Report to NSAC of the Rare-Isotope Beam Task Force

April 24, 2007

NSAC Rare-Isotope Beam (RIB) Task Force Report

1. Executive Summary

"Nuclear science is entering a new era of discovery in understanding how nature works at the most basic level and in applying that knowledge in useful ways." So wrote the Rare-Isotope Science Assessment Committee (RISAC), which was charged by the National Academies' Board on Physics and Astronomy, the Department of Energy, and the National Science Foundation to define the science agenda for a next-generation U.S. Facility for Rare-Isotope Beams (FRIB). In considering the relevance of nuclear structure and astrophysics within the broader context of nuclear science, the Committee wrote: "The committee believes that studies of nuclei and nuclear astrophysics constitute a vital component of the nuclear science portfolio in the U.S. Failure to pursue such a capability will not only lead to the forfeiture of U.S. leadership but also will likely erode our current capability and curtail the training of future American nuclear scientists. The committee concludes that a next generation, radioactive beam facility of the type embodied in the US FRIB concept represents a unique opportunity to explore the nature of nuclei under conditions that previously only existed in supernovae and to challenge our knowledge of nuclear structure by exploring new forms of nuclear matter." The RISAC report is comprehensive and scholarly and we have adopted it as a reference document for the scientific opportunities of rare isotope science.

Five years ago, the Nuclear Science Advisory Committee (NSAC) prepared a long-range plan that gave highest priority for new construction to a Rare Isotope Accelerator (RIA) which would have been the most powerful in the world for this area of research; as a facility, RIA would undoubtedly have met the expectations of RISAC in full. Alas, because of budget constraints, the Department of Energy announced in early 2006 that it would not proceed with construction of RIA but expressed strong interest in a facility to be built early in the next decade that would have lower cost and would be complementary in capability to other facilities existing or planned. It is in this context that our Task Force has been asked by NSAC to perform an evaluation of the scientific 'reach' and technical options for the development of a world-class facility in the United States for rare isotope beam studies within a constrained funding envelope, and in the context of existing and planned research capabilities world-wide. We have adopted the following guiding principles for any recommended technical option: the facility must have outstanding scientific opportunities as endorsed by RISAC; it must be complementary to other facilities, worldwide; and it must have a compelling day-one science program.

The RIA concept was developed in the late nineties after a broad investigation into different methods of isotope production by another NSAC task force, the ISOL (Isotope Separation On Line) Task Force. The conclusion of that study was that a superconducting heavy-ion linear accelerator offered the greatest scientific reach for rare-isotope science. Seven years later, we find that a heavy-ion driver remains the best approach for addressing the outstanding scientific opportunities identified by RISAC. This view has been shaped by the successful RIA R&D program, which has prototyped many key parts of such an accelerator and has shown that performance of individual components exceeds that anticipated for RIA by the ISOL Task Force.

Thanks to these technical advances, a world-class facility can be built at approximately half the cost of RIA, employing a 200 MeV, 400 kW superconducting linac. The scientific reach of such a facility is comparable to RIA although there will be a significant reduction in scientific productivity due to the lack of multi-user capability and reduction in the top beam energy.

We recommend that DOE and NSF proceed with solicitation of proposals for a FRIB based on the 200 MeV, 400 kW superconducting heavy-ion driver linac at the earliest opportunity. This unique facility will have outstanding capabilities for fast, stopped, and reaccelerated beams. It will be complementary in reach to other facilities existing and planned, world-wide.

We are confident that this facility will meet the first two of our guiding principles. The third is also achievable, but will require careful management of the project and targeted investments between now and the start-up date of FRIB. A strong day-one science program will be possible with a balanced investment in the driver and in the experimental facilities. A significant amount of equipment already exists, and more is expected to be available at turn-on assuming that additional investments are made in the coming decade. It is not necessary to define the details of the experimental program today as long as the facility has the capability to provide fast, stopped and reaccelerated beams. The important decision is to begin construction of the driver, which will consume at least 80% of the project costs. During the next five years planning for experiments can begin, taking into account the progress made by the new facilities coming on line in Japan, Europe, and Canada. It would be wise to form a Program Advisory Committee, with broad representation from the scientific community, as soon as a commitment to the facility has been made.

The Task Force heard detailed presentations from Argonne National Laboratory and Michigan State University of conceptual designs meeting these specifications. The presentations were of exceptionally high quality. Both of these institutions have indicated that they will respond to a request for proposals for a FRIB; each has strong scientific and technical credentials that will make the choice of site a difficult one. We also heard from all the laboratories in North America that are engaged in rare-isotope studies at this time. This includes TRIUMF, located in Canada, the world's most advanced ISOL-based radioactive beam facility. In the United States, these include national user facilities at Michigan State University, Oak Ridge National Laboratory and Argonne National Laboratory, and three university laboratories: Notre Dame, Florida State and Texas A&M. The range of activities is most impressive and these facilities are very competitive on the world scene. However, in the next few years, powerful new facilities will come into operation in Europe and Japan and there will be a substantial upgrade of TRIUMF in Canada. We share the view of RISAC that, without a new facility like FRIB, the U.S. will be relegated to niche experiments in this field.

In a separate exercise, a subcommittee studied the costs presented by Argonne and MSU. We conclude that the cost estimates are realistic and include all appropriate project cost elements. We find that these cost estimates are very well advanced for a project at this stage and can be used with some confidence by NSAC in developing its long-range plan.

A second subcommittee investigated the scientific reach of a FRIB and of the many facilities coming on line worldwide. In particular, we have studied the reach of the linac options as a function of energy (and cost) with some care; we find that while significant cost reductions could be made by scaling back the power of the linac even further, they would result in a drastic loss in both scientific reach and impact in the international context. Other technical options may be possible to provide significant reach at even lower cost, but they would require extensive R&D and are not ready for an RFP at this time.

Finally, we wish to comment on the ability of FRIB to contribute to research in the national interest. Once again, we draw on the wisdom of RISAC, which considered this issue and concluded: "The applications of rare-isotope technology could influence many areas including medical research, national security, energy production, materials science, and industrial processes. It will provide an important contribution to the education and training of future U.S. scientists in the physics of nuclei." Our task force endorses the RISAC findings and notes that the proposed FRIB options fully address these needs.

2. Assessment of RIB Facilities

In order to make recommendations in this report, we have taken some time to understand the future of various international and U.S. facilities. As one reads through the present U.S. facility plans and plans of our European (GSI/FAIR and GANIL/SPIRAL2), Canadian (TRIUMF/ISAC-II), and Japanese (RIKEN/RIBF) colleagues, one is struck by the world-wide activity of research in nuclear astrophysics and the physics of nuclei. In order to make a complete assessment of FRIB capabilities, we have very briefly outlined here the basic machine capabilities of these four world-leading centers, and also of the present status of U.S. facilities. In many instances, the U.S. facilities are performing interesting R&D both for the purposes of upgrading these facilities and for enabling a more productive FRIB when it becomes a reality.

Taking a snapshot today, we find that the U.S. program is competitive and world leading in some aspects of rare isotope science. However, the timescales for future international facilities to become fully productive suggest that the U.S. cannot maintain this position for longer than about 10 years without substantial investments. Upgrades of existing U.S. facilities, which are outlined below, will enable the U.S. to maintain world leadership in some aspects of rare isotope research for several years to come, but cannot be viewed as a replacement for the FRIB facility which we will argue in Chapter 4 represents a world-leading scientific opportunity.

2.1. Major International RIB Facilities

RIBF at RIKEN. The new Rare-Isotope Beam Factory (RIBF) at RIKEN in Japan recently began commissioning the heavy-ion driver accelerator complex and U^{86+} was successfully accelerated to 345 MeV/u in March 2007. First spectra of fission fragments from this beam were recorded in the BigRIPS fragment separator. The driver uses an ECR (Electron-Cyclotron Resonance) ion source to feed a room temperature linac, which is followed by four separated-sector cyclotrons. The existing RIKEN Ring Cyclotron has been augmented by two additional room temperature cyclotrons followed by the world's first superconducting separated-sector cyclotron, the SRC, which has a K value of 2500 ($B\rho$= 8 Tm) making it the largest cyclotron ever constructed. The goals for the facility are to produce 2 particle μA of light to medium energy heavy-ions up to 450 MeV/u and 1 particle μA for heavy-ions such as uranium up to 350 MeV/u. These beams will be used to produce fast radioactive ion beams with fragmentation or in-flight fission, which will be separated in the BigRIPS superconducting separator. The production of high beam intensities such as 1 particle μA of uranium requires further R&D on two aspects. First, the ECR ion source will be required to produce 16 particle μA of U^{35+}, which is a factor 3 greater than has been achieved on the VENUS prototype superconducting ECR source at Berkeley. Second, the uranium beam requires two carbon strippers operating at power levels much greater than used on any existing strippers.

The experimental program is scheduled to begin in 2007 using BigRIPS. Experimental equipment in Phase I will include a zero-degree beam line spectrometer equipped with a gamma-ray detector array and various focal-plane and tracking detectors. The SHARAQ magnetic spectrometer is under construction in collaboration with the University of Tokyo and is scheduled to be installed in 2007. Phase II calls for two storage rings, the large-aperture magnet SAMURAI, and other equipment and is awaiting approval.

FAIR at GSI. The FAIR facility at GSI-Darmstadt is a major expansion of the GSI accelerator complex, beginning with the enhancement of the existing accelerator system (high-intensity heavy-ion ion source, Unilac and SIS-18 synchrotron) and adding two superconducting synchrotrons arranged in a double ring. A wide range of new experimental equipment is planned including a new superconducting separator, the Super-FRS, a low-energy area, and storage and cooler rings. The new facility will support a broad research program including nuclear structure and astrophysics, nuclear matter physics with 35 to 45 GeV/nucleon beams, hadron physics with antiprotons, plasma physics, and applications. The first upgrades to the existing systems including the linac and SIS-18 are underway and scheduled for completion in 2008. Major new capabilities including the S-FRS are scheduled to begin operation in the 2011 time frame and project completion including multiple user capability is expected in 2015. Presently, the upgrade work focuses on increasing the performance of the linac injector, including a new high-intensity, low-charge-state pulsed ion source capable of producing 15 mA of U^{4+}, improved linac transmission and upgrades of the SIS-18 vacuum, and increasing the cycling rate of the synchrotron by a factor of almost 10. The final goal is to have 3×10^{11} particles per second of uranium up to 1.5 GeV/nucleon for use with the fragment separator, which corresponds to 17 kW of beam power. This will require acceleration of U^{28+} through both SIS-18 and SIS-100, a daunting task due to the very high peak current densities needed to match the low duty factor of the synchrotrons. Other R&D issues include the design of a fragmentation target capable of operating with the enormous peak powers associated with the pulsed nature of the synchrotron beams. Slow-extracted beams are used for the low-energy program and the associated target requirements are reduced because of the larger duty cycle.

ISAC and ISAC-II at TRIUMF. At the TRIUMF facility located in Vancouver, British Columbia, the ISAC facility (Isotope Separation and ACcelerator) provides both reaccelerated and stopped beams for RIB physics. The driver accelerator is a 500 MeV H^- cyclotron, which is capable of producing up to 300 μA. The first phase of the project (ISAC-I) is in operation and it uses up to 100 μA or 50 kW of beam power on one of two ISOL targets. ISAC-I has a CW RFQ (Radio-Frequency Quadrupole) and room temperature drift tube linac that can accelerate 1^+ ions with $A/q \leq 30$ extracted from the target to 1.9 MeV/u. Construction of a more powerful post-accelerator utilizing superconducting RF (radio-frequency) accelerator cavities for ISAC-II is underway and scheduled for completion in 2009, which will boost the energy to 6.5 MeV/u for $A \leq 150$. The first phase of the super-conducting linac project is complete with 5 of the planned 8 cryomodules commissioned and experiments have begun. The present energy is 4.5 MeV/u for $A/q \leq 6$ with a mass limit of 30, limited by the RFQ.

An ECR charge breeder is under development to boost the charge states of the RIBs, which are extracted from the target ion source with charge state 1, and thereby extend the mass energy range of the post-accelerator. When the charge breeder is commissioned in 2008 the mass limit of ISAC-II will be increased. Currently, intensive R&D efforts are underway on several types of target ion sources, which will augment the existing target ion sources that utilize surface ionization to efficiently ionize elements such as Li, Na, K and Al. First enhanced intensity beams have been delivered from the new resonance laser ion source (RILIS) with Al, Ga and Ag beams made available to experiments. A FEBIAD source (Forced-electron beam induced arc-discharge ion source) is under development for producing beams of gaseous elements. In a first trial a beam of ^{34}Ar was produced and used in an experiment. In 2006 the ISAC facility delivered more than 4000 hours of RIBs to experiments with isotopes from 19 different elements produced for extended periods, and yields measured for many more.

SPIRAL2 at GANIL. SPIRAL2 is an upgrade planned for the SPIRAL facility at the French laboratory GANIL in Caen, France. The SPIRAL2 project is based on a multi-beam driver in order to allow both ISOL and low-energy in-flight techniques to produce rare-isotope beams. A superconducting light/heavy-ion linac with an acceleration potential of about 40 MV capable of accelerating 5 mA deuterons up to 40 MeV and 1 mA heavy ions up to 14.5 MeV/u will be used to bombard both thick and thin targets. These beams could be used for the production of intense beams by several reaction mechanisms (fusion, fission, transfer, etc.) and technical methods. The production of high intensity beams of neutron-rich nuclei will be based on fission of a uranium target induced by neutrons, obtained from a deuteron beam impinging on a graphite converter (up to 10^{14}fissions/s) or by a direct irradiation with a deuteron, ^{3}He or ^{4}He beam. The post-acceleration of beams in the SPIRAL2 project would be obtained using an existing cyclotron. An important aspect of this project is that it will allow GANIL to provide beams in parallel to up to five different experiments. This new capability is scheduled to be commissioned in 2012.

2.2 Current National U.S. Rare-Isotope Beam Capability and Modest Upgrade Paths

ATLAS at Argonne National Laboratory. ATLAS is a DOE National User Facility for investigations of the structure and reactions of atomic nuclei. ATLAS delivers about 5500 research hours per year with high reliability when running seven days per week. Of these, about 1000 hours per year have been radioactive beams in recent years. The radioactive beams are used for both nuclear astrophysics and nuclear structure research. These radioactive beams are produced employing two distinct approaches: the two-accelerator method and the in-flight technique, and the intensities of these beams vary from about $10^4 s^{-1}$ to $6 \cdot 10^6 s^{-1}$ on target. The facility is well equipped with various state-of-the-art detector systems, including ion and atom traps, magnetic spectrographs, the Fragment Mass Analyzer, and Gammasphere.

Ongoing upgrades to ATLAS include a project to increase the energy by about 25%, the Californium Rare-Isotope Breeder Upgrade (CARIBU), the Helical Orbit Spectrometer (HELIOS), and an RF beam sweeper to improve rare-isotope beam purity. CARIBU uses fission fragments from a 1-Ci ^{252}Cf source coupled with a gas catcher and charge breeder to provide unique beams of neutron-rich nuclei with intensities up to $7 \cdot 10^5 s^{-1}$ for stopped and reaccelerated-beam research. HELIOS, a collaboration between ANL and Western Michigan University, is a large acceptance solenoidal spectrometer for studying transfer reactions in inverse kinematics with radioactive beams.

Planned upgrades of ATLAS include Super CARIBU that will give about 10 times more beam intensity of radioactive fission-fragment stopped and reaccelerated exotic beams for the era leading towards the next generation exotic beam facilities. This project involves the construction of a high-efficiency, low-charge-state injector for ATLAS and an increase of spontaneous fission yields via the use of both a stronger ^{252}Cf source and a ^{254}Cf source.

The independently phased superconducting resonator technology developed at Argonne for ATLAS is the basis for both the high power heavy-ion driver and the post-accelerator of rare isotopes at the future facility.

HRIBF at Oak Ridge National Laboratory. The Holifield Radioactive Ion Beam Facility (HRIBF) was developed from an existing accelerator complex at Oak Ridge National Laboratory in the mid 1990s. Radioactive species are produced by intense light-ion beams from the Oak Ridge Isochronous Cyclotron and post-accelerated by the 25-MV tandem electrostatic accelerator. The radioactive-ion-beam injector system (IRIS1) links production and post-acceleration. More than 175 isotopes have been accelerated and approximately 30 additional species are available as low-energy (~50 keV) beams. More than 50 post-accelerated beams, including ^{132}Sn, have intensities of at least 10^6 s^{-1}. The ability of HRIBF to deliver beams of reaccelerated beams of neutron-rich fission fragments at energies above the Coulomb barrier is unique, world-wide.

An extensive suite of state-of-the-art equipment optimized for radioactive-ion-beam experiments is available at HRIBF, including two recoil separators, a gas-filled spectrograph, the CLARION γ-ray detector array, the HYBALL charged-particle detector array, silicon-strip arrays, specialized detectors and electronics for decay studies, and detectors to monitor and image low-intensity radioactive ion beams. Major equipment development now planned or underway includes a doubling of CLARION efficiency, a new low-energy beam facility, development of neutron detector arrays for β-n studies, a high-density gas-jet target, a novel detector system for fusion-fission studies, and a large-scale silicon barrel array.

A program is underway to improve HRIBF performance substantially. In 2005, the High Power Target Laboratory (HPTL) for enhanced ISOL production R&D capability was completed. A second, fully-functional, ISOL production station (IRIS2) is now being configured that will substantially improve the operational efficiency of HRIBF by 2009 and thereby increase the number of RIB hours available to researchers by about 50%. A plan has been developed to improve the RIB production capability by installing a turnkey electron accelerator capable of delivering a 100 kW electron beam, at an energy in the range of 25 to 50 MeV. With existing HRIBF target technology, and modest-sized targets, such a facility would be capable of generating 10^{13} photo-fissions per second. This is about twenty times larger than the current HRIBF proton-induced fission capability, but, since photo-fission is a much "cooler" process, the yields of the most neutron-rich species are even more strongly enhanced. For example, the yields of ^{132,134,138}Sn will be around 300, 1000, and 12,000 times larger than current capability, respectively.

National Superconducting Cyclotron Laboratory at Michigan State University. The Coupled Cyclotron Facility (CCF) started operation in 2001 and is currently the nation's premier rare-isotope facility. The beams from the CCF are primarily used to explore the properties of nuclei with unusual ratios of protons and neutrons, the nuclear processes that are responsible for the synthesis of the elements in the cosmos, and the isospin dependent properties of hot nuclear matter at sub- and supra-normal densities.

The in-flight production method allows the CCF to be very flexible. From 2001-2006 the facility delivered over 250 different rare-isotope beams; on average 3.5 rare-isotope beams per experiment. Typical beam energies range from 50 – 120 MeV/u and experiments with beam energies as low as 5 MeV/u have been performed. Experimental setups can utilize beams from very low ($10^{-5}s^{-1}$) to high intensities ($10^{8}s^{-1}$). The availability of the CCF has been over 90%; the resulting reliable and predictable operating schedule is important for the large number of different experiments and users.

The NSCL is implementing full capabilities to perform experiments with reaccelerated beams produced with the gas-stopping technique. This development includes an advanced concept for a cyclotron gas stopper, an EBIT (Electron Beam Ion Trap) charge breeder and, in the initial stage, a reaccelerator up to 3 MeV/u. A further upgrade to 12 MeV/u is possible. When completed it will be the first facility in the world that will have the unique capability of reaccelerated beams produced from in-flight fragmentation. The NSCL is a world-class facility. However, for the NSCL to remain a world-leading facility, a major upgrade such as that outlined in the recent "Isotope Science Facility" white paper is essential.

The existing, state-of-the-art, experimental equipment is well suited for future use at a FRIB. For example the high-resolution spectrometer S800, the low-energy beam and ion trap facility LEBIT, the segmented germanium array SeGA, the modular neutron array MoNA, the high-resolution charged-particle array HiRA, and the beta-decay end station, are all well matched to the currently proposed 200 MeV/u energy of the FRIB.

Low-energy University- based Facilities. We also heard from federally funded, university-based accelerator facilities at Florida State, Notre Dame, and Texas A&M. These facilities constitute an extremely productive and cost-effective component of the national program. Federal investment in these facilities is generally supplemented by significant state or university contributions. On the national level, these facilities play an important role as focal points for attracting and educating the next generation of nuclear scientists.

The John D. Fox Superconducting Accelerator Laboratory at Florida State University is based on a 9 MV FN tandem electrostatic accelerator with a superconducting linac booster. Unique capabilities include an optically pumped polarized ^{6,7}Li source and a sputter source dedicated to ^{14}C beam production. The facility provides in-flight production of radioactive beams with the RESOLUT beamline. RESOLUT is equipped with RF cooling and a high-acceptance magnetic spectrograph. Experimental tools include a Ge γ-ray detector array, scattering chambers with a variety of highly segmented charged-particle detector arrays and a neutron wall.

The FN Tandem Pelletron at Notre Dame is used for radioactive beam, nuclear structure and nuclear astrophysics experiments as well as for a program in radiation chemistry. The radioactive beam program at NSL is centered on the TwinSol facility which utilizes two superconducting solenoids to separate radioactive beam products from the primary beam. The TwinSol program is primarily directed toward the study of nuclear reaction mechanisms and the structure of unstable nuclei.

The centerpiece of the Texas A&M University Cyclotron Institute is a K500 superconducting cyclotron, from which first beams were extracted in 1988. Using two electron-cyclotron-resonance (ECR) ion sources, the accelerator can produce a wide variety of beams: those with intensities of at least 1 enA range in energy up to 70 MeV/u for light ions and to 12 MeV/u for heavy ions such as U. High-purity secondary beams are produced in the recoil spectrometer MARS via inverse-kinematics reactions. The BigSol spectrometer has been commissioned and now serves as a second location that provides radioactive beams. Cyclotron Institute staff members have developed a plan to upgrade the present facility to one that would yield high-quality radioactive beams directly from the K500 superconducting cyclotron. The first stage of the plan involves re-commissioning the 88-Inch (K150) Cyclotron. Intense light-ion and heavy-ion beams from that cyclotron will be used to produce radioactive ions, which will then be slowed down in a He-gas stopper and collected by ion guides as 1^+ ions. A 1^+-to-n^+ ECR ion source will then be used to produce the highly charged radioactive beams for reacceleration in the K500 cyclotron. The project, which has been underway for about two years, will cost around $4M to complete.

2.3. Assessment

Current U.S. Rare-Isotope Beam Facilities are world-class. However, they do not have the capability of the new facilities being built overseas, including GSI/FAIR, GANIL/SPIRAL2, RIKEN/RIBF and TRIUMF/ISAC-II. Modest upgrades to existing facilities will enable niche science to continue for the next 10-15 years in the U.S., but as these larger international facilities become completely operational (in 2009 for ISAC-II, 2011 for RIKEN/RIBF, 2012 for GANIL/SPIRAL2 and 2015 for GSI/FAIR) the U.S. scientific leadership position in the physics of nuclei and nuclear astrophysics will be gradually eroded.

The committee believes that the research efforts at FSU, Notre Dame, and TAMU continue to produce innovative science in this region and should continue to be supported both for their excellent science and for their role in student training.

3. Technical Options

3.1. Heavy-ion Drivers

Superconducting Heavy-Ion Linacs. The present concept for FRIB consists of a high-power heavy-ion driver linac which will provide heavy ions up to 200 MeV/u and protons up to approximately 600 MeV. The design beam power is 400 kW and the most challenging beam is uranium. The driver accelerator will use a high performance ECR ion source, a room temperature RFQ, and a heavy-ion linac with several types of superconducting cavities with increasing values of beta to match the beam velocity as it accelerates from low energy to full energy. The design of the linac follows closely the original baseline design for RIA, which was developed following the ISOL taskforce effort, which ended in 2000. The baseline design included a longer, higher-energy linac (400 MeV/u uranium and about 1000 MeV protons). Following the announcement by the Department of Energy that a facility of up to roughly half the cost of RIA should be considered, both Argonne and MSU developed modified driver designs with a maximum uranium energy of 200 MeV/u while keeping the 400-kW beam power. Both designs take advantage of the advances made during the RIA R&D program.

The superconducting heavy-ion linac, while modified with respect to the RIA design primarily by a reduction in the length and cost of the linac, remains the preferred choice of meeting the requirements for FRIB. The use of heavy ions, rather than just protons, provides greater scientific opportunities, since ISOL, gas stopping with reacceleration and fast beams following fragmentation can all be utilized, while a proton driver only permits the use of ISOL. While both cyclotrons and synchrotrons can provide heavy-ion beams at the energies needed for FRIB, reaching the required beam powers is far more difficult. The superconducting linac can accelerate multiple charge states and this significantly increases the efficiency and reduces the demands on the ion source. The front end of the FRIB linac would accelerate two charge states U^{33+} and U^{34+} through the RFQ and low beta linac, strip the beam at 17 MeV/u to U^{77+} to U^{81+} (about 80% efficiency) and then accelerate those five charge states to full beam energy. Acceleration in synchrotrons and cyclotrons is limited to a single charge state and this means only 20 to 25% efficiency of FRIB at each stripping stage. Both linacs and cyclotrons produce CW (continuous wave) beams; this makes stripping and target design easier in comparison with synchrotrons where the low duty factor requires very high instantaneous beam power, leading to much higher thermal stresses for strippers and targets.

Superconducting RF is well matched to the beam needs of FRIB, since it provides both high accelerating gradients and CW operation with low RF power requirements and relatively low line power. Finally, the SRF is now a proven technology and is being utilized at the Thomas Jefferson National Accelerator Facility (JLAB), the SNS and ATLAS. Prototype cavities have been developed and tested for the various beta values needed for a heavy-ion linac and advances in this area provide significant cost savings.

The current concept for the FRIB driver differs from the RIA baseline design in several ways. First the linac is shorter since the maximum energy has been reduced from 400 to 200 MeV/u. Secondly, and the high beta section does not use elliptical cavities. Thirdly, only one stripping stage is needed. Lastly, the 6-fold increase in beam intensity and increase in the charge-state distribution demonstrated in the VENUS ECR ion source developed at Berkeley have been incorporated into the design to provide the same beam power at half the energy while reducing the cost of the low-beta accelerator.

Synchrotron-based Heavy-ion Drivers. Synchrotrons provide the possibility of reaching high beam energies more cost effectively than either cyclotrons or linacs and are, therefore, the preferred solution for high beam power drivers that are used for secondary particle production of kaons, muons, neutrinos etc., all of which are produced most efficiently at high beam energy. For a high-power heavy-ion driver, synchrotrons, therefore, typically have a high beam energy of 1 to 2 GeV/u. The relatively slow repetition rate requires accumulation of heavy-ion beams using high power electron cooling and results in challenging requirements for the fragmentation target. The GSI FAIR facility will use synchrotrons for its radioactive beam facility. Synchrotron drivers are well suited to the production of secondary fast beams and for accumulation of such beams for storage-ring-based research. The use of low abundance separated isotope feed materials for key driver beams such as ^{48}Ca can be problematic for synchrotrons, because of high consumption in the ion source.

The committee was presented with an upgrade proposal for the Brookhaven AGS to produce 90 kW, 2 GeV/u of uranium beam. Even though the proposal makes use of the existing AGS, its estimated cost for the driver is comparable to the driver costs of the linac-based FRIB proposals from MSU and ANL.

Fixed Field Alternating Gradient (FFAG) Heavy-ion Driver. Fixed Field Alternating Gradient accelerators could, in principle, overcome the disadvantages of the slow repetition rate of synchrotron drivers and the many expensive RF structures of the heavy-ion linac drivers. The fixed magnetic field allows for much higher repetition rate while still using rings to reuse the expensive RF structures. The preferred non-scaling FFAG has a very strongly focusing lattice with very large momentum acceptance. With just two rings beams can be accelerated from 10 MeV/u to 400 MeV/u. The RF system could be a broadband, low-frequency, Finemet-based system that would not need any active tuning. FFAG-based drivers are presently under intense study and development and could offer a more cost effective solution in the future. At this time, however, the designs are not mature enough to be the basis of a cost estimate.

3.2. Proton Drivers

High intensity proton beams are presently being used at several laboratories to produce radioactive ion beams via the ISOL technique. The ISAC facility at TRIUMF in Vancouver, Canada represents the present state-of-the-art for such facilities using up to 50 kW of 500 MeV protons on a variety of production targets/ion sources, each optimized for specific ions. A planned expansion of this facility would provide another 50 kW proton beam to a second target station. To be competitive a decade from now, a new facility would have to provide for a significant power increase over the 100 kW that is available at TRIUMF.

The option of using either of the two high-power proton drivers operating in the United States was explored by the committee with presentations from the SNS in Oak Ridge and LANSCE in Los Alamos.

Spallation Neutron Source (SNS). The SNS consists of a 1.3 GeV superconducting linac feeding an accumulator ring that provides pulsed proton beams to a liquid mercury target for neutron production. This facility is presently being commissioned with the goal of 1 MW beam power by 2009. Already there is a planned SNS Power Upgrade Program to increase the beam power to 3 MW by 2012.

Some fraction of this beam could be used to drive ISOL targets, for example 100 kW for a direct target similar to ISAC and 1 MW for a two-stage fission target. There is nearby space for a target hall, isobar separator, linac post-accelerator, experimental areas and associated support buildings. The advantage of such a facility is that the high power driver exists so that funding can be applied to the other parts of the RIB facility. The disadvantage is that the ISOL technique, which relies on chemistry and other separation techniques, is limited, with very high intensities of certain ion beams produced while others are produced weakly or not at all, e.g., refractory elements. The 1 MW two-stage fission target, assuming technical feasibility, would be unique and offer high fluxes of some of the interesting r-process fission fragment nuclei. There is a great deal of overlap between this idea and the EURISOL concept currently being considered in Europe.

A rough costing of an SNS ISOL facility produced an estimate in the range of \$340-560M (2006\$), albeit with a significant contribution of \$80M applied to a detector trust fund.

Los Alamos Neutron Science Center (LANSCE). The LANCE facility consists of an 800 MeV room temperature linac with a 1 mA proton current capability and a pulsed storage ring which provides 100 μA on target for neutron scattering and other applications of neutrons. There is a planned upgrade to LANSCE which would construct a material test station (MTS) with targets located in Target Hall A, previously used for meson production. This facility would operate at 0.7 mA with a future power and energy upgrade to 1.5 mA at 3 GeV. A LANSCE ISOL facility could be envisaged with an initial proton current of 100 μA shared with neutron scattering but after the MTS upgrade this intensity could be increased to concurrent operation at 250 μA or higher. The beam repetition rate of 10 Hz (present) to 80 Hz (future) is high enough so that there are no significant target issues due to the pulsed nature of the beam. No proposed layout of the ISOL facility or estimate of the cost was provided.

Summary of proton drivers. The existing proton drivers at Oak Ridge and Los Alamos have the required beam power to provide a competitive ISOL facility. However, the fact that ISAC already exists in North America makes a second ISOL facility, with only a power increase, less attractive. Another concern is that SNS is funded by DOE Basic Energy Sciences and LANSCE is funded by DOE Defense Programs; it would be expected that neutron production for those programs would have higher priority than the production of rare-isotope beams.

4. Scientific Reach of the Linac Options

In this Chapter we discuss the scientific reach of the various technical options. We begin with a brief budget description for various options of the FRIB, and then move to the science that those options can attack. We end this section with a brief overview of key scientific campaigns where FRIB will play a leadership role.

We considered the scientific reach of a FRIB with a heavy-ion linac driver with beam energies for uranium of 200, 150, and 100 MeV/u and beam powers of 400 kW, 300 kW, and 200 kW, respectively, in order to investigate the relationship between cost and reach. All of our options include gas stopping, reacceleration and fast beam capability. The 200 MeV+ISOL option includes ISOL experimental capability.

LINAC Option	Operations	TEC	OPC (R&D, CDR, Pre-ops)	Experimental Equipment	TPC
200 MeV+ISOL	50	359	67	50	476
200 MeV	50	359	67	0	426
150 MeV	46	330	63	0	393
100 MeV	41	293	58	0	351

Table I. Cost estimates for several options of FRIB. The energies listed in column 1 are uranium beam energies in MeV per nucleon for the different driver configurations. The first row (200 MeV+ISOL) includes a $50M allocation for experimental equipment. All costs are listed in FY2006 M$. The procedure used to obtain these costs is described in the appendix.

Given that the cost of RIA from the Harrison Report was $990M (escalated to FY06), these options represent a range from 35.5% (for the 100 MeV driver option) to 48% of the original RIA cost. At the top end of the range, the facility can perform a large fraction of the scientific program of RIA (with somewhat reduced intensities, decreased energies of in-flight beams, a loss of multi-user capability, and hence reduced scientific output) and can address the important scientific missions of FRIB as outlined in the RISAC report.

Table I shows the breakout of these options and their associated cost. Using 3% inflators, the FY06 $426M option meets our charge for as spent budgeting for up to half the cost of RIA. In each case the primary cost driver is the linac. Each case also includes gas stopping and reacceleration as well as fast beam capability. The 200MeV+ISOL option includes an equipment trust fund that could, for example, be used to build an ISOL experimental end station. However, in our judgement, this trust fund does not fit within our budget guidance if all appropriate cost elements are included.

We make an assessment in the following concerning the scientific reach of the various technical options described above. Before doing so, it is important to briefly review the scientific drivers that make for a compelling case to build FRIB. These drivers are discussed in detail in the RISAC report, and we only briefly restate them here.

Nuclear structure. A FRIB would offer a laboratory for exploring the limits of nuclear existence and identifying new phenomena, with the possibility that a more broadly applicable theory of nuclei will emerge. FRIB would investigate new forms of nuclear matter such as the large neutron excesses occurring in nuclei near the neutron drip line, thus offering the only laboratory access to matter made essentially of pure neutrons; a FRIB might also lead to breakthroughs in the ability to fabricate the superheavy elements with larger neutron numbers that are expected to exhibit unusual stability in spite of huge electrostatic repulsion.

Nuclear astrophysics. A FRIB would lead to a better understanding of key issues by creating exotic nuclei that, until now, have existed only in nature's most spectacular explosion, the supernova. A FRIB would offer new glimpses into the origin of the elements, which are produced mostly in processes very far from nuclear stability and many of which are not within reach of present facilities. It would provide information on weak interaction rates in stellar cores critical to understanding how and why stars explode. A FRIB would also probe properties of nuclear matter important to theories of neutron-star crusts.

Fundamental symmetries of nature. Experiments addressing questions of the fundamental symmetries of nature will similarly be conducted at a FRIB through the creation and study of certain exotic isotopes. These nuclei could enable important experiments on basic interactions because aspects of their structure greatly magnify the size of the symmetry-breaking processes being probed. For example, a possible explanation for the observed asymmetry between matter and anti-matter in the universe could be studied by searching for a permanent electric dipole moment larger than Standard Model predictions in heavy radioactive nuclei.

Example:	200 MeV +ISOL	200 MeV	150 MeV	100 MeV
1. Shell Structure	X	X	X	X
2. Superheavies	X	X	X	X
3. Skins	X	X	X	X
4. Pairing	X	X	X	
5. Symmetries	X	X		
6. EOS	X	X	X	
7. r-process	X	X		
8. $^{15}O(\alpha,\gamma)$	X	X	X	X
9. ^{59}Fe	X	X	X	
10. Medical	X	X	X	
11. Stewardship	X	X	X	
12. Dipole Moment	X			
13. Limits of Stability	X	X	X	
14. Weakly bound	X	X	X	
15. Mass Surface	X	X	X	
16. rp-process	X	X	X	X
17. Weak interactions	X	X		

Table II: Experimental campaigns of a FRIB facility. X denotes world-class capability.

Other Scientific Applications. Applications from stockpile stewardship, materials science, medical research and nuclear reactors have long relied on a wide variety of isotopes. Presently, each of these areas would be significantly advanced by a facility with high isotope production rates especially for producing high specific activity samples for experimental use.

These scientific drivers are captured in the twelve classes of experiments described in the RIA Brochure and augmented by experiments described in the RISAC document. Listed in Table II are the various experimental examples. We note that these examples are representative of the types of physics one can pursue at the FRIB facility. They actually represent campaigns that would span numerous experiments. Here we list the capability of the three driver energy regimes to perform physics within these options. We note that *absence* of an X means that a world-class experimental program would unlikely be performed in that category because of limited beam intensity or the inability to cleanly separate key isotopes, not that one would be unable to devise a good experiment. The significant loss in capability in going to a 100 MeV driver comes mainly from the inability to separate nuclei heavier than mass 80 or so; the 150

MeV driver, while more capable, would still not exceed other facilities for heavy r-process nuclei or studies of weak interaction strengths. We stress that this Table presents only one measure of facility capabilities. Others, equally important, are discussed below, and it is the overall perspective resulting from these comparisons that point to the greatly enhanced capabilities and scientific opportunities available with a 200 MeV driver as compared to the lower energy options.

FRIB's research program touches several areas of science. A future FRIB should be able to access a wide range of nuclei in order to amplify and isolate key physics issues. For example, important components of the effective nuclear interaction are poorly known from the data near stability. In heavier nuclei, the increased shell size gives enormously larger configuration spaces that can lead to correlations not seen in lighter systems, such as various dynamical symmetries that simplify the description of certain nuclei. Indeed, in extremely neutron-rich nuclei, we anticipate new many-body symmetries to present themselves as one increases neutron numbers for a given proton number. Moreover, access to those nuclei at or near the drip lines will enable studies of the many-body problem in weakly bound systems where continuum effects are believed to play an important role in determining both the structure (through pairing) and reaction characteristics of these nuclei. A future FRIB will be able to reduce or eliminate experimental and theoretical uncertainties concerning various r-process and rp-process nucleosynthesis paths, as well as enable forefront searches for physics beyond the Standard Model via searches, for example, for non-zero electric dipole moments in atoms through the use of special exotic isotopes with large octupole deformations.

Will there be a role for FRIB if it is completed later in the next decade? To answer this we can also assess the scientific reach of technical options through a variety of comparisons. Our first comparison concerns the reach for detailed studies of drip-line nuclei by the GSI/FAIR, RIKEN/RIBF and FRIB facilities. Figure 1 shows this comparison. The FRIB facility at 200 MeV will be able to access about twice as many drip-line nuclei and is the only facility that will reach the heavier drip-line nuclei. This important aspect of the science, reaching to very neutron- rich nuclei near the drip lines can be performed best by FRIB with a 200 MeV driver, and is a clear leadership area for the U.S. facility.

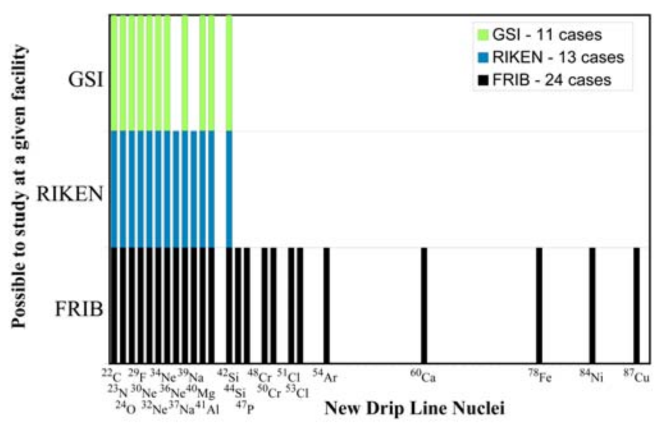

Figure 1: Capability to study specific drip-line nuclei at FRIB, GSI, and RIKEN.

In Figure 2 we compare the international facilities with two choices for the FRIB linac energy. Here we show the scientific reach of these facilities to investigate neutron skin properties of very neutron-rich nuclei. The FRIB will enable a large variety of nuclei to be studied, thus allowing researchers to investigate the residual interactions and changes in nuclear structure of the heavy nuclei. We stress that the machine will be targeted toward selecting experimental examples that isolate and amplify key components of the effective interaction responsible for structural properties and that FRIB will enable the largest scientific reach for these studies. Furthermore, several key experiments that shed light on very dilute neutron skin effects (shown as light-blue examples in the figure) will only be possible at FRIB.

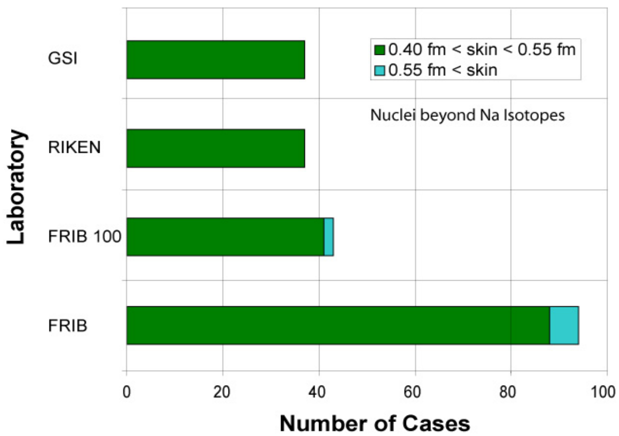

Figure 2: Scientific Reach measured through the capability of a given facility to perform neutron skin measurements of neutron-rich nuclei.

Figure 3 shows a third way of characterizing scientific reach. Here we simply count the number of isotopes that can be produced above a given intensity (particles per second). We compare this measure for the three driver options and plot each option as a function of neutron number beyond stability. Clearly, significant loss of capability occurs as one steps down in driver energy. This is due to several factors, one of which is the loss of separation capability. As the energy of the driver is decreased, one expects that fragmentation will be less efficient and therefore beam purity above some mass number will become problematic. The capability of a 200 MeV machine in this regard enables studies using separated nuclei up to mass 200, while we estimate availability of separated beams up to mass 150 for the 150MeV/u driver, and up to mass 100 for the 100 MeV/u driver. In each case, heavier nuclei very close to stability will still be accessible.

Taken as a whole, the clear message of these plots can be summarized as follows. A FRIB at 200 MeV will clearly enable world leadership in capability to investigate nuclei far from stability. It adds unique capability to investigate nuclei that the other major machines will not have. It will pursue most of the major scientific questions posed in the RISAC report for the three major scientific areas of nuclear structure, nuclear astrophysics, and fundamental symmetries; it provides an excellent opportunity for various applications. As we step down in energy we lose capability quickly. At 100 MeV, the machine capability would still enable a research program in several interesting areas of science, but would clearly not have the scientific reach to cover the broad range of science discussed in the RISAC report and would be much less competitive on the international scene. Especially glaring is the loss of capability to study heavy r-process nuclei.

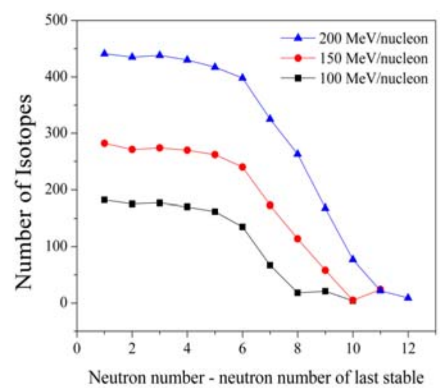

Figure 3: The number of neutron-rich isotopes produced above 0.01 pps as a function of the distance from stability.

As a committee we have not reviewed options for a driver below 100 MeV although we acknowledge that some small fraction of the scientific program could be performed with a smaller driver. The committee was informed of other options including ISOL options at the SNS at ORNL, LANCE at LANL, and the AGS at Brookhaven. In our judgement, these options are likely to provide a more limited scientific reach than any of the linac options, including the 100 MeV driver. If we are to go below the 100 MeV driver cost, it would be necessary to investigate through further R&D alternative options for a facility, with the consequence of continuing delay for the project. Continuing delay translates into lost scientific opportunity and lost capability relative to our international competition. As the cost is reduced, there will come a point at which it becomes more attractive to make modest upgrades of existing facilities or move the program to overseas facilities entirely. The negative consequences of such a strategy for the scientific community can be far-reaching as has recently been noted for high-energy physics.

We close this section by briefly sketching several examples of the science that would be pursued by FRIB and would likely not be pursued significantly elsewhere due to limited machine capability. Our first example is related to the electron capture that occurs on nuclei during a core collapse supernova event. Once a star of 10-20 solar masses has burned up all its nuclear fuel, it begins to collapse due to gravity. Electrons, whose outward pressure impedes the collapse, can obtain chemical potentials that enable them to be absorbed by nuclei through Gamow-Teller resonances. This electron capture serves to deleptonize the core so that collapse can continue until the matter within the core reaches nuclear matter density and a bounce (the beginning of the supernova explosion) occurs. In the last few years, researchers have understood that nuclei above the N=40 closed core play an important role in the electron capture and concurrently these nuclei have been shown to be quite abundant during the collapse phase. Electron capture on these nuclei significantly alters shock propagation in the supernova – a point that was only conclusively shown in the last 5 years. One measures Gamow-Teller strength distributions in nuclei through proton-neutron transfer reactions in the laboratory. Such experiments have been performed primarily in stable nuclei in the iron region, but validation of theoretical models for electron capture on heavier and more neutron-rich nuclei (above about mass 65) is required. FRIB at 200 MeV will enable such theoretical validations across the most important nuclei during the collapse phase, while FRIB at 100 or 150 would only be able to contribute to this program in a similar fashion as RIKEN and GSI.

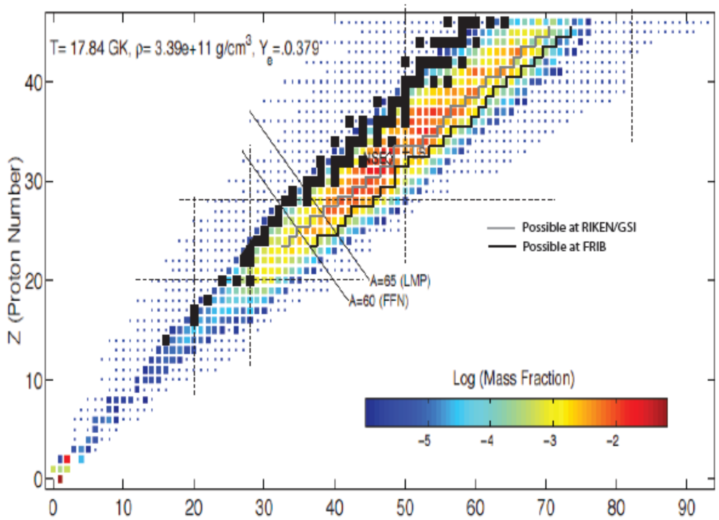

Figure 4: Nuclear abundances during the collapse phase of a supernova. FRIB with a 200 MeV driver will be able to investigate many of the Gamow-Teller strengths of the most abundant nuclei during the collapse.

Numerous nuclear properties impinge on our understanding of astrophysical processes responsible for heavy element production. These same properties are of fundamental interest for understanding nuclei in general. For example, one of the key nuclear physics questions concerns whether the same shell gaps exist in very neutron-rich nuclei as in isotopes closer to stability. Does the shell structure change from a standard nuclear spin-orbit picture to a more reduced spin-orbit picture in very neutron-rich nuclei? We do not know the experimental answer to this question, although there are hints from light nuclei that shell structure does indeed change from our standard picture in neutron-rich nuclei. Such changes impact how nucleosynthesis processes actually occur in a neutron-rich environment: weak shell closures would produce more abundant material near these closures. Thus, an experimental program to measure the shell closures and single particle energies near those closures – through knockout and transfer reactions and more indirect indications from beta decay – is very important to clarify both our understanding of nuclear structure and nucleosynthesis.

The mechanism by which the heaviest elements are produced has been understood since the late 1950s, but the astrophysical site of this production remains a mystery. The candidate environments are core collapse supernovae, gamma-ray bursts, neutron star mergers, and a number of other possibilities. New halo star data show that the heavier r-process elements occur in a reliable and consistent pattern across a number of stars, while the light elements do not, which may imply that the r-process occurs in at least two distinct sites. Measurements of nuclear masses, beta-decay rates, neutron-capture rates and neutrino-nucleus scattering cross sections are all very important. Data in all these categories are required for predicting a final abundance pattern. Without these data, one cannot fully predict an abundance pattern and the effort to find an appropriate site is impeded.

Another example concerns the changes in shell structure and collective behavior that occur when adding neutrons to nuclei of a given Z. In these heavier nuclei a delicate balance between shell effects and collectivity develops as more and more valence neutrons and protons participate to generate coherent motion of the nucleons. In many cases, this can be described in terms of underlying symmetries. Goals include identifying the relevant collective coordinates, understanding their connections to these symmetries, and how they arise from microscopic theory. For example, shell structure enhances the importance of the valence nucleons which, in turn, means that the addition of only a couple of nucleons can radically change the equilibrium configuration. This leads to rapid shape/phase transitions with N and Z that have been described in terms of new critical point symmetries. Far from stability one expects new examples of critical point nuclei (see Figure 5) and possibly new classes of shape transitions.

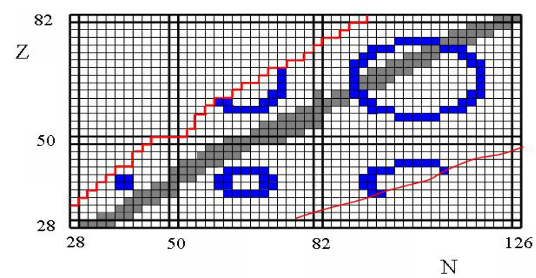

Figure 5: The evolution of collective motion in complex nuclei: many heavier nuclei are expected to exhibit novel collective properties such as (see blue squares) phase transitions in the equilibrium shape.

Shell gaps, magic numbers, and shell structure are not merely details but are fundamental to our understanding of one of the most basic features of nuclei – independent particle motion. If we do not understand the basic quantum levels of nucleons in the nucleus, we don't fully understand nuclei. Moreover, perhaps counter-intuitively, the emergence of nuclear collectivity itself depends on independent particle motion (and the Pauli Principle).

FRIB studies of nuclear properties between the major proton shells at Z=28 and 50, and spanning the regions from mid-shells below and above N=50 can be carried out with beams of Sr (A=74-104), Zr (A=78-110), and Mo (A=82-116). Similar studies in the region well above the major proton shell at Z=50 and spanning the regions from the mid-shells below and above N=82 can be carried out with beams of Ba (A=106-152) and Ce (A=120-156). For these beams the intensities of reaccelerated beams are above 10^2/s at the proton- and neutron-rich extremes and rise to 10^{10}/s closer to stability. Studies would include multiple-coulomb excitation and proton and neutron transfer reactions to explore new collective modes, mixed symmetries, and shape coexistence.

Furthermore, FRIB with a combination of reaccelerated heavy-ion fragments and ISOL capabilities would enable investigations of both the reaction mechanisms and the evolution of nuclear structure of the heavy elements, above Z=100, to develop new approaches to discover pathways to the island of superheavy elements that is predicted by several theories. Based on the use of heavy radioactive targets of Pu, Cm, and Cf, as have been developed by the Livermore group and used with stable ^{48}Ca beams in Dubna, together with neutron-rich reaccelerated beams at FRIB, new neutron-rich isotopes of Z=100 to 107 are predicted to be produced at rates of 0.1 to 1000 atoms per day. Some of these isotopes are the predicted daughter products of the neutron-rich Z=114-118 isotopes that have been reported, but not confirmed to date. The yields are predicted to be high enough to learn details about the energy dependence of the fusion cross sections and the nuclear structure, binding energies, and half-lives of these new isotopes, as well as, support studies of their chemical properties. Depending on the evolution of understanding of the possible synthesis reactions for even heavier, neutron-rich elements in the Z=116 to 120 range, further studies could be carried out with the intense neutron-rich beams of fission products produced via the 2-step ISOL mechanism. For these studies beams from ^{80}Ge to ^{90}Kr with intensities from 10^{10}-10^{12}/s would be available.

Rather than provide a complete overview of the scientific case we have chosen a few key experiments here to highlight the world leading capability that this facility will have when it is constructed. There is a much broader scientific program, which has been described in a number of documents including the RISAC report and the RIA Users Community Document. These include investigations of the neutron/proton asymmetry energy and the density dependence in the equation of state, measurements of nuclear pairing properties, or the possible electron-dipole-moment experiments on octupole-deformed nuclei, among others.

5. Applications

5.1. Introduction

In the executive summary of the National Academy of Sciences report, *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*[i], a case is made for the essential role that science and technology play in the country:

> "The United States takes deserved pride in the vitality of its economy… That vitality is derived in large part from the productivity of well-trained people and the steady stream of scientific and technical innovations they produce. Without high-quality, knowledge-intensive jobs and the innovative enterprises that lead to discovery and new technology, our economy will suffer and our people will face a lower standard of living."

Among the many applications that will be discussed elsewhere in this section, FRIB will also produce the next generation of "well-trained" people in the disciplines of low-energy nuclear physics and nuclear chemistry. FRIB will be a new facility that will provide an exciting research environment attractive to graduate students and young faculty. The increased opportunities to perform frontier research at a world-class facility will also attract international scientists and graduate students, many of whom will stay to make a career in the U.S.. The effect that a new facility such as FRIB has on the scientific workforce pipeline is evidenced in the successful histories of CEBAF at TJNAF and RHIC at BNL.

The scientific opportunities available at FRIB will also motivate the expansion of academic faculty in the disciplines of low-energy nuclear physics and nuclear chemistry.. This growth is essential both to support the increased activities in these areas, but also to support the future needs of all applications requiring nuclear science.

5.2. National Security

In a planning document recently released by the NNSA, *Complex 2030: An Infrastructure Planning Scenario of the Nuclear Weapons Complex Able to Meet the Threats of the 21st Century*[ii], one of the four over-arching, long-term strategies is:

> "*Strategy 4: Drive the science and technology base essential for long-term security:* Long-term health of the science and technology at our nuclear weapons laboratories and plants is essential for our future. For more than a decade, a comprehensive, science-based approach has been the basis for the assessment of the continued viability of the nuclear stockpile. The need for a robust, scientific underpinning will remain as legacy systems are retained for the next few decades and the stockpile is transformed via development of RRW concepts. It is essential to maintain the capability to deal with technological surprise, to cope with planned and unforeseen changes to the U.S. stockpile and to respond to new threats."

The document goes on to outline a number of activities to be initiated to achieve this strategic goal. The current goal of the stockpile stewardship program is to develop a set of scientific and technological tools that will allow "predictive science" to be applied to all aspects of the nuclear weapons complex. The disciplines of nuclear physics, nuclear chemistry, material science and high-energy-density physics come together to provide the foundations for this predictive science capability.

Many specific areas of experimental and theoretical nuclear science have been identified in the FRIB experimental program that address the needs of stockpile stewardship. An overview of these is contained in the NSAC report: *Comparison of the Rare Isotope Accelerator (RIA) and the Gesellshaft für Schwerionenforschung (GSI) Future Facility* report[iii].

Since the events of 9/11, homeland security has become an imperative. In the area of creating and maintaining nuclear security, the securing of nuclear materials has become an important component of creating global security. The Domestic Nuclear Detection Office (DNDO) within the Department of Homeland Security (DHS) was given the mission to “strengthen the deployment of the nuclear detectors at home while working to improve the quality of those detectors over time.” Included in this mission was a component for “research and development of advanced-detection devices to minimize the likelihood of a radiological or nuclear device entering the United States[iv].”

The FRIB capability with the most direct impact on national security programs is the ability to produce large enough quantities of specific near-stability isotopes to use as targets for neutron irradiation. While the previous RIA design indicated that particle production rates of at least 10^{10} atoms per second were achievable, the current intensity production is significantly less. For most isotopes identified as potential subjects for direct measurements, the target sizes would be limited to 100 ng of material. This is illustrated in Figure 1 below.

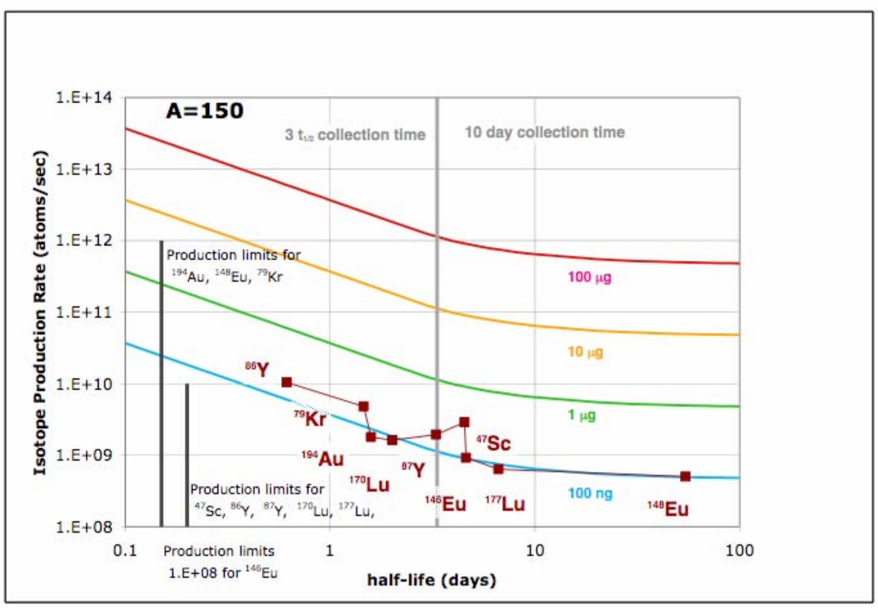

Figure 1. Estimated target mass as a function of isotope half-life and isotope production rates. The solid lines are calculated for an A=150 nucleus for 4 different target masses, as indicated. A further assumption limits the isotope collection time to the shorter of 10 days or 3 half-lives. Specific isotopes of interest to the Stockpile program are shown. The known isotope half-lives are used to estimate the isotope production rates required to produce a 100 ng target. The vertical gray bars indicate the estimated production rates of proposed FRIB facilities (200 MeV/nucleon, 400 kW) for those specific isotopes.

5.3. Nuclear Energy

The research needs of the nuclear energy program have been the topic of studies under the auspices of the Organization for Economic Co-operation and Development (OECD) in the Nuclear Energy Agency (NEA). That research program has focused on areas of nuclear science important to the development of nuclear energy. The report *Research and Development Needs for Current and Future Nuclear Energy Systems*[v] identifies a number of areas of research strongly overlapping the research program at a FRIB.

The need for nuclear data is an obvious area of interest, and the FRIB programs would contribute to the data needs of the community for which "nuclear data are required for the design, safety assessment and operation of nuclear power plants and associated waste management facilities."

A host of measurements are required. Examples from the study include:

- High-resolution total, capture and fission cross sections in resonance regions. These require white source time-of-flight facilities.
- Energy and angular distributions of scattered neutrons or secondary particles.
- Neutron- and charged-particle-induced activation cross sections.
- Yields of prompt and delayed neutrons in fission.
- Yields of fission products and their decay properties (measured using the on-line separators).
- Radioactive decay characteristics of unstable nuclei.

These measurements could be extended through techniques developed at FRIB, particularly the use of indirect cross-section measurements using inverse kinematics, etc.. FRIB could also be the source of isotopes and radioactive materials needed for direct measurements. A program of direct measurements requires that large enough quantities of target material can be produced for which an irradiation can be performed and the irradiated target counted. In most specific cases, an ISOL capability provides the source for the high fluxes of isotopes required to produce such targets.

5.4. Medicine and Biology

The ability to produce a wide variety of radionuclides in quantities useful for medical and biological research is likely to be the most important application area for the FRIB. The specific case for these applications was made in the recent NAS RISAC report *Scientific Opportunities with a Rare-Isotope Facility in the United States*[vi]. These application areas include targeted therapy, radiotracers and imaging. All of these applications benefit from FRIB's capability to produce isotopes, especially ones with high specific activity, across the periodic table while finding select isotopes with the prescribed radioactive properties.

5.5. Industry

As for medicine and biology, the ability to produce radioisotopes with chemical specificity and radioactive characteristics matched to measurement requirements is the primary capability a FRIB would bring to material science applications. The general nature of the applications is the use of radioisotopes as *in situ* detectors of the local environment within materials. Techniques that have been developed for material science applications include perturbed gamma decay (PAC), Mössbauer spectroscopy, β-NMR and electron channeling.

The requirements for such a facility have been discussed in the literature[vii]. To quote: “the ideal facility would deliver isotopes of all elements as an isotopically clear beam with a yield of at least 10^8 ions/s and variable beam energies ranging from a few keV up to several MeV.”

[i]http://www.nap.edu/catalog/11463.html
[ii]DOE/NA-0013,
http://www.nnsa.doe.gov/docs/Complex_2030_Infrastructure_Planning_Scenario.pdf
[iii]http://www.sc.doe.gov/np/nsac/docs/RIA-GSI-nsac-022604.pdf
[iv]http://www.whitehouse.gov/omb/pdf/Homeland-06.pdf
[v]http://www.nea.fr/html/science/docs/pubs/nea5188-research-needs.pdf
[vi]http://www7.nationalacademies.org/bpa/RISAC_PREPUB.pdf
[vii]Th. Wichert, M. Deicher, Nucl. Phys. A 693, 237 (2001)

6. Analysis and Recommendation

6.1. Analysis

Both RIA and its derivatives (the Advanced Exotic Beam Laboratory (AEBL) at ANL, and the Isotope Science Facility (ISF) at MSU) propose to use a heavy-ion driver/gas stopper/post-accelerator combination as the source of isotopes. With this choice of driver, many different types of experiments are possible using fast beams, stopped beams, or reaccelerated beams. There is consensus within the low-energy nuclear science community that this is the most powerful and flexible method for production of rare isotopes. This topic was studied in depth in 1999 by the ISOL task force (Grunder Panel). The Panel reviewed several approaches to isotope production and realized that the fragmentation of fast heavy-ion beams combined with gas stopping and reacceleration offered the greatest variety of beams and experiments and the least dependence on the chemical properties of the ions. It also concluded that superconducting radio-frequency cavities were the preferred technology to accelerate the high-current heavy-ion beams. The recommendations of the panel formed the basis of the 400 MeV/u, 400 kW RIA proposal.

After the Grunder panel submitted its report, an extensive R&D program was undertaken to understand how to design and build such a driver. The results of the program have supported the Panel's conclusion. However, in two important respects, its expectations have been far exceeded. The first of these is that advanced ECR ion sources can produce much higher intensities than anticipated. The second is that methods have been devised to accelerate several charge states simultaneously in the superconducting cavities. This allows one to reduce the energy of the driver by a factor of two while retaining the same beam power as RIA. This is a key fact in our analysis because beam power is a critical factor in determining isotope yields and beam energy is a critical factor in determining the cost of any accelerator, especially a linear accelerator.

Following the decision by the DOE to pursue a lower cost technical option than RIA, these considerations led two laboratories, Argonne National Laboratory and the National Superconducting Cyclotron Laboratory at Michigan State University, to propose a FRIB based on the RIA technology, but with a 200 MeV/u driver. Both laboratories propose to take advantage of the increased beam intensities demonstrated by the VENUS ECR ion source, and both propose to accelerate multiple charge-states simultaneously.

In considering our charge generally, and these two proposals specifically, the principal questions facing our task force have been the following. Is the Grunder panel technical analysis still valid at this lower cost point? Are the costs laid out in the Argonne and MSU proposals credible? Given that the energy has to be reduced, how far can this be taken while retaining an exciting and cost-effective project? Will sufficient scientific opportunities remain for an accelerator turning on late in the next decade, however powerful it may be? After careful consideration, we feel that the answer to each of these questions is positive as discussed below:

Is the Grunder panel technical analysis still valid at this lower cost point? We have studied in detail a 200 MeV/u heavy-ion driver, coupled to a gas catcher and post-accelerator, and able, therefore, to deliver fast beams, stopped beams, and reaccelerated beams to the experimenter. It has been demonstrated to the satisfaction of this task force that this technical option retains many of the advantages identified in 1999 by the Grunder Panel. It would allow a wide range of isotopes to be produced and reaccelerated by a method that is independent of the chemical properties of the individual elements. It will not have quite the production reach of RIA but will still produce the highest intensity rare-isotope beams of any facility in the world. Compared to the pure fragmentation facilities such as FAIR or RIKEN, it will offer complementary high-quality reaccelerated beams. Compared to pure ISOL facilities such as ISAC II, it will offer a much greater variety of beams. We are confident that this facility would meet the criteria for a world-class facility given in our charge and will add both unique and complementary capabilities to the international research community.

The Grunder Panel's choice of superconducting continuous wave linac cavities to accelerate the heavy ions remains sound; other possible technologies such as FFAG Cyclotrons are not yet sufficiently mature and would require extensive R&D. We have also revisited the possibility of using an existing proton accelerator as the driver, but three factors weigh against this option: while the SNS or LANSCE accelerators could provide the necessary beam power, these accelerators have their own missions that will be given highest priority; it is unlikely that the cost would be much lower; and, a world-leading facility based on this technique is already sited in North America at the TRIUMF laboratory.

Are the costs laid out in the Argonne and MSU proposals credible? This question was addressed by a subcommittee, which included members of the task force and additional experts with relevant expertise in management of large projects, design of superconducting accelerators, and operation of rare-isotope facilities. The subcommittee found that the costs are well understood for this stage of the project and that a high intensity FRIB can be constructed at a much-reduced cost relative to RIA, albeit with limited multi-user capability, and no detector allowance. The subcommittee report summary and conclusions are included as appendix D. The task force fully endorses the findings and recommendations contained here, and in the full report.

Given that the energy has to be reduced, how far can this be taken while retaining an exciting and cost effective project? With the help of information provided by the ANL and NSCL staffs, the costing subcommittee was able to construct a table of costs for a facility based on a linac driver at three energies, 200, 150 and 100 MeV/u; a gas stopper coupled to a post-accelerator is also included in each case. We have studied the scientific reach of these different options and have presented this analysis in section 4. The bottom line of our analysis is that at 200 MeV/u, and with the addition of an ISOL source, the facility could accommodate world-leading experiments for any of the twelve example topics in the RIA brochure and the five additional experiments given by the RISAC committee. At 100 MeV/u, this would be true for only five of them. Since the FRIB is anticipated to be coming into operation late in the next decade, we are concerned that the reach of these lower energy technical options would be inadequate to ensure a world-class facility at that time.

Will sufficient scientific opportunities remain for an accelerator turning on late in the next decade? In the next few years, we can expect rapid progress in rare-isotope science both here in the U.S., and around the world. Several new facilities are coming into operation with much higher intensities than have been available; they will undoubtedly produce exciting results on a broad range of topics. However, these experimental programs are all very challenging and in most cases are limited by the intensity of the rare-isotope beams. We judge that the higher beam intensities of FRIB will be essential to access key nuclei that will extend the science beyond what will be possible in the first round of experiments. We have given some examples of likely campaigns in our discussion of scientific reach.

Turning now to the experimental facilities that will be fed by the driver, a different set of questions has faced us: What should be the mix of fast, stopped and reaccelerated beam experiments? What about the ISOL target discussed in the AEBL proposal? How should funds be divided between the Driver and the Experimental Facilities? The answers to these questions are less clear-cut.

What should be the mix of fast, stopped and reaccelerated beam experiments? We believe that complementarity and uniqueness in the international context, while extremely important considerations, should not be allowed to become a straitjacket ten years before the anticipated start-up of the accelerator. One of the great advantages of the heavy-ion driver/gas stopper/post-accelerator combination is that it allows fast, stopped and reaccelerated beam experiments to be carried out at the same facility. The low-energy nuclear science community has stated repeatedly that it would like to make use of all three capabilities. We see no advantage in mandating the specific mix of these capabilities today; rather, appropriate steps must be taken to ensure that a new FRIB have the strongest and most exciting science program, in the world context, on the day when it starts to operate, ten years from now.

There is no doubt that difficult choices will have to be made as the project moves forward. RIA had an ample detector trust fund that would have allowed full implementation of all three experimental approaches; with the funding constraints provided by DOE, FRIB will certainly not have this luxury. Fortunately, we will learn a great deal from the experience of RIKEN, GSI, GANIL, TRIUMF and our local facilities in the next few years. This experience, together with the creativity and desire of the experimental community, should guide the development of this program. Also, we cannot assume that overseas facilities will stand still during the next decade, and not enhance their own reaccelerated beam capabilities, because the U.S. is building a reaccelerated beam capability into FRIB. As was the case for RHIC and CEBAF, we believe that the details of the experimental program should be developed in consultation with appropriate International Program Advisory Committees. These committees should be put to work by the host laboratory as soon as possible after the siting decision has been made.

What about the ISOL target in the configuration for FRIB proposed by ANL? ISOL targets can provide the highest RIB intensities, but for a more limited set of beams than the gas catcher. A target of this kind would be particularly valuable for experiments in the fundamental symmetries area; these are usually complex, long drawn-out, experiments that require the highest possible beam intensities. We have two comments on this. First, in contrast to the gas stopper, we view the ISOL target as a part of the experimental equipment rather than a necessary core capability of the accelerator. Provision should be made to accommodate such a target, but the decision to construct it should be based on the existence of a strong collaboration and an approved experimental program. Secondly, we are concerned that the target may not fit within the budgetary constraints provided to us, as discussed in Appendix D.

How should funds be divided between the driver and the experimental facilities? Ultimately, the capability of RIB facilities is limited by the performance of the driver. In the restricted funding scenario, there is then strong pressure to make cuts on the facilities side. However, in this field, the U.S. does not have the luxury of time. There is simply no point in building a Driver unless there is a strong science program on day one of operation. This is one of our three criteria for a world-class facility and will be a challenge for the Funding Agencies, the Laboratory building the FRIB, and the user community.

6.2. Recommendation

We have been asked to provide guidance on the scientific reach of technical options for a RIB facility. We have done this, and details can be found in this report. Nevertheless, one of them stands out so strongly that we are making it the basis of our single recommendation.

We recommend that DOE and NSF proceed with solicitation of proposals for a FRIB based on the 200 MeV, 400 kW superconducting heavy-ion driver linac at the earliest opportunity. This unique facility will have outstanding capabilities for reaccelerated beams, fast beams and stopped beams. It will be complementary to other facilities existing and planned, world-wide.

In conclusion, a facility for rare-isotope beam research as discussed above meets the requirements set by the Agencies in their charge to NSAC. It will address the science identified by RISAC; the cost is substantially less than RIA; and the facility will, without doubt, be world-class. Two decades have passed since the opportunities for rare-isotope research were first identified and other countries around the world are moving aggressively to exploit them. If the United States is to retain a leading role in this research area, there is no time to lose.

Acknowledgements

Reports such as ours always benefit from the efforts of others. However, this has been especially true for our task force since we have taken the recent report of the Rare Isotope Science Assessment Committee as the 'bible' of rare isotope science. We are grateful for their wise and scholarly assessment. We have also used a number of reports by the Nuclear Science Advisory Committee, especially the report of the ISOL Task Force, the 2002 Long-Range Plan, and, the Comparison of the Rare Isotope Accelerator (RIA) and the Gesellschaft für Schwerionenforschung (GSI) Future Facility. We are also the beneficiaries of the energy of the rare-isotope science community which has written many reports and documents. The RIA brochure was particularly helpful for us.

We thank the presenters at our two-day meeting in Chicago. All of the talks were of the highest quality and directly to the point. We especially wish to acknowledge the scientific staffs of the Argonne National Laboratory Physics Division and the National Super-conducting Cyclotron Laboratory at Michigan State University for their enormous efforts to keep us fully informed.

7. Bibliography

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8. Appendix A: Charge to the Committee

U.S. Department of Energy
and the
National Science Foundation

July 17, 2006

Professor Robert E. Tribble
Chair, DOE/NSF Nuclear Science Advisory Committee
Cyclotron Institute
Texas A&M University
College Station, TX 77843

Dear Professor Tribble:

This letter requests that the Department of Energy (DOE)/National Science Foundation (NSF) Nuclear Science Advisory Committee (NSAC) establish a task force to perform an evaluation of the scientific "reach" and technical options for the development of a world-class facility in the United States for rare isotope beam studies within the funding envelope described below, and in the context of existing and planned research capabilities world-wide.

The technical and scientific capabilities of the proposed Rare Isotope Accelerator (RIA), as well as cost (~$1,100 Million), have been refined over the years. Although the DOE has made the decision not to proceed with the construction of RIA as originally envisioned, the Department continues to believe that a facility for research with rare isotopes would add significantly to the Nation's scientific portfolio and is needed to maintain a leadership role in this area of nuclear physics. A modified RIA that focuses on capabilities which would make it unique in the world and would complement the rare isotope capabilities elsewhere will cost less. In the context of the projected out-year budget for the Office of Science, funding is possible to start design and construction of a rare isotope beam facility that is up to half the cost of RIA (Actual Year Dollars) early in the next decade. For the Department to proceed on a schedule that initiates project engineering and design in FY 2011 and construction soon after, the scientific and technical capabilities for such a facility would need to be defined in FY 2007.

The results of this study should determine whether a forefront facility that will produce outstanding science in an international context within the suggested funding envelope can be defined, and if so, should identify the best option(s) for this facility. The report should contain sufficient details of the scientific capabilities and reach of the facility to inform the scientific community and NSAC in their development of the Long Range Plan, and sufficient technical detail so as to provide the guidelines to define such a facility in a request for proposals.

Please submit your final report to the DOE and the NSF by the end of March 2007. We realize that the development of this report during the period that NSAC is embarking on its long range planning exercise introduces an additional burden; however, it is believed that the information and guidance that emerges from this exercise on the requested timetable will be valuable to both the agencies and NSAC in its planning exercise.

Sincerely,

Dennis Kovar
Associate Director of the Office of Science
for Nuclear Physics
Department of Energy

Judith S. Sunley
Acting Assistant Director
Mathematical and Physical Sciences
National Science Foundation

9. Appendix B: Committee Membership

Task Force Members

Ewart Blackmore, TRIUMF
Rick Casten, Yale University
David Dean, Oak Ridge National Laboratory
Ed Hartouni, Lawrence Livermore National Laboratory
Claude Lyneis, Lawrence Berkeley National Laboratory
Brad Meyer, Clemson University
Jerry Nolen, Argonne National Laboratory
Thomas Roser, Brookhaven National Laboratory
Brad Sherrill, Michigan State University
James Symons, Lawrence Berkeley National Laboratory, *Chair*
Robert Tribble, Texas A&M University, *ex-officio*
Sherry Yennello, Texas A&M University Cyclotron Institute

Staff

Janis Dairiki, Lawrence Berkeley National Laboratory
Dianna Jacobs, Lawrence Berkeley National Laboratory

10. Appendix C: Meeting Agendas

DOE/NSF Nuclear Science Advisory Committee
RIB Task Force Meeting
November 1, 2006
Agenda

9:00 AM	Executive Session
9:30 AM - 11:30 AM	Agency Discussion
11:30 AM - 12:30 PM	Working Lunch
12:30 PM - 1:00 PM	Rick Casten
1:00 PM - 5:00 PM	Executive Session

Discussion Items for afternoon Executive Session:

1. Set the agenda for December 6-8 meeting
2. Finalize guidance to Facilities planning to make presentations in December.
3. Discuss the Subcommittees (Including additional consultants, if necessary)
4. Define tasks for Committee and Subcommittees
    a. Cost Subcommittee
    b. Scientific Reach Subcommittee
    c. International Context Subcommittee

Agency Attendees

Denis Kovar, Office of Nuclear Physics, DOE
Gene Henry, Office of Nuclear Physics, DOE
Jehanne Simon-Gillo, Office of Nuclear Physics, DOE
Brad Keister, Division of Physics, NSF
Ani Aprahamian, Division of Physics, NSF

NSAC Task Force Meeting
December 6-8, 2006
Chicago, Illinois

Wednesday, December 6

Session I		
0830	Introductions	Symons/Tribble Kovar/Keister
0845	RIA Users Group Perspective	R. Casten
0915	Instrumentation needs for Rare Isotope Facilities	I.-Y. Lee
0945	ANL/ATLAS	R. Janssens
1025	Break	
Session II	**North American Rare Isotope Capabilities**	
1040	TRIUMF	A. Shotter
1120	Florida State University	I. Wiedenhover
1150	MSU/NSCL	T. Glasmacher
1230	Working Lunch for Task Force	
Session III	**Argonne National Laboratory**	
1330	Introduction	M. Turner
1350	Rare Isotope Science	G. Savard
1450	Break	
Session IV	**Argonne National Laboratory Continued**	
1520	Technical Concept	P. Ostroumov
1605	Summary	D. Geesaman
1630	Questions and Discussion	
1700	Executive Session	
1800	Close	

Thursday, December 7

Session V	**Michigan State University**	
0830	Overview of ISF Concept	K. Gelbke
0905	Driver Accelerator Details	R. York
0930	RIB Production and Experimental Facilities	G. Bollen
1000	Break	
Session VI	**Michigan State University Continued**	
1030	ISF Cost, Schedule, R&D, and Operating Costs	R. York
1050	Science Program I: Nuclei and Fundamental Symmetries	M. Thoennessen
1125	Science Program II: Nuclear Astrophysics and Applications	H. Schatz
1200	Working Lunch for Task Force	
Session VII	**North American Rare Isotope Capabilities Continued**	
1330	HRIBF	J. Beene
1410	Texas A&M	R. Tribble
1440	Notre Dame	J. Kolata
1510	Break	
Session VIII	**High Power Capabilities**	
1530	ORNL/SNS	G. Young
1600	Brookhaven National Laboratory	V. Litvinenko
1630	Los Alamos National Laboratory	K. Schoenberg
1700	Executive Session	
1800	Close	

Friday, December 8
Session VIV

0900	RISAC Summary - Q&A Session	S. Freedman/ J. Ahearne
1000	Executive Session	
1400	Close	

NSAC RIB Task Force Agenda
February 5 and 6, 2007
Lawrence Berkeley National Laboratory
54-130B Perseverance Hall

Monday, February 5
54-130B Perseverance Hall

0830	(15 min)	Introduction	T.J. Symons
0845	(45 min)	Cost Subcommittee Report	T. Roser
0930	(60 min)	Discussion of Cost Subcommittee	
1030	(30 min)	Performance vs Driver Energy	J. Nolen B. Sherrill
1100	(15 min)	Break	
1115	(20 min)	International Context Subcommittee Presentation	C.M. Lyneis
1135	(40 min)	Discussion of International Context Subcommittee	
1215	(60 min)	Working Lunch	
1315	(45 min)	Scientific Reach Subcommittee Presentation	D. Dean
1400	(75 min)	Discussion of Scientific Reach Subcommittee	
1515	(15 min)	Break	
1530	(30 min)	Proposed NSAC RIB Task Force Recommendations	T.J. Symons
1600	(75 min)	Discussion of Proposed NSAC RIB Task Force Recommendations	
1715		Adjourn	

NSAC RIB Task Force Agenda
February 5 and 6, 2007
Lawrence Berkeley National Laboratory
54-130B Perseverance Hall

Tuesday, February 6
54-130B Perseverance Hall

0830 – 1000	Discussion of Technical Options
1000 – 1200	Discussion of NSAC RIB Task Force Recommendations Cont.
1200 – 1300	Working Lunch
1300 – 1700	Discuss Report Structure, Writing Assignments and Schedule for Completing Report
1700	Adjourn

11. Appendix D: Cost Analysis Subcommittee Summary and Conclusions

Cost Analysis Summary and Conclusions from the Report of the Cost Subcommittee of the NSAC task force on a Facility for Rare-Isotope Beams

Subcommittee members: Jim Beene (ORNL); Jean Delayen (JLab); Mike Harrison (BNL); Ed Hartouni (LLNL); Claude Lyneis (LBNL); Thomas Roser (Chair, BNL)

Summary

The Cost Subcommittee met on January 16 and 17, 2007, at Brookhaven National Laboratory and was presented with cost estimates for a reduced scope Facility for Rare Isotope Beams (FRIB) by teams from Michigan State University (MSU) and from Argonne National Laboratory (ANL). The MSU project is called Isotope Science Facility (ISF) and the ANL project is called Advanced Exotic Beam Laboratory (AEBL). Both teams made excellent and extensive presentations on the cost estimates of their respective project proposals.

Both proposals are based on the original proposal for a larger scale Rare Isotope Accelerator (RIA) and are taking full advantage of the RIA-related R&D that was pursued over the last years to reduce cost. In particular, due to the success of the ECR source development at LBNL in producing high intensity, high charge-state uranium beams, both proposals have reduced the linac energy from 400 MeV/u to 200 MeV/u but maintained the beam power on target at 400 kW. Further cost reductions were achieved by eliminating the “detector allowance” and by reducing the facility to basically a single user facility. Both proposals have a gas stopper of the heavy-ion beam fragments and a post-accelerator. ISF also includes a fast beam experimental beam line using the existing NSCL in-flight facility. AEBL includes an ISOL target station. Both proposals assume that the existing gas stopper and post-accelerator (ATLAS at ANL, a new post-accelerator presently under construction at MSU) will be used by their respective projects.

The original RIA project had a preliminary cost review in 2001. To allow for a comparison with this cost review and also for comparing the two proposals with each other, both teams were asked to also present costs that could be compared to the RIA cost estimates escalated to 2006 from the cost review in 2001. Table 1 below shows the cost numbers of RIA, AEBL and ISF all in 2006 M$. Both teams were also asked to present cost savings that can be obtained from reducing the driver linac energy further to 150 MeV/u and to 100 MeV/u, but keeping the beam current constant.

	Management, and Central Systems	Cryogenic Plant and Distribution	Driver	Exp. Safety Systems	Target Systems	Low Energy Facilities	High Energy Facilities	**Total**
Central Facilities:								
RIA	49.6	52.0						101.6
AEBL	30.0	24.0						54.0
ISF	76.4	35.8						112.2
Civil and Utilities:								
RIA	31.5	5.3	30.2		21.2	29.3	24.2	141.7
AEBL	55.0	7.0	20.0		10.0	15.0	9.0	116.0
ISF	51.9	7.8	22.6		4.1	2.4	0.0	88.8
Driver:								
RIA			239.0					239.0
AEBL			140.0					140.0
ISF			144.2					144.4
Exp. Facilities:								
RIA				10.7	51.3	139.1	93.8	294.9
AEBL				10.0	20.0	41.0	0.0	71.0
ISF				5.8	37.6	19.0	0.0	62.4
TEC:								
RIA	81.1	57.3	269.2	10.7	72.5	168.4	118.0	777.2
AEBL	85.0	31.0	160.0	10.0	30.0	56.0	9.0	381.0
ISF	128.3	43.6	166.8	5.8	41.7	21.4	0.0	407.6
Pre-ops, R&D,…:								
RIA								212.7
AEBL								47.0
ISF								55.5
TPC:								
RIA	81.1	57.3	269.2	10.7	72.5	168.4	118.0	989.9
AEBL	85.0	31.0	160.0	10.0	30.0	56.0	9.0	428.0
ISF	128.3	43.6	166.8	5.8	41.7	21.4	0.0	463.1

Table 1. Cost elements from the 2001 RIA cost review and for AEBL (ANL) and ISF (MSU) as presented by the proposers. All figures are in FY2006 M$.

Isotope Science Facility (MSU)

The Total Project Cost (TPC) for building ISF at the present NSCL site was presented as $463M. This includes overhead (15%), contingency (overall rate of 24%), project R&D ($6M), Preliminary Engineering Design (PED) costs ($37M), construction cost, and pre-operations ($25M). The committee was presented with a detailed WBS-based cost estimate and a risk-based contingency calculation. The facility operations cost was presented as about $60M per year. Without including research staff the cost is about $50M.

The committee judged the overall contingency of 24 % to be too low at this stage of the project. Also, the pre-operations cost for this technically very challenging facility should be increased to about 1 year of operations cost (+ $25M).

The cost savings from reducing the driver energy to 150 MeV/u and 100 MeV/u were presented as $18M and $34M, respectively. A second option of locating ISF at a new site "South Campus" would cost $554M and have much better future expandability.

Advanced Exotic Beam Laboratory (ANL)

The AEBL driver would be built adjacent to the present ATLAS facility at an estimated TPC of $428M. This includes overhead (full ANL burden on labor, ~1% overhead on procurements), an average 30% contingency, project R&D ($10M), PED costs ($43M), construction costs and pre-operations ($30M). The committee was presented with detailed WBS-based cost estimates for the driver. Other parts of the facility were costed by scaling from the well-developed RIA costs. The civil construction cost was determined by scaling from the actual costs of the SNS facility. The facility operations cost was presented as about $60M per year. Without including research staff the cost is about $50M.

The Committee judges the overall contingency of 30% adequate. However, the pre-operations costs are again too small and should be increased to 1 year of operations cost (+ $20M).

The cost savings from reducing the driver energy to 150 MeV/u and 100 MeV/u were presented as $29M and $66M, respectively. It is noted that the AEBL cost could be reduced by $22M by eliminating the ISOL target.

Conclusions

The two proposals demonstrate that a high intensity FRIB can be constructed at a much reduced cost relative to RIA, albeit with significantly reduced experimental facilities and no detector allowance. In fact, both proposals arrived at remarkably similar costs for a 200 MeV/u heavy-ion driver with a gas stopper and post-accelerator. The somewhat higher cost of the ISF (MSU) could well be reduced to the level of AEBL (ANL) by reducing the management cost and adopting the more optimized SRF cavities of the Argonne design.

As outlined above the Committee estimates the total cost of AEBL with increased pre-operation costs (+ $20M) and without the ISOL target (- $22M) to be $426M. We will use the AEBL facility with this revised cost as an example for FRIB. This option is shown in Table 2 on the second line. The option on the first line also includes funding for a detector allowance. The third and fourth options are for a reduced driver energy of 150 and 100 MeV/u, respectively. The pre-operations costs, which are included in the “Other Project Costs” (OPC), were scaled with the TEC. Note that the last three options are below the maximum guidance cost of $550M in at-year dollars for a FY2011 to FY2017 construction period ($428M in 2006 $).

Description	TEC	OPC	TPC	Detector	Total
200 MeV/u +	359	67	426	50	476
200 MeV/u	359	67	426	0	426
150 MeV/u	330	63	393	0	393
100 MeV/u	293	58	351	0	351

Table 2. Cost options in FY2006 M$ for a FRIB based on the AEBL proposal without the ISOL facility and increased pre-operations costs. OPC (Other Project Costs) includes funding for a CDR, project R&D, and pre-operations costs. The first option includes funding for a detector allowance. The last two options are for a reduced energy driver. The pre-operations costs are scaled with the TEC.