director, and the Accelerator Systems Advisory Committee who will advise the FRIB project manager.

1.b.1.3 User Input in Developing Experimental Equipment

In order to execute a science program with a reach to the 17 benchmarks on day one of operations (see Section 1.a), it is highly desirable that the larger experimental setups be designed, built and tested prior to CD-4. The devices that should be available at FRIB start-up were identified by the user community during the last few years at two workshops on experimental equipment [EER03,RFW04] held at ORNL and MSU. Initial groups have already been formed and are designing experimental devices related to FRIB science. **Figure 1-16** illustrates the strong connection between MSU and the user community. It lists the collaborating institutions on joint proposals for FRIB related science.

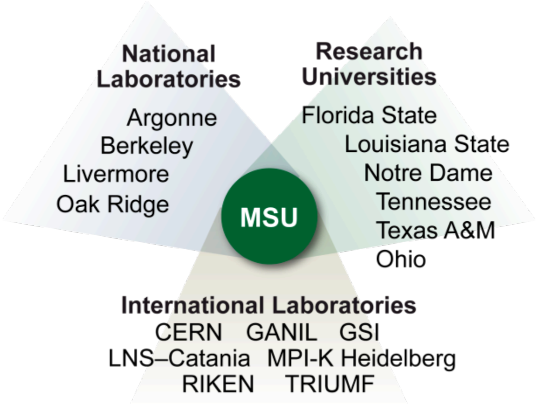


Figure 1-16. Institutions Collaborating with MSU on Joint Proposals for FOA, DE-PS02-08ER08-10, "Research Opportunities at Rare Isotope Beam Facilities" [FOA08]. *MSU has formed strong collaborations with major national and international institutions to design and build equipment relevant to FRIB. The institutions shown in the figure have submitted joint preproposals with MSU to FOA, DE‑PS02‑08ER08‑10.*

FRIB will build on and appropriately strengthen this approach by engaging users in defining and articulating emerging scientific opportunities and needs, while fostering effective collaborations to design and build the most relevant and powerful new experimental instruments. The Chief Scientist will organize topical workshops with input and advice from the Rare Isotope Research and Education Board (REB) (see Sections 1.b.3.1 and 3.b.1.2) and the FRIBUO. The FRIBUO will initiate the formation of strong user collaborations and working groups that will articulate and communicate user needs, and develop and refine new experimental concepts.

Equipment concepts developed by collaborations will be vetted and prioritized by the SAC. After funding is secured, collaboration will interface with the Experimental Systems Division to complete, install and commission equipment. Figure 1-15, captures an overview of the user-integrated approach to build equipment for FRIB, which takes advantage of strong, effective communications.

MSU will bring its extensive experience and expertise in design, construction, and integration of the equipment to FRIB. MSU understands that different sizes and complexities of the devices require different approaches for integration into the facility. The Division Director for Experimental Systems will monitor cost and schedule with guidance from the Experimental Systems Advisory Committee. He/she will appoint appropriate technical review committees that will conduct in-depth reviews on a regular basis; he/she is ultimately responsible for integration of experimental equipment into FRIB.

1.b.2 Encouraging and Supporting Research Projects and Users

As outlined in the previous section, we understand that the scientific agenda and equipment development will be driven by the FRIB users. During the construction phase, users will have the opportunity to design, build, install, and test equipment in conjunction with FRIB pre-term operation at NSCL. The ability to use NSCL prior to FRIB operations will be invaluable for seeding, establishing, and fine-tuning new experimental techniques and science programs. This early start will strongly encourage user participation in FRIB and support their research projects by providing experimental results to form the basis of publications and thesis projects prior to CD-4.

The result will be that by the time FRIB operations begin, MSU's management team will already have in place an established, sound, and experienced group of FRIB users. Our first-hand experience operating NSCL as a rare-isotope research facility with a strong user group commitment demonstrates our ability to encourage and support research projects that can grow a strong user community.

1.b.2.1 FRIB User Relations Office

At the beginning of the project, a FRIB User Relations Office will be created to conduct activities under the best practices outlined in Section 1.b.2.3. This office will evolve from the NSCL Department for User Relations and will report to the Chief Scientist. The User Relations Office will have the staff and resources to provide a broad range of administrative services to users. The intent is to allow the users to concentrate on research and not be distracted by logistical (such as travel and housing) concerns. The Users Relations Office will help coordinate local transportation and hotel arrangements, as well as assist with other administrative and logistics functions.

The office will be a source of information and point of contact to help users gain access to NSCL/FRIB technical services and MSU campus infrastructure, services, or amenities. MSU will make available on a non-discriminatory basis (comparable to MSU students and employees), housing, food services, recreational facilities, cultural events, the library, new state-of-the-art fiber optics infrastructure, and the MSU high-performance computing facility.

1.b.2.2 Users' Equipment Support

Users who are building equipment as part of the FRIB scope or are selected by the SAC and FRIB management to contribute equipment to the project, will interface with the Experimental Systems Division (ESD). The main goal is to ensure that the equipment interfaces properly into the FRIB system and meets safety requirements. The division will also support users with matrixed resources from the FRIB project and NSCL as needed and allocated by the ESD Director.

1.b.2.3 FRIB Use of Established Best Practices

The MSU team's experience and existing use of best practices provide a proven approach to ensure FRIB is available to the science community. Our approach takes advantage of the ReA3 reaccelerator project in 2010 by starting experimentation with reaccelerated beams of rare isotopes prior to FRIB operations (FRIB pre-term goals are discussed in Section 1.a.1.1). The NSCL user community has expressed great interest in this new capability and approached NSCL management with regard to their emerging needs. MSU in turn responded to the users' requests for more experimental space by providing a new 11,140 sq ft experimental area to house user devices.

NSCL operations has a history of user-focused and success-oriented performance. The technically complex NSCL facility has operated above its 90% availability performance rating over the last four years, contributing to overwhelmingly positive customer feedback. As the only ISO-9001 registered rare-isotope laboratory, MSU will build upon best practices to establish and manage a culture of continued quality improvements to the benefit of the scientific user community.

We will also implement new practices to ensure full and open access to rare-isotope research. The experienced staff of FRIB, coupled with proven processes, will have a significant and positive impact in engaging, attracting, and supporting users and enabling them to conduct their research effectively and successfully. Remote viewing capabilities for onsite and offsite users will be installed to display the up-to-date operating status of the facility. Remote participation in experiments, seminars, and workshops will be offered to all users. MSU will leverage a web-based communications system that promotes a collaborative approach to managing the information required to build and operate the FRIB.

As a large research university and the host of a world-class user facility, MSU appreciates the need to encourage interactions among FRIB users. The new office addition includes a new, enlarged collaboration space designed to bring researchers together in an informal, comfortable environment as shown in **Figure 1-17**.

Figure 1-17. New FRIB User Collaboration Space. *MSU will create a new, enlarged collaboration space where users can brainstorm with their peers.*

1.b.2.4 Visiting Scientist Program

MSU will fund a visiting scientist program to support researchers from universities and other laboratories for long-term (6-12 months) stays at FRIB similar to the program at JLab [JSA08]. This will be especially useful during the commissioning of equipment before and during start-up of the facility. The program will support up to six simultaneous visitors.

1.b.2.5 Theoretical and Astrophysical Collaboration

The successful research programs of users will interface with nuclear theory, and in some cases with the astrophysics community. MSU will encourage these interactions. FRIB will benefit by the co-location of FRIB and the Joint Institute for Nuclear Astrophysics (JINA) at MSU [JIN08], which is an NSF-funded Physics Frontiers Center designed to stimulate collaboration between nuclear scientists and astronomers. The collaboration initiated by JINA between FRIB users and the astrophysics modeling community will benefit research programs aimed at improving astrophysics models. A similar benefit will be available by interaction with the Mesoscopic Science Center located at NSCL and supported by MSU [MTC07]. This center plays a role similar to JINA, but aims to connect experimental nuclear physics with the nuclear modeling community and related work in chemistry and condensed matter physics.

MSU will also encourage the activities of the RIA Theory Organization (RIATO) [RTG02] and offers to support their activities. The RIA Theory Organization is a group of over 140 scientists that was formed following the 2002 Fall DNP meeting held at Michigan State University. The primary purpose of RIATO is to organize the nuclear theory community interested in FRIB physics.

1.b.3 Developing and Maintaining a Program of Broad National and International Collaboration of Interest to FRIB and DOE

FRIB will be a center that draws the best scientists and students from around the world because it will enable world-unique experiments that will help answer fundamental questions about the atomic nucleus and the cosmos. MSU's leadership approach will ensure that the best science will be performed by capitalizing on our past experience and success, as demonstrated throughout this section. As discussed in Section 1.a, the ability to provide unique experimentation opportunities to achieve the 17 benchmarks will be the most effective way to attract broad national and international collaborations to FRIB.

The integrated approach will also achieve the broader DOE goals to include Goal 3.2, “Foundations of Science,” of the 2006 DOE Strategic Plan to “Deliver the scientific facilities, train the next generation of scientists and engineers, and provide the laboratory capabilities and infrastructure required for U.S. scientific primacy” [DSP06]. This approach maximizes FRIB’s potential for developing and maintaining a broad science program with the additional benefit to the nation of providing year-round hands-on education opportunities for the next generation of nuclear physicists and engineers.

1.b.3.1 Rare Isotope Research and Education Board (REB)

The REB will represent core institutions that have a stake in FRIB-related research areas. **Figure 1-18** shows an overview of the committed initial membership of the REB. REB members will be updated on the ongoing activities at FRIB and share their views directly with the FRIB Lab Director at least quarterly. We have 31 Memoranda Of Understanding (MOU) with institutions that have agreed to participate in the REB. The REB will represent five distinct groups of institutions:

- National laboratories involved in the design of major research equipment for FRIB. The laboratories shown in Figure 1-8 are currently collaborating on equipment development.
- Major research universities involved in the design of research equipment for FRIB. The universities listed in the figure have already agreed to be an REB member (11 signed MOUs).
- Michigan Rare Isotope Research Alliance (6 signed MOUs, including the University of Michigan and Wayne State University).
- Alliance for Minority Participation in Rare Isotope Research (5 signed MOUs).
- Alliance of Undergraduate Rare Isotope Research Institutions (9 signed MOUs).

There will be opportunities for additional labs/universities to join the REB in the future.

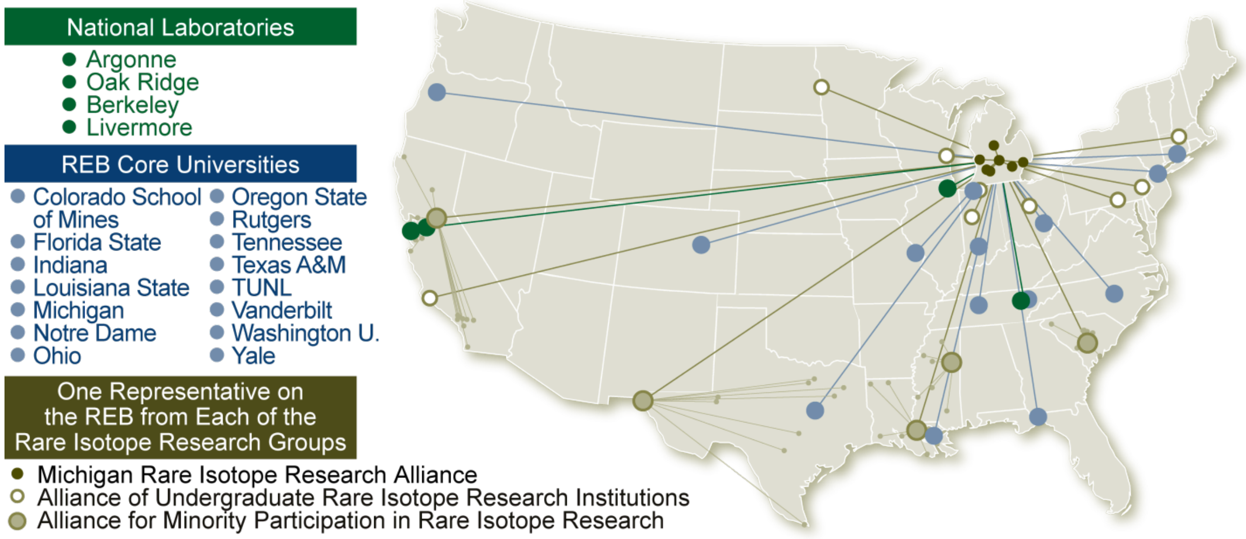


Figure 1-18. Equipment Collaborators, Members of the FRIB Research and Education Board (REB), and the Alliances of Universities and Colleges Interested in Rare Isotope Science. *The REB will be made up of a diverse group of institutions interested in FRIB science. The members of the Alliance for Minority Participation will serve as outreach hubs.*

1.b.3.2 Train the Next Generation of Scientists

With the creation of the Office of Workforce Development for Teachers and Scientists in the Office of Science, the DOE recognizes the importance of educating a science-literate workforce as outlined in the America COMPETES Act of 2007 [ACA07]. As the nation’s top-ranked university in rare-isotope research and the second-ranked nuclear physics graduate program [USN08], MSU is ideally suited to serve as a center for education in FRIB-related science fields.

Recognition of excellent young researchers is an important aspect of career development. MSU will institute a prestigious biennial award for the most outstanding young researcher in the field of rare isotopes. For postdoctoral researchers, we will implement named fellowships in nuclear structure or nuclear astrophysics at FRIB.

For the U.S. to remain a leader in rare-isotope research, it must develop the next generation of scientists. The NSAC Report on education [ENS04] recommends that students be engaged in research early in their graduate careers. The chance to combine classwork with research, beginning in the first semester and throughout the students' careers can best be offered at universities which have major research facilities on campus. MSU offers the added benefit of allowing a unique synergy between research and education, where students are afforded opportunities for hands-on research side by side with world-leading scientists throughout their graduate careers. These opportunities, combined with formal coursework and teaching programs, will foster the development of the next generation of world-class nuclear scientists. MSU will offer easy access to nuclear and accelerator physics experts during on-campus courses and special summer programs. We will continue to invite world-leading experts to teach some of these courses and to give special seminars at MSU.

The NSAC Report also stressed the importance of undergraduate research opportunities. MSU is a leader among U.S. universities and national laboratories in providing opportunities for high school and undergraduate students to conduct research in nuclear physics. Over the last ten years, undergraduate students from 68 institutions in 29 states and Puerto Rico have performed research at MSU. **Figure 1-19** shows the number of participants at the Conference Experience for Undergraduates program of the annual Division of Nuclear Physics meeting who performed research at a given institution. We understand first-hand that exposing undergraduate students to cutting-edge research is a critical factor in the recruitment of graduate students in physics. Our expertise in this area will enable FRIB to achieve its full potential as a national rare-isotope research and education hub.

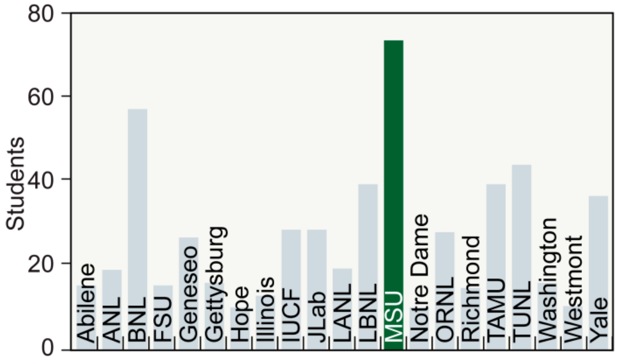


Figure 1-19. Presentations at the Conference Experience for Undergraduates. *Over the last 10 years, more undergraduate students who performed research at MSU presented their research at the Conference Experience for Undergraduates than from any other institution.*

Over 30% of our country's population has "minority status." In an increasingly technological world, it is essential that minority participation in advanced science and technology studies be increased. We will help DOE meet its goal of, "attracting, motivating, and retaining a highly skilled and diverse workforce" [DSP06]. MSU will encourage members of underrepresented societal groups to enter careers in science and engineering by creating a focused education outreach program and by using MSU's broad network of educational connections.

MSU will create a program of joint positions that will be especially targeted to minorities similar to the JLab approach [JSA07]. MSU will employ the Alliance for Minority Participation in Rare Isotope Research as outreach hubs, which in turn reach out to their regional minority college constituents to identify, actively engage, and attract talented minority students and researchers into the FRIB user community, and participate in FRIB activities and programs (Figure 1-18).

1.b.3.3 Creating National and International Collaboration Forums

MSU has a proven track record in fostering high-caliber national and international collaborations, both at the informal scientist-to-scientist and at the formal laboratory-to-laboratory level. The experimental collaborations, involving national and international colleges, universities, and other laboratories that are already forming will be continued by encouraging and supporting an active exchange program between FRIB research staff and the faculty and staff of the collaborating institutions. The teamed institutions will participate in collaborative research both at FRIB and at the partner laboratories. MSU will capitalize on communication strategies to further enhance the efficiency and effectiveness of the collaborative forums.

Researchers from collaborating institutions will be fully integrated into the design and development of new research tools and/or thrusts. Formal memoranda of understanding and formal joint proposals exist between MSU and 16 international institutions, including the world's major rare-isotope research facilities at CERN, GSI, GANIL, RIKEN, and TRIUMF. FRIB will continue to foster these collaborations. The teamed institutions will participate in research performed at FRIB, while the FRIB scientists will be involved in technical and experimental developments at the partner laboratories.

With 3,800 international students from 131 countries, MSU has the experience and infrastructure to launch an effective international users and guest scientists program. As is currently offered to all external NSCL users, and discussed in Section 1.b.2.1, the FRIB User Relations office will assist FRIB users with their visa, travel, and housing arrangements.

FRIB management will assume responsibility for organizing user meetings, equipment planning and prioritization workshops, technical reviews, and program reviews. In all the fore-mentioned activities, FRIB management will be closely engaged with the FRIBUO and the REB, and seek expert advice from the SAC to take MSU's already strong reputation for collaboration to the next level.

MSU has extensive experience in hosting large nuclear science meetings. MSU has organized large national (APS/DNP Fall 2002) and international (ENAM 1998, Nuclear Structure 2000, Cyclotrons 2001, Nuclear Structure 2008) meetings. In addition, MSU hosted large international workshops (FRIB Facility 2004, Fragment Separators Experts meeting 2008), four summer schools, and 25 topical nuclear science workshops since 2001.

In the recent past, MSU will hosted the following major international conferences:

- The 10th International Symposium on Nuclei in the Cosmos (NIC X), July 27-August 1, 2008.
- The 8th International Conference on Radioactive Nuclear Beams (RNB8), May 26-30, 2009.
- The 3rd International Conference on Collective Motion in Nuclei Under Extreme Conditions (COMEX3), June 2-5, 2009.

MSU has the existing infrastructure to host large meetings on campus to support FRIB. The Henry Center for Executive Development and the Kellogg Hotel & Conference Center are large conference centers located on campus. Additional meeting space is available at the Biomedical and Physical Sciences building located directly next to the NSCL.

1.c. Experimental Equipment

The technical scope proposed by the MSU team (as described in Section 1.a.1) includes a versatile and state-of-the-art suite of scientific instrumentation (**Figure 1-20**) for fast, stopped, and reaccelerated beam research. The goal is to be highly flexible to ensure that the facility will do the best science, can adjust to evolutionary changes in the scientific goals, and that the user community is given broad opportunities to engage in world-leading programs.

	Instrument	Benchmark	Selected Short-Term Science Example	Status
F	3-stage separator	Limits of stability, ^{59}Fe, medical, stewardship 9 13 10 11	Dripline to A~70, harvesting of ^{149}Tb, ^{88,89}Zr, and other isotopes for applications	In FRIB scope
F	S800 MSU	Shell structure, neutron skins, mass surface, rp-process, weak interactions 1 3 15 16 17	Knockout around ^{60}Ca, Brho-TOF for masses and (p,n) for nuclei above ^{132}Sn for supernovae simulations	Exists
F	Sweeper+MoNA MSU	Shell structure, weakly bound, weak interaction rates 1 14 17	Structure of ^{40}Mg, Pygmy resonance in ^{80}Ni	Exists
F	AT-TPC MSU	EOS, weakly bound nuclei, rp-process 6 14 16	Isospin diffusion, p/n ratio, and π^+/π^- ratios for ^{52}Ca+^{48}Ca and ^{35}Ca + ^{40}Ca	MSU commitment
F	HiRA MSU	Shell structure, EOS, rp-process 1 6 16	Transfer reactions on neutron-rich nickel and tin nuclei	Exists
F	Neutron walls MSU	EOS 6	p/n ratio ratios for ^{52}Ca+^{48}Ca and ^{35}Ca+^{40}Ca	Exists
F	SeGA MSU	Shell structure, symmetries 1 5	Knockout and Coulex for N=50,82 nuclei	Exists
F	GRETINA	Shell structure, symmetries, weak interactions 1 5 17	Knockout around ^{78}Ni, Coulex and M1 modes in medium-mass nuclei	DOE, complete 2011
F	Plunger	Shell structure, symmetries 1 5	Lifetimes of non-yrast states in ^{148}Ba and ^{138}Ce	Exists
F	CEASAR MSU	Shell structure, weakly bound 1 14	Coulex of fpg-shell and new island-of-inversion nuclei	NSF MRI, Complete 2009
F	BCS MSU	Shell structure, symmetries, r-process, superheavies 1 2 5 7	Half-lives of N=82 and N=126 waiting points	Exists
F	LENDA MSU	Weak interactions, neutron skins 3 17	(p,n) on neutron-rich nuclei	Complete 2009
S	LEBIT MSU	Mass surface 15	S_{2n} near ^{100}Sn and ^{54}Ca	Exists
S	Laser spectroscopy MSU	Shell structure, neutron skins 1 3	Nuclear moments and charge radii of calcium, nickel, and tin nuclei	Funded
R	Gas target	rp-process, ^{15}O(α,γ) 8 16	^{64}Ge(p,γ)	Funded
R	ANASEN	Shell structure, rp-process, ^{15}O(α,γ) 1 8 16	^{52}Ca(d,p), ^{15}O(α,α')	Funded NSF MRI
R	GRETINA	Shell structure, symmetries, Superheavies, EDM 1 5	Coulex of ^{100}Sn, Coulex of ^{148}Ba, study of nuclear shapes by yrast levels	DOE, complete 2011
R	AT-TPC MSU	Weakly bound 14	Resonance states in ^{10}He and ^{19}B	MSU commitment
R	Solenoid + Si detectors MSU	Shell structure, weakly bound, pairing 1 4 14	^{68}Ni(d,p), resonance states, pair transfer	MSU commitment
R	ISLA	Superheavies, mass surface, rp-process, EDM 2 15 16 12	Fusion cross sections for ^{22}O and ^{95}Kr, yrast structure of actinide and trans-actinide nuclei	In FRIB scope

Figure 1-20. Scientific Instrumentation Planned for the FRIB Base Facility. *The icons indicate the energy of the rare-isotope beams: F–Fast,S–Stopped, R–Reaccelerated.*

The approach for the implementation of scientific instrumentation is to consider both the community needs and to drive the formation of collaborations where the need exists, to ensure that FRIB has a modern and complete technical capability.

MSU offers a benefit to the Government by providing, a significant portion of equipment necessary for fast and stopped beams. In addition, MSU is constructing its new reaccelerator facility (to be operational in 2010) and is actively pursuing research collaborations with users to develop the instrumentation needed to address the reaccelerated beam science goals. This equipment will be available for FRIB. Within the technical scope of FRIB, we propose to augment this equipment by the addition of a large-acceptance recoil separator, ISLA, with the functionality of VAMOS, but with the added possibility to identify mass by time-of-flight (TOF) using a philosophy similar to TOFI [Wou87]. This recoil separator will be optimized for fusion-evaporation experiments at up to 20 MeV/u, and very efficient collection. It could double as an efficient recoil separator for astrophysics studies in the short term if an astrophysics recoil separator is not available.

This equipment meets and exceeds the needs of the short-term experimental program, as indicated in Figure 1-5 at the end of Section 1.a.1. This scientific instrumentation is a match to the needs articulated by the community of users in meetings at equipment workshops at MSU (2004), ORNL (2003), LBNL (1998), and Columbus

(1997). The community has expressed its equipment needs [Wuo04].

1.c.1 General Description of Experimental Areas and Their Arrangement Relative to FRIB Facility for the Short Term

A possible layout of the FRIB experimental complex on the MSU site is shown in **Figure 1-21**. The actual layout will be the result of user input and review by the Scientific Advisory Committee, as described in Section 1.b.2. Four major experimental areas are planned, distinguished by the rare-isotope beam energies delivered to each area. The stopped beam area will receive beams with well-defined energy up to a maximum of 60 keV. The scientific instrumentation in this area will include a laser spectroscopy and polarization beamline and a beamline for ion trapping and high-precision mass measurements. The user community will have these instruments fully developed and commissioned prior to the start of FRIB operations, and these are important devices for addressing the overarching science goals related to nuclear structure and astrophysics.

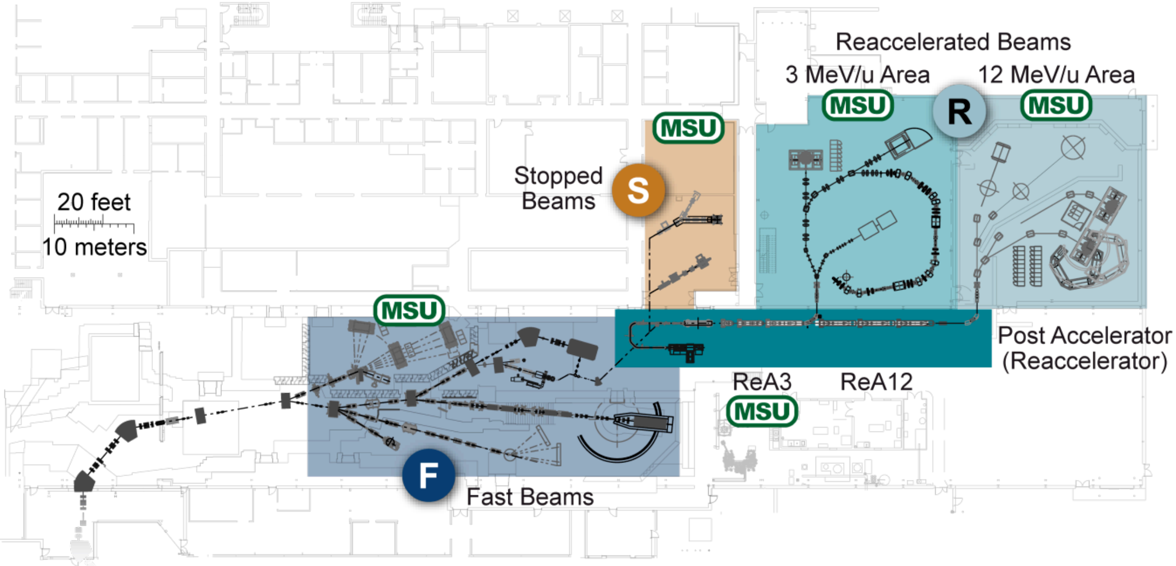


Figure 1-21. Proposed Layout of Experimental Areas for Short-term Implementation at MSU. *The actual layout will be the result of user input and review by the Scientific Advisory Committee. Four major experimental areas are planned, distinguished by the rare-isotope beam energies delivered to each area. MSU will fully develop and commission instrumentation prior to the start of FRIB operations.*

Reaccelerated rare-isotope beams with maximum energy 3 MeV/u for uranium and up to 6 MeV/u for ions with A<50 will feed the low-energy 3 MeV/u area primarily for astrophysics studies. This area has sufficient floor space to accommodate a recoil separator with gas target, SECAR (added in the mid-term, if the JINA proposal to DOE, DE-PS02-08ER08-10 is not funded in an earlier term), ANASEN, a Si-barrel detector array (LSU/FSU collaboration proposal funded by NSF), and two general-purpose beamlines for portable and/or temporary user installations such as GRETINA (funded by DOE) in stand-alone mode and the active target time projection chamber funded by MSU.

Rare-isotope beams will feed the 12 MeV/u area for nuclear structure and reactions studies with energies up to 12 MeV/u for uranium and greater than 20 MeV/u for ions with A<50. A large-acceptance spectrometer, ISLA, for experiments near and above the Coulomb barrier, will be located in this area (with funding requested in this application), and is needed for experiments exploring the structure of heavy elements, and neutron-rich nuclei produced in deep-inelastic collisions. Two general-purpose beamlines will also be available in this area: one for stand-alone GRETINA experiments, and another that can house, for example, the solenoid spectrometer that will be used to explore shell structure via nucleon transfer reactions (based on the TWIST magnet [Hen05] and augmented by a silicon detector array).

In the short term, the fast-beam area at FRIB makes use of the current-day layout of NSCL. The three-stage fragment separator can provide beams to any of the three experimental vaults, which will house the following equipment: the state-of-the-art Sweeper/MoNA setup, the S800 high-resolution spectrometer, and a general-purpose beamline to accommodate a versatile suite of transportable scientific instrumentation, which has already been developed by NSCL users and will be available for the planned experiments utilizing fast beams at FRIB.

1.c.2 Description of Stopped Beam Equipment

Two experimental end stations will be available at FRIB in the short term: a laser spectroscopy and polarization facility, and the LEBIT facility for ion trapping and high precision mass measurements. Both end stations receive low-energy ions in a low charge state (typically 1^+ or 2^+) from the gas stopping stations or highly charged ions (up to Z^+) from the electron beam ion trap. Capabilities to thermalize the high-velocity rare-isotope beams from projectile fragmentation, a central theme to the FRIB concept, were demonstrated at various laboratories and have, for example, led to a world-unique science program with mass measurements at NSCL. The existing 9.4 T Penning trap mass spectrometer of LEBIT is the centerpiece of this high precision ($\Delta m/m < 10^{-8}$) mass measurement program. The low-energy rare-isotope beams are cooled and bunched to improve emittance before injection into the Penning trap. Rare isotopes with half-lives down to 100 ms have been studied at LEBIT [Sch07]. The option of receiving rare-isotope beams in a highly charged state will increase the precision capabilities of the device, as it increases the cyclotron frequency and thereby the precision for measurements of which decay half-life is the limiting factor [Dil03].

The laser spectroscopy beamline is presently under development, and will begin operations in 2010. A next-generation, high-intensity cooler/buncher has been designed for the laser beamline. The beamline immediately after the cooler/buncher will have a switchyard serving two laser end-stations. One end-station will be dedicated for laser polarization experiments [Ott89,Lev02] and beta-NMR measurements. The NSCL beta-NMR system, a 0.5 T dipole magnet and accompanying 250 W fast-switching RF system [Min08], already established at NSCL, will be stationed at the end of the laser polarization beamline. The other laser end-station will be used for laser spectroscopy measurements with low count-rate ions and/or atoms. The determination of hyperfine structure, as well as isotope shifts, will be conducted at this end-station.

1.c.3 Description of Astrophysics Equipment (3 MeV/u Area)

The 3 MeV/u area will be fed by the ReA3 which provides reaccelerated beams with energies from 0.3 to 3 MeV/u for uranium and up to 6 MeV/u for ions with $A<50$. The area can accommodate four experimental end-stations. In the short term, the scientific instrumentation includes a windowless gas target, a Si-barrel detector array for nuclear astrophysics studies with exotic nuclei (ANASEN), and two general-purpose beamlines. The gas target is an important instrument for reaction studies in inverse kinematics, where the small cross sections at low reaction energies demand high-target densities of pure gases such as hydrogen, deuterium, and helium. The Joint Institute for Nuclear Astrophysics will develop the gas target with funds from their Science Frontier Center grant. The gas target will be a windowless design, similar to the targets developed at TRIUMF-ISAC [Hut03] and ORNL-HRIBF [Fit05]. ANASEN is similar to the ORRUBA detector [Pai07] developed by the Rutgers/ORNL group at HRIBF, and will be placed in the 3 MeV/u area for studies of elastic and inelastic scattering, and transfer reactions. This detector will also be important for the inverse-kinematics studies of reactions such as (α,γ) and (p,γ). Funding of the ANASEN array has been approved by the NSF/MRI program for a collaboration led by Louisiana State University and Florida State University.

Two general-purpose beamlines will be constructed in the 3 MeV/u area. The first beamline will accommodate the planned active target time projection chamber (AT-TPC). A collaboration led by MSU faculty and including researchers from LBNL, UC Davis, and LLNL has proposed construction of a next-generation detector for reaction studies that can be adapted to a broad range of experimental situations with change of target/detector gas and pressure. The solenoid magnet for the AT-TPC will be acquired from TRIUMF (the former TWIST solenoid [Hen05]). The second beamline will accommodate GRETINA in stand-alone operation. GRETINA, which is outside of the technical scope of this proposal, is a gamma-ray detector with auxiliary equipment that has been developed by the community of users and will be available for experiments in 2011.

1.c.4 Description of Nuclear Structure and Reactions Equipment (12 MeV/u Area)

The scientific instrumentation for nuclear structure and reaction experiments with reaccelerated beams will address open questions in nuclear science on the nature of nucleonic matter and the source of simple patterns in complex nuclei that are discussed in the NSAC 2007 LRP. The nuclear structure and reactions experimental area is fed by the reaccelerator and provides reaccelerated beams with energies from 0.3 to 12 MeV/u for uranium and up to 19 MeV/u for ions up to A<50.

Three experimental end-stations are planned for the short term: a large acceptance spectrometer, ISLA, with sufficient room to locate GRETINA at the target position; a beamline for stand-alone devices, such as GRETINA or Gammasphere (currently at ANL), or the MSU CAESium iodide Array (CAESAR); and a general-purpose beamline that will have enough floor space to accommodate a solenoid spectrometer for transfer reaction measurements in inverse kinematics. The large-acceptance spectrometer will be of the TOFI-type [Wou87], and have alternative optics modes to study both highly asymmetric and symmetric reactions. The spectrometer will be developed in collaboration with the nuclear structure and reactions community of users, and is presently a collaboration between Catania, FSU, and MSU. It will be important for the measurement of fusion cross sections and the study of nuclei produced in deep-inelastic and compound-nuclear reactions. Effective space will be provided for high-performance, gamma-ray detectors such as GRETINA, Gammasphere, or the MSU High-Efficiency Scintillation Array for photon detection (CEASAR) at the target position.

Certain in-beam gamma-ray spectroscopy studies planned with the GRETINA plus spectrometer combination will be enhanced by charged-particle detection at the focal plane of the spectrometer. For example, spectroscopic studies of trans-fermium nuclei to search for new shell gaps at high excitation energy are only possible with a clean trigger from alpha-decay tagging. The NSCL Beta Counting System, BCS, [Pri03] will be available for such measurements at FRIB. A proposal was submitted to the DOE FRIB Science FOA DE-PS02-08FR08-10 to increase the efficiency of the BCS by an order of magnitude by constructing a 12π counter called CERDA.

The option of running GRETINA in standalone mode is planned for inelastic scattering experiments to study shell structure and symmetries. Fusion barrier studies for the most asymmetric reactions, where the recoil products do not have sufficient energy to reach the focal plane detectors of the large-acceptance spectrometer, will also use GRETINA in standalone mode. Such studies will require auxiliary detectors for particle identification, such as the super-CHICO residue detector being developed by LLNL and the nanoball particle-detector array from Washington University.

The general-purpose beamline will be available for mounting other experimental devices brought to FRIB by the community of users. One instrument that will be deployed on this beamline is a solenoid spectrometer for transfer reaction studies with rare-isotope beams in inverse kinematics.

1.c.5 Description of Fast-beam Equipment

The fast-beam area will receive intermediate-energy beams (with magnetic rigidity up to 6.0 Tm, corresponding to greater than 200 MeV/u energy for most ions) directly from the three-stage fragment separator–without the inevitable losses from gas stopping and reacceleration. NSCL already has four experimental end-stations in place and this will likely remain unchanged for the short-term FRIB program. NSCL's instruments are well understood and provide complete coverage of the needs of the short-term fast beam rare-isotope program.

1.c.6 Expansion Opportunities in Scientific Instrumentation and Achievement of FRIB Mid- and Long-term Science Goals

Upgrades to the suite of scientific instrumentation in the mid- and long-terms at FRIB will be in response to the evolving capabilities of the FRIB accelerator complex and the evolving needs of the FRIB user community. Equipment additions in the mid-term will focus on increasing sensitivity and selectivity. In the long term, addition of experiments made possible by ISOL will be a likely focus.

A listing of potential scientific instrumentation initiatives is given in **Figure 1-22**. Additional scientific instrumentation for the stopped beam experimental area includes an on-line laser atom trapping area that includes magneto-optical traps to enable the electric dipole moment measurements. The possible scientific instrumentation includes the addition of two ISOL production targets and an isobar separator, and a transfer line to the reaccelerator. MSU proposes to include the infrastructure, with remote handling, in the base facility, so that this option can be added at low cost and little downtime when needed.

Instrument		Science Benchmark	Science Objective
F	Zero degree spectrometer	Shell structure, symmetries, weak interaction rates 1 5 17	Single-particle structure for fpg-shell nuclei new collective modes in exotic nuclei
F	MoNAx2	Shell structure, neutron skins, mass surface, rp-process, weak interaction rates 1 3 15 16 17	Reliability of configuration-interaction theories at the dripline
F	GRETA	Shell structure, weakly-bound nuclei, symmetries, skins, weak interaction rates 1 3 5 14 17	Single-particle structure for fpg-shell nuclei Mass surface for r-process calculations Weak interaction rates for stellar explosions
F	12π counter CERDA	Shell structure, symmetries, r-process superheavies 1 2 5 7	r-process quantification
S	MOTs	EDM 12	Dipole moment measurement to test time reversal symmetry
R	Gas-filled separator	Superheavy elements 2	Breakthrough experiments for production of superheavy elements
R	Gas jet target	rp-process, $^{15}\text{O}(\alpha,\gamma)$ 8 16	Reaction rates to quantify rp-process
R	GRETA	Shell structure, symmetries, superheavies, EDM 1 2 5 12	Double-magic nature of ^{100}Sn Critical-point symmetry in ^{148}Ba Octupole deformation and EDM enhancement in actinides
R	SECAR	rp-process, $^{15}\text{O}(\alpha,\gamma)$ 8 16	Reaction rates to quantify rp-process

Figure 1-22. Potential Scientific Instrumentation Initiatives. *Scientific instrumentation expansions and upgrades for the mid- and long-term science goals at FRIB.*

We envision upgrading the reaccelerated beam experimental areas in both the astrophysics and the nuclear structure and reactions areas. In the 3 MeV/u area, a recoil spectrometer, SECAR, for astrophysics measurements will be added in the mid-term if the JINA proposal to DOE DE-PS02-08ER08-10 is not funded in an earlier term. This device is necessary for the science goals of understanding astrophysical processes, in particular for a direct measurement of the $^{15}\text{O}(\alpha,\gamma)$ capture rate. Prior to the mid-term, indirect measurements of resonance properties can be completed, while the beam intensity available at the facility increases. Direct capture measurements can be performed using the ISLA separator for selected cases not requiring high beam intensities. In the 12 MeV/u area, an efficient gas-filled separator for superheavy element studies similar to the Berkeley gas-filled separator will be added [Nin98].

The 4π gamma-ray detector GRETA will be a critical device for FRIB in the mid- and long-terms. GRETA is needed to provide the sensitivity for the programmatic studies envisioned at this stage of the facility operation. We presume it will be developed by the community of users in parallel with FRIB, and will be available for experiments at FRIB in the mid-term. The implementation of GRETA at FRIB will provide an important increase in sensitivity for detecting photons emitted from rare isotopes, particularly in cases where the photon multiplicity is high.

In the mid-term and beyond, systematic studies will require a high-efficiency decay-spectroscopy device, CERDA. The goal is to build a device that has high solid-angle coverage for charged particles, photons, and neutrons. This device will be important for nuclear structure studies to track changes in the shell structure by studying the systematic variation of low-energy quantum states. It will also be needed for nuclear astrophysics to determine necessary half-lives, Q-values, and delayed particle channels needed for accurately modeling the mass flows along the r- and rp-processes, as well as what happens on “freeze out”, when these processes cease and the nuclei decay back to stability.

MSU will enhance the fast-beam experimental program with the addition of a new zero-degree spectrometer to replace the S800. This upgrade will allow fast-beam experiments requiring reaction-product identification to make full use of the high-energy rare-isotope beams that would be available should the heavy-ion linac driver for FRIB be upgraded to 400 MeV/u. Improvement in neutron detection efficiency will be required for the proposed fast-beam measurements of weakly-bound nuclei and charge-exchange studies via the (p,n) reaction.

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