Report

HRIBF, Upgrade for the FRIB Era

An HRIBF Users Workshop

November 13-14, 2009

http://www.phy.ornl.gov/workshops/users09/

The case for the 70-MeV cyclotron proposal

Credits and Acknowledgements

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Introduction and Executive Summary

In the quest to understand the structure of the atomic nucleus, nuclear reactions, and nuclear astrophysics, and to provide new opportunities for societal applications, nuclear science with rare isotope beams is blooming worldwide. In order to advance this exciting science and its applications, it is necessary to develop beams of evermore exotic nuclear species. To that end, a number of accelerator facilities are in the various stages of planning, construction, or upgrade. In the United States, a decision was made in late 2008 by the Department of Energy to proceed with the design and construction of the Facility for Rare Isotope Beams (FRIB) at Michigan State University. The timeline for the FRIB, as presently conceived, would result in fast and re-accelerated beams of radioactive species from in-flight fragmentation being delivered around 2018, with reaccelerated beams of on-line separated isotopes (ISOL) possibly becoming available at a later time.

There are many radioactive ion beam (RIB) experiments involving nuclear structure and reactions, nuclear astrophysics, and applications of nuclear science that require the high intensity beams and high resolution characteristic of the ISOL method. Beginning in the late 1990s, a number of such experiments have been performed at the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL), using a 1960s-era cyclotron (ORIC) to produce RIBs which are then reaccelerated with the 25-MV tandem electrostatic accelerator. It is essential that such capabilities be maintained and advanced, both in the nearer term, prior to the availability of ISOL beams at the FRIB, and as a complementary facility afterwards. Thus, with the FRIB on its way, the time has come for the HRIBF facility at ORNL to better define itself in a new era, characterized by the continuing development of ISOL capabilities, both in the medium and long term.

Pursuant to this goal, the HRIBF Users Executive Committee called a user workshop meeting on Friday and Saturday, November 13-14, 2009, at the Pollard Conference Center on the campus of Oak Ridge Associated Universities (ORAU) in Oak Ridge, Tennessee. The purpose of the workshop was twofold: *(i) to solicit user input and support for a proposed new production driver, a 70-MeV variable-energy, light-ion cyclotron to replace the ORIC; (ii) to solicit user input to update the HRIBF strategic plan.* The result of the meeting is this document, a user-driven White Paper that contains a strong science case for a modern, reliable ISOL facility at ORNL. A description of the proposed hadron accelerator driver upgrade (HDU) is given in Refs. [HDU08, Bee09, Tat09]. The discussion in these documents, and throughout the workshop assumed that the upgrade is based on a commercial cyclotron with specifications equivalent to or exceeding those of the recently developed IBA C70. The C70 specifications are given in Ref. [C7007]. A proposed facility layout is shown in Figure 1.

In order to accurately plan future experiments using an upgraded HRIBF, the workshop participants were provided with beam intensity estimates. These estimates are given at http://www.phy.ornl.gov/workshops/users09/intensities.shtml. They were based on solid assumptions, derived from a decade-long experience of producing RIBs at the HRIBF with a 50-MeV cyclotron (see http://www.phy.ornl.gov/workshops/users09/baseline-description.pdf for details).

By any measure, the workshop was a resounding success. In all, there were 151 participants representing 44 institutions from 10 countries, and many suggestions and proposals for exciting work at HRIBF were made by this group. This high level of participation is clear evidence that user interest in a cyclotron upgrade for the HRIBF is both widespread and intense.

At the workshop, there were introductory talks on Friday morning on the following topics:

- Overview of proposed 70-MeV cyclotron upgrade
- Performance of upgraded HRIBF for neutron-rich and proton-rich beams
- Implementation and technical details of the upgrade
- FRIB

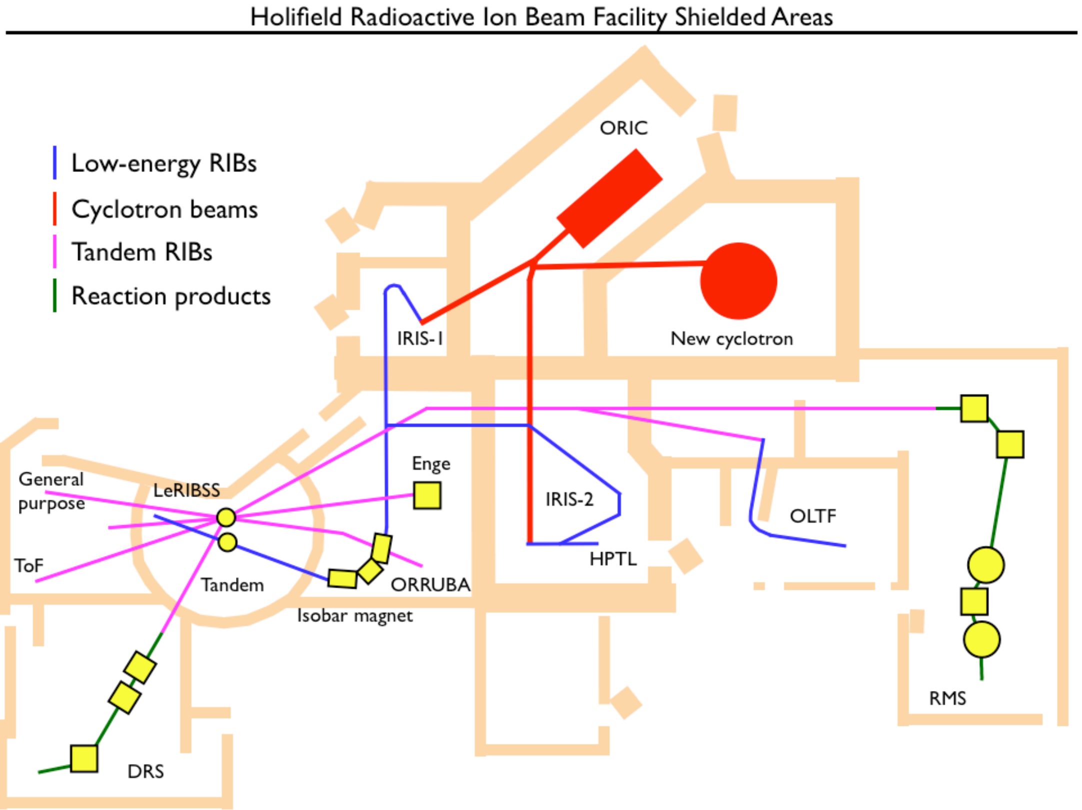

Figure 1: Layout of proposed facility using existing shielded areas.

- ISOL facilities
- Radioisotope production

This was followed on Friday afternoon and Saturday morning by parallel, breakout discussion sessions in working groups on nuclear structure (in-beam and decay), reactions, astrophysics, applications, and ISOL technology. During the breakout sessions, there were lively discussions on the unique capabilities the HRIBF would have in the future FRIB era to perform complementary research in support of FRIB science. Most sessions included a series of presentations illustrating the type of research the users would like to do with the new beams and higher intensities that would be available with the new cyclotron driver. The ancillary equipment needs were discussed in detail. Theoretical perspectives were offered on the specific type of data needed to impact the development of models for nuclear structure, reactions, and astrophysics. A brief outline of the presentation and discussion topics is given here:

- Upgraded HRIBF
  - Technical aspects of a commercial turnkey 70-MeV cyclotron
  - HRIBF and its relation to other ISOL facilities in the world

- Isotope research opportunities with the cyclotron
- Research areas
  - Nuclear structure by in-beam spectroscopy
  - Nuclear structure by decay spectroscopy
  - Nuclear astrophysics
  - Nuclear reactions
  - Applications with radioactive ion beams
  - ISOL technologies
- Associated areas
  - Instrumentation
  - Coupling between nuclear theory and experiment
  - World-wide context
  - Coupling between FRIB and HRIBF
  - Education and outreach

The majority of the proposed research centered on neutron-rich beams from proton-induced fission. In addition, proton-rich beams important for astrophysics and unique ^{56}Ni beams with low ^{56}Co contamination were highlighted. Major research thrusts discussed included studies of the following:

- Single-particle strengths using light-ion transfer
- Collectivity and g-factors of excited states using Coulomb excitation
- Heavy-ion fusion
- Radioactivity, encompassing level structure, beta-delayed neutrons, and beta strengths
- (n,γ) surrogate reactions
- Low-energy resonance and proton capture reactions of importance for understanding explosive astrophysical processes.

Separate sessions were devoted to laser and electromagnetic techniques for producing and enhancing radioactive beams and to various applications of radioactive beams at the HRIBF, especially in the context of new, unique opportunities associated with the proposed HDU. Examples of the latter included isotope research and development, fission-fragment data of interest to nuclear reactor operations, stockpile stewardship, medical wear studies, and accelerator mass spectrometry.

Working group summaries were presented later on Saturday morning, and the workshop closed early Saturday afternoon. Presentation files for the introductory (Friday morning) talks and the working group summaries may be viewed at http://www.phy.ornl.gov/workshops/users09/talks/. The conveners of the working groups were responsible for writing drafts of their respective sections of this white paper. They were recruited from the user community and included both non-HRIBF scientists and local personnel (see Credits listed on page ii).

As stated earlier, one clear outcome of this workshop is that user interest in the HDU for the HRIBF is both widespread and intense. Another outcome is a compelling science case for the upgrade in each of the main research areas. Some excerpts from the various sections of this document are given below in support of this conclusion.

From ***Nuclear Structure (in-beam spectroscopy):*** "Replacing ORIC with a new cyclotron driver will increase beam intensities significantly and make it possible to carry out many types of experiments such as:

- Measurements of Coulomb excitation in the regions of crucial magic and doubly-magic rare isotopes, including multiple excitation, and magnetic dipole and electric quadrupole moments.
- Single-particle transfer reactions in inverse kinematics to locate and perform detailed studies of crucial single-particle states, including angular correlation and lifetime measurements.
- Two-nucleon transfer reactions to measure symmetries, correlations, and excitation modes in neutron-rich systems.
- Explorations of new regions of excitation energy and angular momentum in many nuclei.
- Measurements of isomeric states near closed shells."

From ***Nuclear Structure (decay spectroscopy):*** "The HRIBF equipped with a new driver will continue to be a world-leading laboratory for the decay studies of exotic nuclei, in particular for the large variety of ^{238}U fission products. One should note that the current predictions of the rates to be achieved for new neutron-rich nuclei at the next generation ISOL facilities are based on extrapolated cross-sections and half-lives. The upgraded HRIBF will be in a position to reach the fission products at the limits of applicability of the ISOL method and help to guide future directions of radioactive ion beam facilities including FRIB."

From ***Reactions:*** "We discuss two major areas: the study of fusion and other reactions where the macroscopic behavior of nuclei is being explored and the study of direct reactions. In both these areas, certain key features of the HRIBF upgrade play an important role. The higher beam intensities and improved reliability are central to the new science that can be addressed. For typical fission fragment beams such as ^{87}Br and ^{132}Sn, the increase in beam intensity with the upgrade is estimated to be a factor of 50. Such increases in on-target beam intensities will have a profound impact on the studies with these beams. With these increased beam intensities, one can chop or bunch the beams (with the concomitant loss of intensity) to allow the introduction of improved measurements of reaction product time of flight, etc. One can also undertake the measurement of sub-barrier fusion and other small cross section processes along with undertaking studies with more exotic n-rich projectiles that are not feasible with today's beam intensities. Another important aspect of the increased beam intensities will be the opportunity to employ auxiliary detectors in various studies to measure the emitted neutrons and other particles."

From ***Nuclear Astrophysics:*** "Higher beam intensities from the 70 MeV cyclotron upgrade will enable us to measure a wide variety of transfer reactions, going beyond our current (d,p) studies. Using multiple reactions to populate levels of interest will give valuable complementary information that will provide strong constraints on nuclear models. For example, with 10^8 pps of ^{132}Sn, we will have the exciting possibility of measuring (d,t), (^{3}He,α), (t,p), (^{3}He,n), (d,p), and (d,^{3}He) at HRIBF – in essence, using this beam as a powerful *spectroscopic tool* to investigate all neighboring nuclei. Such complementary measurements can also greatly aid determinations of level densities and spin distribution functions critical for statistical model calculations of (n,γ) cross sections... For higher mass proton-rich beams, the intensity gains with the upgrade will enable the study of thermonuclear burning in supernovae, such as the νp-process, the p-process, and explosive burning that creates long-lived radionuclides. Specific examples include probing the structure and reactions for nuclei near ^{64}Ge (νp-process), ^{74}As (p-process), and ^{55}Co (radionuclides), none of which is possible with current intensities."

From ***Applications:*** "The applications working group discussed a wide range of research and development areas that would benefit from the proposed driver upgrade, as well as activities that would generally enhance the HRIBF research portfolio… Specific topics discussed included:

- *The proposal for an isotope production R&D facility as an addition to the driver upgrade. The isotope facility was described in a plenary presentation during the Workshop [Sal09] and discussed in the context of the recent report [ISO09] of the Nuclear Science Advisory Committee Isotopes Subcommittee (NSACI).*
- The application of the "surrogate reaction" approach for obtaining compound nuclear cross-sections of interest to RIB facilities.
- Opportunities for the use of tritium beams and targets, with particular emphasis on cross-section needs from NIF.
- Accelerator mass spectrometry at extremely high sensitivities.
- Other applications such as implantation of RIBS for material characterization

…The ORNL Isotope Program is proposing to take advantage of the dual-beam capabilities of the cyclotron upgrade, and the intrinsic operating characteristics of the HRIBF upgrade, to carry out a program of radioisotope R&D in a new adjacent facility [Sal09]. By constructing an isotope irradiation vault external to the upgraded HRIBF facility the isotope program could be provided ~4500 hrs/yr of beam time with no significant impact on the HRIBF mission... Because the new cyclotron would already exist, and the fact that ORNL already has the extensive infrastructure required to mount a full isotope production R&D mission, the incremental cost to the national isotope program would be modest (currently estimated as 7-10M$). "

From ***ISOL Technology:*** "For the future, in this section we show that HRIBF personnel are researching ways to provide the research community with almost any beam via the ISOL method and with purity and intensity unparalleled in today's ISOL community. This combination of existing capabilities and active, forefront ion source/target research programs guarantees that the investment of funds for an HDU at HRIBF will provide the US with a state of the art production-ISOL facility… In summary, the HRIBF staff and facilities serve to provide strong leadership in the development of ISOL technology. Existing personnel and laboratories at HRIBF have developed and are now developing the technology necessary to carry out forefront ISOL-type experiments. With the technology being developed, it is expected that the HRIBF, within a very few years, will be capable of providing a beam of almost any element and will also be capable of providing pure beams. Upgrading HRIBF to its full potential would provide the US nuclear physics community with intense beams of crucial rare isotopes and create the only US development facility for high power ISOL targets for next generation RIB facilities. With the addition of the HDU to provide reliability and increased primary beam intensities, the HRIBF will enhance its already strong position among the world's leading ISOL RIB facilities."

This document includes a section on ***Instrumentation***, which details the apparatus that are currently available or under development in support of experiments at the HRIBF. As pointed out in I.Y. Lee's talk on Saturday, there is already enough equipment in place to make good use of the new science opportunities provided by the HDU, and a number of new apparatus are under construction or being planned to be used at the HRIBF. The HRIBF is thus well situated to take full advantage of the new capabilities of the HDU with the very first beams produced. There is also a section on ***Education and Outreach*** in which the many facets of student involvement at the HRIBF are described. This is very important for training the next generation of nuclear scientists, including those who will one day work at the FRIB. Various aspects of education and training for workforce development were also discussed in the context of an isotope facility at HRIBF, see Applications section. Education and Outreach and Instrumentation are both strong features that greatly enhance the science case for the HDU at the HRIBF.

Additionally, and perhaps most importantly, the proposed upgrade is consistent with the community's strategic planning process. This is detailed in a separate section of this White Paper on ***HRIBF Driver Upgrade in the context of the 2007 NSAC Long Range Plan***: "The proposed cyclotron upgrade of HRIBF is consistent with the most recent NSAC planning exercise for the field, i.e., 2007 NSAC Long Range Plan [LRP07]. This Plan gave priority to FRIB, of course, but also quite clearly noted the need for productive use of our other facilities, including the necessary modest upgrades that are needed to keep them world class… In summary, the proposed cyclotron upgrade of HRIBF is fully aligned with the long-range plan of the U.S. nuclear physics community. This investment will provide this community with unique rare-isotope beams, it will produce groundbreaking research, and it will provide opportunities for important societal applications. As mentioned in the next Section (***Relationship of the HRIBF Upgrade to FRIB***), the upgraded HRIBF will provide training of the next generation of scientists in nuclear physics and nuclear astrophysics and in the techniques for exploiting exotic nuclei, and will also improve and develop the instrumentation that will ultimately be used at and will improve the capabilities of FRIB itself."

A group was assigned to compare an upgraded HRIBF with ***Other ISOL Facilities*** in the world. Their report is given in this document and says, in part, "The main niche of HRIBF remains in its ability to provide high-quality radioactive ion beams for research. The facility delivers a large range of isotopes with tandem energies and beam quality – this is unique worldwide and reflects the outstanding contributions from the target-ion source group. In this respect it is superior, in terms of range of radionuclides that can be post-accelerated to Coulomb barrier energies, to any other ISOL facility worldwide." The report goes on to say, "The replacement of ORIC by a high intensity driver such as the HDU is important to the future provision of intense beams of neutron-rich radionuclides for the US and international user community. This will build upon the existing strength of the facility and complement FRIB by accessing mass regions vital for studies of shell evolution and the astrophysical r-process." The report concludes, "Thus, due to the accumulated expertise in RIB production at HRIBF and provided a new cyclotron can be installed on a relatively short time scale, there is good reason to believe that Oak Ridge could retain its lead in RIB from fission production well into the next decade." The conclusions of this group can be supported by viewing some of the research highlights at the HRIBF over the past decade, summarized at http://www.phy.ornl.gov/hribf/science/, and the beam details given at http://www.phy.ornl.gov/hribf/beams/. When one considers that these many significant achievements took place with currently existing equipment (or less), one can only imagine what could be accomplished if the HRIBF is provided with a new, reliable, intense cyclotron driver.

Since theoretical relevance has been discussed throughout all Science sections of this White Paper, there is no separate section on nuclear or astrophysics theory created for this document. However, it is very clear that the proposed 70-MeV cyclotron upgrade is very important for theoretical progress in nuclear structure and reactions and in nuclear astrophysics. Experiments at the upgraded HRIBF, particularly in the regions around the exotic Ni and Sn isotopes, will provide theory with the most important benchmarks that constrain theoretical mass, reaction and structure models. These regions are of particular interest for the development of a universal nuclear energy-density functional, optical potentials, and shell-model interactions. Together with measurements of direct astrophysical relevance that will become possible with the proposed 70-MeV cyclotron upgrade, this improved theoretical proficiency is essential for the understanding of nuclear processes in astrophysics. Complementarily, the continuing refinement of theoretical astrophysics calculations provides improved understanding of the reactions in need of measurement.

Apart from soliciting user input and support for the upgrade proposal, the rich information collected during the workshop will be used to update the HRIBF strategic plan. As usual, the facility management will do this, in close consultation with the HRIBF Users Executive Committee, HRIBF Program Advisory Committee (PAC), and HRIBF Scientific Policy Committee (SPC). We are pleased that 13 of the 18 members of these HRIBF advisory bodies attended the meeting and were actively involved in discussions and the actual production of this White Paper.

In conclusion, it is very clear that a very strong, compelling science case has been made by the HRIBF Users Group for a cyclotron driver upgrade. Perhaps the tone of the workshop is best summarized by a remark made during an informal conversation by a European participant, who said, in effect, "The more I looked at this upgrade plan, the more I was convinced that it was the right thing to do."

The HRIBF Users Executive Committee would like to thank all those who made the workshop and this document possible, including the ORNL central administration and Physics Division staff, ORAU, and the many conveners from various institutions who contributed to this document.

Raymond L. Kozub, for the HRIBF Users Executive Committee

Science

Nuclear structure (in-beam spectroscopy)

A. Overview

This is a time of great opportunity in nuclear structure and gamma-ray spectroscopy. The development of radioactive-beam capabilities around the world is opening a new landscape for discovery. Added to that, new detector technologies are evolving which can meet the challenges of the new generation of experiments. The expansion of capability of the HRIBF with the addition of the new cyclotron [HDU08, Bee09, Tat09] along with the next generation for detection of gamma rays emitted by nuclei produced far from stability will open many exciting areas of nuclear structure physics, as described in this section.

B. Opportunities with GRETINA at upgraded HRIBF

The key detector technology development that will enable a new era of in-beam spectroscopy studies is γ-ray tracking. During the last few years this technology has been shown feasible and GRETINA [GRE10], a national 1π detector facility, is now nearing completion. The presence of GRETINA at HRIBF with the cyclotron upgrade will be highly significant and extend the discovery potential of the facility enormously. GRETINA was the most discussed instrument in this session of the workshop and many of the reasons for this are outlined below.

The improved sensitivity or resolving power of GRETINA compared to earlier instruments is due to the technique of tracking, which identifies the position and energy of γ-ray interaction points in the detector segments. Since most γ rays interact more than once within the crystal, the energy-angle relationship of the Compton scattering formula is used to track the path of a given γ ray. The full γ-ray energy is obtained by summing only the interactions belonging to a particular γ ray. In this way there are no gamma rays lost through scattering into suppression shields (which cover nearly 50% of 4π in Gammasphere; this lost solid angle is also regained in tracking detectors) and so a much higher overall efficiency can be achieved. Other key design benefits of a highly segmented Ge array include high energy resolution, high counting rate capability (a factor of ~5 over Gammasphere), good position resolution (1.4° versus 6° for Gammasphere) which is critical for Doppler shift corrections since many experiments involve high recoil velocities, the ability to handle high multiplicities without a high double-hit probability, and the ability to select low-multiplicity events hidden in a higher-background environment due to background rejection by direction. Another asset is that the large segmentation also makes high-precision linear polarization γ-ray measurements possible. The modularity of the detector design makes it extremely versatile and flexible for use in many different configurations.

The combination of GRETINA with beams available at HRIBF will allow the community to address critical questions at the frontier of nuclear structure (and nuclear astrophysics) in a unique and powerful way, and will significantly enhance the productivity of the HRIBF research program. The scientific questions addressed will coincide with the main scientific nuclear structure thrusts described in the recent NSAC 2007 Long Range Plan [LRP07], in particular questions such as: *What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?* These key themes are related to other questions such as: *How do extreme proton-to-neutron asymmetries affect nuclear properties, such as shell structure and collectivity? What are the* *properties of doubly magic nuclei far from stability and the alteration of shell structure far from stability? What are the important symmetries and excitation modes in exotic nuclei?*

C. Science highlights

HRIBF has the capability to accelerate approximately 175 radioactive isotopes including 140 neutron-rich species to energies above the Coulomb barrier for all species. More than 50 of these beams, including ^{132}Sn, are available at intensities of 10^6 ions/s or greater. With the IRIS-2 completion, substantial improvements in facility efficiency, reliability, and predictability will be realized [Bee09]. Replacing ORIC with a new cyclotron driver will increase beam intensities significantly and make it possible to carry out many types of experiments such as:

- Measurements of Coulomb excitation in the regions of crucial magic and doubly-magic rare isotopes, including multiple excitation, and magnetic dipole and electric quadrupole moments.
- Single-particle transfer reactions in inverse kinematics to locate and perform detailed studies of crucial single-particle states, including angular correlation and lifetime measurements.
- Two-nucleon transfer reactions to measure symmetries, correlations and excitation modes in neutron-rich systems.
- Explorations of new regions of excitation energy and angular momentum in many nuclei.
- Measurements of isomeric states near closed shells.

The driver upgrade opens many exciting avenues for detailed structure studies of exotic neutron-rich nuclei and the ^{132}Sn region is of special interest [Ter02,Bro05,Cor08,Sev08]. For both Coulomb excitation and transfer studies, this proposed upgrade expands the physics reach of HRIBF by approximately four additional neutrons. The impact of this expansion can be seen in Figure 2. With the new driver and GRETINA, one could extend the trend of measured B(E2) values to ^{132}Sn and ^{134}Sn, where existing measurements using the BaF_2 array could now be repeated with high-resolution Ge detectors, and to ^{138}Te and ^{140}Te (N = 86 and 88).

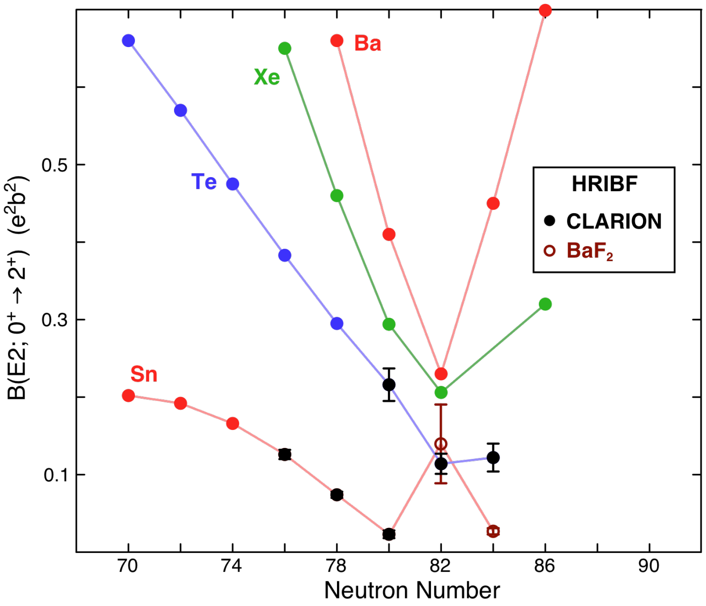

Figure 2: Collectivity measurements in Sn, Te, Xe and Ba isotopes around the N=82 magic shell gap [Rad05].

It is also important to understand in more detail the pattern of collectivity around N = 82 by performing Coulomb excitation measurements on odd-A nuclei in this region. With the upgrade of the HRIBF driver, it will be possible to expand these studies to the odd-A nuclei around ^{132}Sn, e.g.,^{127,129,131,133}Sn, ^{131,133,135}Sb, ^{131,133,135,137}Te, and ^{133,135}I. Such Coulomb excitation studies require gamma-gamma coincidence detection, due to the high level density; GRETINA will provide significantly better capability in this regard than does CLARION.

In this and other regions, (^{9}Be,^{8}Be) and (^{13}C,^{12}C) transfer reactions with GRETINA will be excellent tools to identify new single-particle levels, and for detailed study of selected states. Higher intensities will allow proton-transfer studies as well as neutron transfer, e.g., single-proton states in ^{133}Sb [Cor09]. Light-ion transfer reactions will provide good complementary information.

It will be possible to also explore collectivity around the N = 50 shell closure, to see how similar the trend is compared to the N = 82 behavior shown above. Coulomb excitation measurements could be performed on heavy Ge isotopes with the higher beam intensities associated with the cyclotron upgrade, and the reach can be extended even farther with GRETINA coupled with a new generation heavy-ion detector. With these tools, it should be possible to have the experimental sensitivity necessary to go beyond the closed shell at N=50, and study spectroscopically ^{84}Ge (N=52) and ^{88}Se (N=54). Very little is known about these important nuclei [Hak08,Leb09].

The study of N=Z nuclei, which are laboratories of isospin symmetry and isospin breaking, is clearly of special importance in nuclear physics [Ben07,Sat09]. At HRIBF with the driver upgrade, significant progress will be possible in the study of heavier mass N = Z nuclei which have stalled in recent years due to low cross sections and the lack of necessary beams. This break though will be achieved using reactions with a ^{56}Ni beam, which can now be used ultra-pure since the laser ion source technique enables one to significantly reduce ^{56}Co contamination, which has been a major problem in the past. This development will allow further investigations of the stability of the ^{56}Ni core, and the development of effective interactions above ^{56}Ni [Hon04].

Utilizing the full capabilities of GRETINA for these kind of experiments will require new auxiliary detectors for charged particles and/or recoils, including a 2π CsI array with high granularity, a fine-pitch Si DSSD array, a recoil detector at a distance of around 1 m with ~1° resolution, and a plunger apparatus that interfaces properly with GRETINA and these other auxiliary particle detectors. Also, a BaF_2 array can be used for niche experiments that need the highest efficiency while energy resolution is not so important, e.g., ^{132}Sn in which the first excited state is at 4 MeV. However, an upgrade of the existing BaF_2 array would be highly beneficial to such measurements.

With the cyclotron upgrade and GRETINA, a new set of in-beam gamma-ray spectroscopy measurements become possible for a wide variety of other nuclear structure investigations. For example, unsafe Coulomb excitation measurements have been performed recently with a ^{180}Hf beam (N = 108) on a ^{232}Th target [Tan08] populating rotational bands in the I = 20 range. The expected alignment in the Hf nucleus is delayed relative to lighter isotopes and is at variance with standard theoretical predictions. Experiments at higher spins are needed to resolve this puzzle but this is very difficult to do with stable beams. It is possible to study the N = 108 Yb, Hf and W isotopes with RIBs from an upgraded Holifield facility, using ^{132}Sn and ^{134}Te beams with ^{48}Ca and ^{50}Ti targets.

Such in-beam spectroscopy measurements would require GRETINA, which will have detection efficiency similar to Gammasphere but also will provide vastly superior Doppler reconstruction for inverse kinematics. It seems reasonable to set the limit for use of fusion-evaporation reactions at 1x10^6 particles/s for 100 mb cross sections in favorable Q-value cases. Such RIB-induced reactions will allow measurements of level structures at high excitation energies and spins as well as lifetimes using the DSAM technique where the inverse kinematics are a real benefit.

There are many opportunities here and the success with this type of RIB-induced fusion reactions at N = 108 would allow the first opportunity to explore the spectroscopy of Yb, Hf, and W nuclei with N > 108. Possible reactions to populate these isotopes at high spins include ^{134}Sn and ^{136}Te beams with ^{48}Ca and ^{50}Ti targets. Recent calculations of Ref. [Rob09] suggest this is a region where ground states could have static triaxial shapes. Studies of level structures and lifetimes would test this exciting prediction.

Developing this program at the upgraded HRIBF to investigate the limits of nuclear structure would be an effective pathway to in-beam spectroscopy measurements at FRIB with GRETA. We should not forget that looking at highly excited states in exotic nuclei allows one to chart trends and thus extrapolate how the single-particle levels are changing even farther from stability, especially the behavior of intruder shells which play a key role in defining the magic numbers.

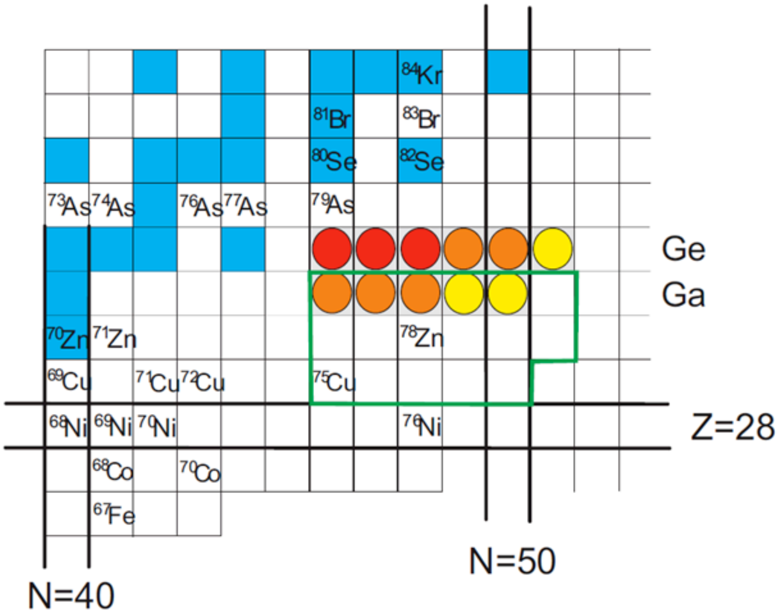

Figure 3: Heavy Ge and Ga isotopes that could be studied with accelerated RIB beams after the driver upgrade with rates of 10^6 particles/sec (yellow), 10^7 particles/sec (orange), and 10^8 particles/sec (red).

Exploring the doubly magic region around Z = 28 N = 50 ^{78}Ni is another high priority for nuclear structure studies [LRP07]. Yrast isomers have been found in Ni isotopes, and now the focus is on expanding these studies to isomers in neutron-rich Cu and Zn isotopes. In Cu isotopes, the goal is to find yrast configurations dominated by $\nu g_{9/2}$ configurations similar to the known $(\nu g_{9/2})^2$ excitations of Ni isotopes and to investigate the role of proton-neutron residual interactions between $f_{5/2}$, $p_{3/2}$ protons and $g_{9/2}$ neutrons [Lis04]. In Figure 3 heavy Ge and Ga isotopes are highlighted that could be studied with accelerated RIB beams after the cyclotron upgrade with rates of 10^6 particles/sec (yellow), 10^7 particles/sec (orange), and 10^8 particles/sec (red).

In addition, the whole chain of Ni isotopes becomes accessible to examine in detail the $(\nu g_{9/2})^2$ isomers. Work is progressing on a new dual microchannel plate detector system for study of nanosecond isomers in these nuclei.

Magnetic moments have long played an important role in nuclear structure physics. They reveal sensitive information about the contributions of protons and neutrons to the wave function since their intrinsic magnetic moments are very different and have opposite signs. Increasingly efficient multi-detector/position sensitive systems for both particle and gamma detection make the detection of weakly produced activities and the measurement of angular properties of decay more straightforward. A key component of the HRIBF nuclear structure program will continue to be g-factor measurements. These experiments are presently being performed at HRIBF with RIBs, but will extend to even more exotic nuclei with the cyclotron upgrade. Coupled to this experimental program is a need to understand the theory of the RIV (recoil in vacuum) mechanism.

The topic of shape co-existence has always been a fascinating topic yielding a great deal of important physics [Woo92]. One example ripe for further study is that of the Ge isotopes where spherical, weakly-deformed and well-deformed shapes are known to co-exist. Many questions exist but with the cyclotron upgrade a series of few-step Coulex studies become possible. These measurements together with a systematic program with decay and transfer information promise the opportunity of providing key-insight into shape coexistence near sub-shell gaps.

Finally, an urgent need that cuts across the whole experimental program now and in the future is the capability to have enriched stable isotopes for targets and the manpower and expertise to fabricate these essential targets. After investing so significantly to create such exotic beams together with building the sophisticated detector systems needed to record the reaction signals, we must not forget that without the right target, an experiment will not be successful. This targetry capability is critical to the future of our subject. This issue must be considered and discussed as the community moves to new and upgraded RIB facilities.

Nuclear structure (decay spectroscopy)

A. Overview

Studies of spontaneous nuclear decays of ground- and isomeric states play an important role in nuclear research. The phenomena determining nuclear decay properties, e.g., lifetimes and branching ratios, are ultimately driven by the underlying structure of the nucleus. Decay studies can be made at very low rates of produced nuclei, which means that very exotic systems are investigated using the most sensitive spectroscopic methods. These investigations can be and are used to reveal the new nuclear structure phenomena ahead of other experimental methods, thus making it a tool where the frontiers of experimental and theoretical nuclear matter research coincide.

Beyond basic nuclear research, there is a strong need for nuclear decay data in astrophysics and applied research. The astrophysics needs are driven by nucleosynthesis models involving nuclei very far from the valley of beta stability. There is an obvious need for experimental decay data that would be used to verify and benchmark nuclear models providing theoretical input for the regions outside the frontier of the known nuclei. In the "nuclear power revival" era, there is also a renewed interest in investigating the nuclear fuel cycle in order to improve the viability of energy production from fissionable materials. New focus has to be given to studies of fission products, which can be abundantly produced in the new reactor designs. In a similar manner, decay data from both "precision" and "exploratory" studies play important roles in the research related to stockpile stewardship and homeland security.

All these important studies will be addressed at the upgraded HRIBF. The HRIBF equipped with a new driver will continue to be a world-leading laboratory for the decay studies of exotic nuclei, in particular for the large variety of ^{238}U fission products. One should note that the current predictions of the rates to be achieved for new neutron-rich nuclei at the next generation ISOL facilities are based on extrapolated cross-sections and half-lives. The upgraded HRIBF will be in a position to reach the fission products at the limits of applicability of the ISOL method and help to guide future directions of radioactive ion beam facilities including FRIB.

The advanced measurement techniques and detector arrays, already available or under construction at the HRIBF, will facilitate the decay studies at the upgraded facility. The high-resolution RIB injector magnet combined with post-acceleration in the HRIBF Tandem allows us to obtain samples of neutron rich isotopes with very high purity and measured intensity [Gro05]. The detector arrays include the Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS) with its Clover Array for Decay Spectroscopy Studies (CARDS), the high-efficiency segmented digital β-delayed neutron counter ^{3}Hen, and the Versatile Array of Neutron Detectors at Low Energy (VANDLE). The high-energy resolution Bellows Electron Spectrometer for Conversion Electrons (BESCA) [Bat03], made at Louisiana State University, and BaF_2 detectors having excellent timing properties complement a variety of "4π" β- and X-ray counters. The construction of the Modular Total Absorption Spectrometer (MTAS), an array having a γ-ray photo-peak efficiency approaching 90%, which is unprecedented in γ-spectroscopy, will facilitate the measurements of the true distribution of the β feeding pattern followed by γ-ray radiation. The mass resolving power of the HRIBF decay studies will be improved by at least an order of magnitude after the commissioning of the Oak Ridge Isomer Separator and Spectrometer (ORISS). ORISS together with MTAS will be the system of choice for the verification and correction of the spectroscopic data used for the licensing process and operations of nuclear reactors.

The investigations of fission products will be complemented by experiments reaching new nuclei produced in fusion-evaporation reactions. The driver upgrade makes possible the use of proton-rich radioactive projectiles to create exotic compound nuclei allowing the study of the evaporation products at the HRIBF Recoil Mass Separator (RMS).

B. Evolution of nuclear structure

Studies of the evolution of nuclear structure for nuclei with extreme ratios of neutrons to protons follow the main directions in modern nuclear structure physics. Understanding the origin of this evolution and its consequences, see, e.g., Refs. [Dob94, Dob98, Ots05, Dob07, Bri07, Col07, Ots10], is the main science driver for these investigations. The merging of effective field theories with *ab initio* many-body methods [Hag08] and linking *ab initio* methods with energy density functional theories offer great promise for a truly quantitative description of atomic nuclei [THE05, Ber07]. However, we don't yet fully understand how the many-body forces evolve as we add or remove many nucleons to and from stable nuclei [Hjo09].

The HRIBF with an upgraded driver accelerator will allow us to identify nuclear decays in the unknown territories of the nuclear chart. Two key regions to be studied are located in the vicinity of exotic doubly magic ^{78}Ni and ^{132}Sn nuclei. The single-particle orbitals with high angular momentum present near these doubly magic nuclei offer an excellent opportunity to test the effects of the proton-neutron interaction, see Figure 4. Single-particle properties of the nucleus ^{132}Sn have recently been extracted from a pioneering experiment at HRIBF [Jon09], showing that this doubly magic nucleus is perhaps the very best of its kind. This has important consequences for both theoretical modeling and experimental studies of nuclei in this mass region, with large implications for nuclear astrophysics [Dil03]. It was expected earlier [Ots05, Dob07] and confirmed recently [Fla09,Ily09] that the interaction of protons with neutrons filling the $1g_{9/2}$ orbital between N=40 and N=50 causes a change in the energy separation within the proton spin-orbit partner pairs, specifically the $\pi 2p_{3/2}$-$\pi 2p_{1/2}$ and $\pi 1f_{7/2}$-$\pi 1f_{5/2}$ orbitals. This results in a change of the ground-state configuration in Z=29 Cu isotopes, from $\pi 2p_{3/2}$ in ^{73}Cu to $\pi 1f_{5/2}$ in ^{75}Cu [Fla09,Hon09] and ^{77}Cu [Ily09]. Decay spectroscopy studies at the upgraded HRIBF will provide a perfect opportunity to verify the expected merging of the $\nu 3s_{1/2}$ and $\nu 2d_{5/2}$ states as Z=28 is approached, and a potential weakening of the ^{78}Ni core for nuclei beyond N=50. The β- and β-delayed neutron decays populating odd-N isotopes (N>50) of Zn, Ge and Se will help to establish the energies of neutron levels near the Fermi surface. The β- and βn-decays of odd-Z nuclei like Cu, Ga and As will define the properties of the 2^+ and 4^+ levels in the ground-state band in the N=52 to N=58 isotones. These decay studies should offer the first hints for the emerging N=58 neutron energy gap, see Figure 4 (upper panel), and the possibility that nuclear properties will create a $3s_{1/2}$ neutron halo nuclei beyond ^{78}Ni [Win10].

The dramatic changes in the low energy structure of nuclei are also observed just beyond doubly-magic ^{132}Sn, see, e.g., a sudden drop in the energy difference between the $7/2^+$ ground state and $5/2^+$ first excited state in ^{135}Sb, a nucleus with three particles above the doubly magic core [Kor05, Mac07]. The relative energies of the $\pi 1g_{7/2}$ and $\pi 2d_{5/2}$ states are actually expected to increase in the region beyond ^{132}Sn, with a simultaneous decrease in the energy for the $\pi 2d_{3/2}$ orbital, see Figure 4 (lower panel). These effects can be studied and understood using β-decay data on neutron-rich In, Sn and Sb isotopes with neutron numbers between N=82 and 92, see also [Col07, Bri07]. These exotic isotopes, potentially up to ^{138}In (N=89), ^{140}Sn (N=90) and ^{142}Sb

(N=91), can be expected at the level of 10 to 100 ions per hour, sufficient for decay studies with high selectivity at the upgraded HRIBF.

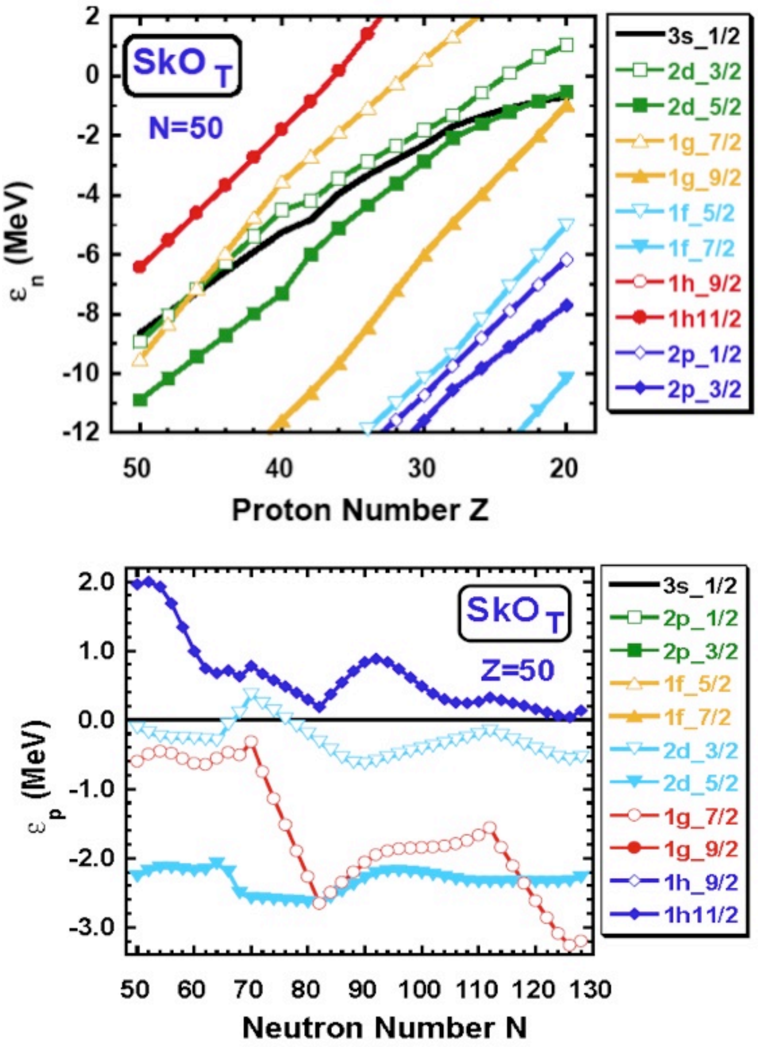

Figure 4: Theoretical evolution of single-particle levels near the doubly magic nuclei ^{78}Ni and ^{132}Sn [Dob09]. The modeling is based on spherical HFB calculations with an SkO$_T$ functional [Rei99] including the tensor term [Zal08, Kar08]. Upper panel: neutron orbitals around N=50 are drawn as a function of atomic number Z. The merging of the $\nu 3s_{1/2}$ and $\nu 2d_{5/2}$ states can create an N=58 sub-shell closure, eventually replacing the N=50 energy gap. Lower panel: proton orbitals in the region of ^{132}Sn are drawn as a function of neutron number N. One can see the changes in the properties of the $\pi 1g_{9/2}$, $\pi 2d_{5/2}$ and $\pi 1h_{11/2}$ orbitals predicted to occur after crossing of the N=82 magic neutron number.

Understanding the competition in β-decay between the allowed Gamow-Teller and First-Forbidden transformations of neutrons into protons is crucial for the analysis of the half-lives and β-delayed neutron probabilities in neutron-rich nuclei. Studies of the β-strength function can be performed at the upgraded HRIBF with pure and intense beams of ^{238}U fission products with a variety of detectors allowing measurement of the full β-decay feeding pattern. These studies will be used to develop a universal description of the β-strength function using an extended energy-density functional approach and accounting for both the allowed Gamow-Teller and first-forbidden neutron-to-proton transformations, see, e.g., [Bor03, Bor05, Win09]. The recent work at HRIBF has demonstrated [Win09] that the current reference data for β-delayed neutron emission [Pfe02] can be wrong by large factors, see Figure 5. A major revision of our understanding of this important decay mode is expected. Particularly important are the studies beyond the closed neutron shells at N=50 and N=82, where first-forbidden beta decays are expected to reduce the β-delayed neutron branching ratio and simultaneously decrease the half-lives, see Figure 6.

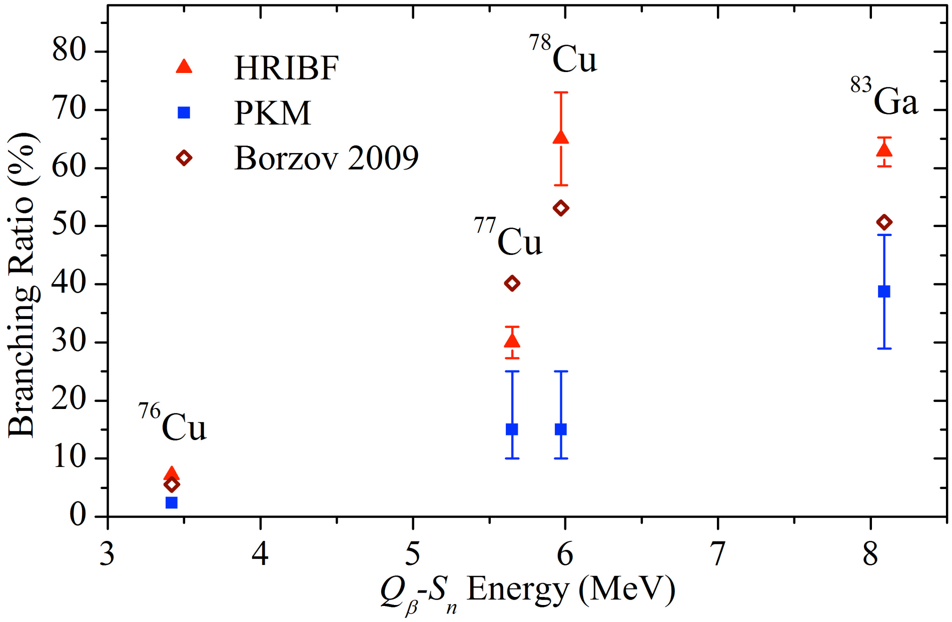

Figure 5: The probabilities for β-delayed neutron emission as a function of the energy window Q_β - S_n . The results of the recent HRIBF experiment (red points) are compared to those listed in [Pfe02] (blue points) and to new theoretical estimates (brown points) [Bor05, Win09]. These new theoretical estimates account for the inversion of $\pi 1f_{5/2}$ and $\pi 1p_{3/2}$ orbitals in the Cu isotopes with A>75 and new experimental data on the S_n and Q_β-values.

The Recoil Mass Spectrometer (RMS) is used to study nuclear structure for nuclei produced through heavy ion fusion-evaporation reactions, primarily for proton-rich nuclei. The intensity of proton-rich beams like doubly magic ^{56}Ni and ^{69}As should be sufficient to produce detectable amounts of very exotic nuclei. In particular, it should be possible to reach new nuclei beyond the proton drip line in the Re to Au region [Pag09]. In addition, the intensities of a few neutron-rich beams such as ^{87}Br may allow us to identify and study new isotopes of very heavy nuclei in the Z=100-110 region as a part of the study of superheavy elements.

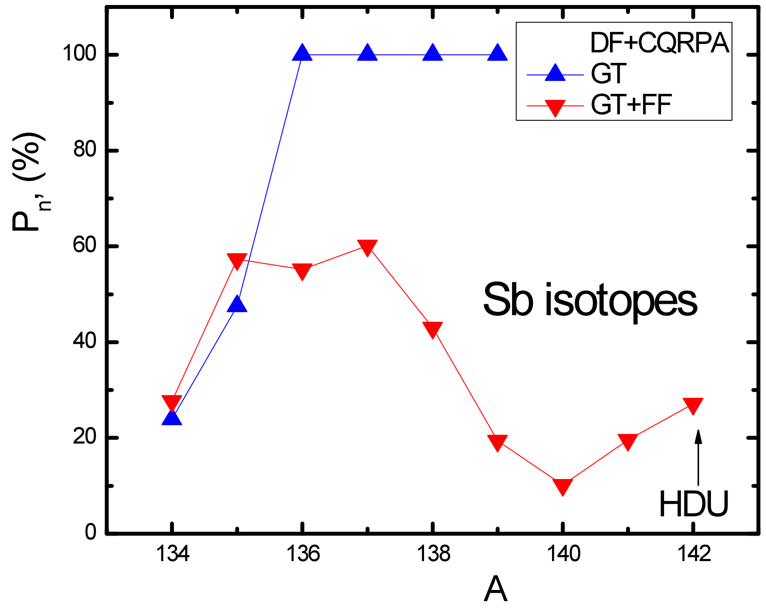

Figure 6: The β-delayed neutron branching ratio P_n for Z=51 Sb precursors. The P_n values are analyzed using the energy density functional of Ref. [Fay00] in its DF3 version [Bor96] in the continuum quasi-particle random phase approximation (CQRPA). The calculations accounting only for allowed Gamow-Teller (GT) transformation are compared to the modeling taking into account GT and first-forbidden (FF) β-transformations, see [Bor03, Bor05, Bor06, Win09]. The reach of the upgraded HRIBF (HDU) is marked by the arrows.

C. Nuclear astrophysics and decay studies

The decay studies of nuclei far from β-stability help in the analysis of astrophysical processes like the rapid neutron capture (r-) process and the rapid proton capture (rp-) process occurring in high density and high temperature stellar events such as supernovae and X-ray bursts. The decay modes, decay rates, and the properties of ground-state and low energy levels are among the important input parameters for the modeling of these nucleosynthesis scenarios. The results achieved at the HRIBF for nuclei above doubly magic ^{100}Sn have already helped to analyze the rp-process termination path [Lid06, Maz07]. It turns out that the rp-process might end up in a fast loop, including a 0.6 μs activity of α-emitting ^{105}Te, which enhances the α-particle density in the X-ray burst environment. New HRIBF results on βn-branching ratios for very neutron-rich nuclei above doubly magic ^{78}Ni [Win09] are relevant for the analysis of the post r-process isobaric distributions. The βn-emission probabilities (Figure 5), much larger than reported earlier [Pfe02], shift the mass distribution towards lower mass numbers.

New areas for these astrophysics-applicable investigations can be opened by the upgrade of the HRIBF RIB driver. As illustrated in Figure 7, new nuclei, predicted to be produced during the extreme conditions of the r-process for densities up to 10^{26} neutrons/cm^3, can be reached in decay studies. The HDU HRIBF will truly be an "r-process laboratory" providing the half-lives and decay patterns for so far unknown but critical r-process waiting point nuclei [Sch09].

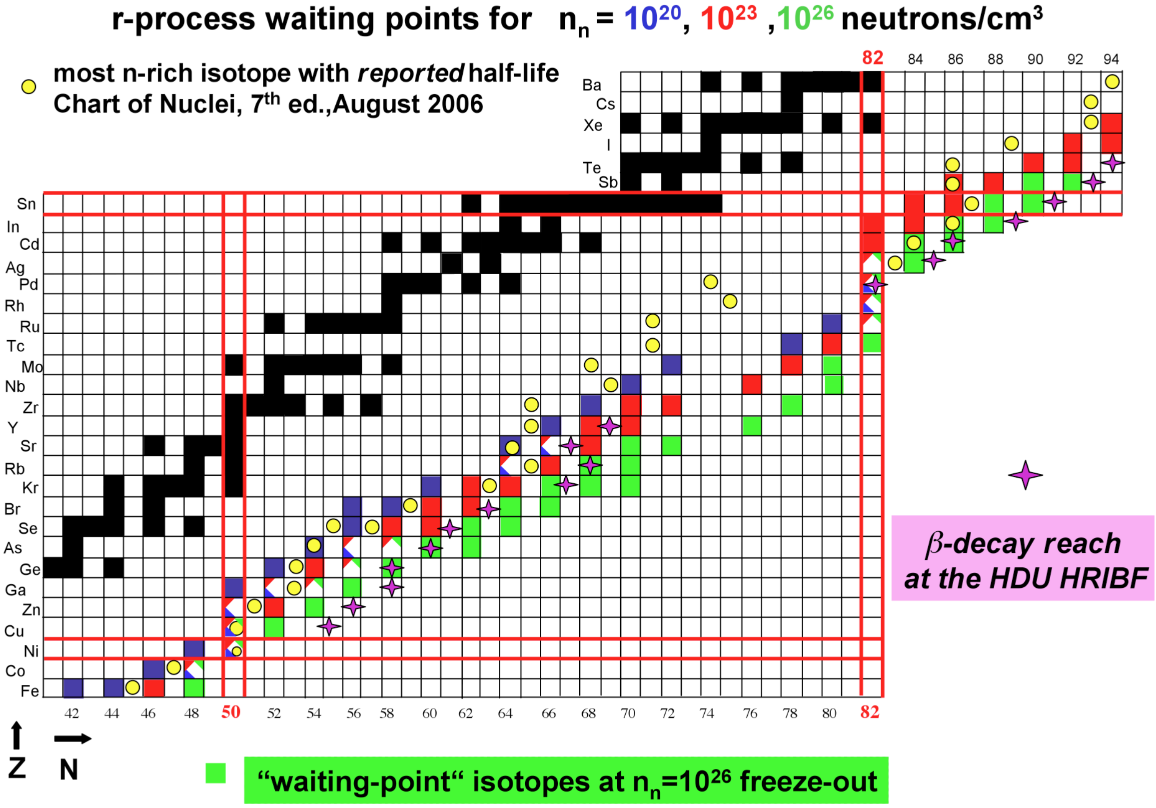

Figure 7: The chart of nuclei showing the predicted path and waiting point nuclei along the rapid neutron capture nucleosynthesis process [Kra06, Thi93, Thi03]. The waiting-point nuclei are indicated for different r-process scenarios involving neutrons at densities of 10^{20} neutrons/cm^3 (blue squares), 10^{23} neutrons/cm^3 (red squares) and 10^{26} neutrons/cm^3 (green squares). Also, the most neutron-rich isotopes with reported experimentally determined half-lives are given (yellow circles). The reach of the upgraded HRIBF in the beta-decay studies is given by purple symbols.

D. Decay studies for nuclear energy and homeland security

The decay properties of neutron-rich isotopes are particularly important for the environments where these nuclei are produced in large quantities during the fission of very heavy nuclei. A nuclear reactor powered by the fission of nuclear fuel is a site where complex nuclear processes occur including the decays of neutron-rich isotopes [AFC06]. Imprecise data on nuclei generated in nuclear fuel may contribute to inaccuracies in theoretical modeling and extrapolations, which can lead to unnecessary or erroneous requirements in the operation of fission reactors [Dan02] as well as nuclear waste handling and potential transmutation [Gud00]. The complex reactor licensing process involves large-scale simulations using the computer code SCALE [SCA76], see Figure 8. In SCALE, there is an irradiation and decay module called ORIGEN (Oak Ridge Isotope Generation and Decay Code), where the individual decay schemes are included [Gau09, ORI09]. The absorption of emitted radiation in bulk nuclear fuel, as well as in the surrounding materials, must be accounted for in the analysis of criticality safety and the radiation shielding of the nuclear reactors. In addition, the transportation and storing of spent nuclear fuel requires precise decay data on the remaining inventory of radioactive materials. This means that the energies and intensities of emitted γ- and β-rays as well as of neutrons have to be precisely known – which is the domain of decay spectroscopy. ORIGEN already accounts for the decays of about 1150 fission products. However, these data, taken from the Evaluated Nuclear Structure Data

File, are often outdated and sometimes inaccurate. For example, Ref. [Win09] observed serious discrepancies between recently measured beta-delayed neutron branching ratios and the previously best values [Pfe02], see Figure 5. Total Absorption Spectrometry (TAS) is the most precise method to obtain a correct picture of "decay heat" related to βγ-emission (all γ-ray radiation emitted after β-decay). So far, there are only a few tens of radioactive neutron-rich nuclei, which have been measured with early, small versions of a TAS device [Gre92, Gre97, Jok08]. HRIBF has a funded project to construct a modular NaI detector array (MTAS) which will be larger and more efficient than previous TAS detectors.

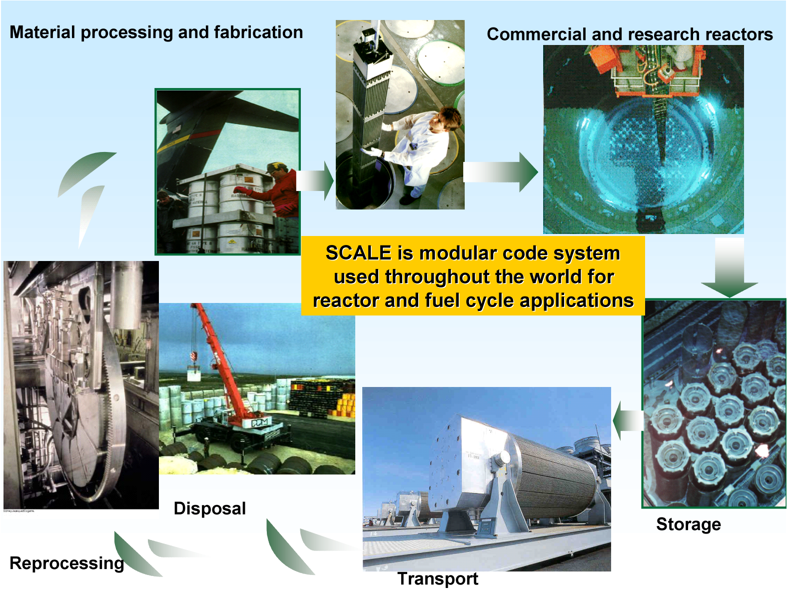

Figure 8: Schematic demonstration of the applicability of the calculations performed within the Standardized Computer Analyses for Licensing Evaluation (SCALE). The Oak Ridge Isotope Generation and Decay Code (ORIGEN), accounting for the individual decay schemes of fission products, are parts of the SCALE package.

Many nuclei occurring in the nuclear fuels during power reactor operation can be produced in proton-induced fission of ^{238}U at the upgraded HRIBF. Most of the elements can be released from the HRIBF ion sources in sufficient amounts to perform decay spectroscopy measurements. The funded construction of MTAS and VANDLE, in conjunction with the upgraded production capabilities and excellent separation of radioactive species, will allow us to provide precise landmarks for the "decay heat" analysis. The ORISS, already funded and to be commissioned at HRIBF in 2013, will add an isomer separation capability to the existing isobaric mass separation for the HRIBF decay studies. Beta-delayed neutron emission from very neutron-rich nuclei produces a spectrum of neutron energies up to several MeV. Such fast neutrons will contribute to the quantity of neutrons in the next generation reactors. Neutron energies and intensities will be measured using separated beams with on-line verified intensities using the ^{3}Hen and VANDLE neutron arrays. These data are particularly needed for the advanced reactor concept, where the utilization of fast neutrons for energy production is being planned. All these important data can be measured at the HRIBF, reliably operating after the driver upgrade. The stockpile stewardship and homeland security programs will also profit from the advanced detection methods and precise spectroscopy data, which can be gained at the upgraded HRIBF. For both programs, the fissile material interrogation methods require precise data on high-energy γ-ray transitions emitted by fission products.

Reactions

A: Overview

The Strategic Plan for HRIBF [HRI09] suggests that a major research area for HRIBF will be a study of the synthesis of the heavy elements. The research implementation plan calls for studies of the fusion mechanism with n-rich radioactive beams culminating in 2015 in accord with the DOE Office of Science Milestone *"Measure properties and production mechanisms of the elements above Z~102 to understand the nature and behavior of these nuclei, and to assist theoretical predictions for the structure and production of superheavy elements."* These studies have already begun with significant progress being made in understanding the fusion of ^{132}Sn [Lia08].

The measurement of direct reactions is critical for understanding the microscopic structure of nuclei away from stability. Such reactions can provide detailed information on properties of the nuclear wavefunction, such as energies, spin-parity assignments and spectroscopic information for individual states. In the neutron-rich regime, understanding the shell structure of neutron-rich nuclei is crucial for developing structure models in this exotic region, and for understanding the nucleosynthesis of heavy elements in r-process events [Sur09, Chi08]. In the proton-rich regime, the technical challenges of measuring directly many reactions that are important for nuclear astrophysics can be circumvented by performing indirect measurements, such as transfer reactions [Koz05, Pai09]. Furthermore, the detailed measurement of direct nuclear reactions away from stability helps the development of more accurate and complete nuclear reaction theory. These aims will address directly a number of DOE Office of Science milestones, including "*Measure masses, lifetimes, spectroscopic strengths and decay properties of neutron-rich nuclei in supernova r-process, and reactions to predict radionuclide production in supernovae"* and "*Measure changes in shell structure and collective modes, from the most proton-rich to the most neutron-rich nuclei accessible, in order to improve our understanding of the nucleus, and to guide theory in every region of the theoretical roadmap (i. e. the lightest element region where ab-initio calculations can be performed, the medium-mass region where effective interactions are used, and the region of heavy nuclei, the domain of density functional theory)."* Furthermore, the development of the techniques used at the HRIBF for these advances will be critical to enable a full exploitation of the beams that will be delivered in the future by FRIB.

To date, the HRIBF has stood at the global forefront for direct reaction measurements using radioactive neutron-rich beams. A number of landmark experiments have been conducted, including the first measurement of a (d,p) reaction on a nucleus understood to be located in the r-process path, ^{82}Ge [Tho05]. Furthermore, the first (d,p) measurements on heavy fission fragments around the doubly magic shell closure at ^{132}Sn have been completed, including (d,p) measurements on ^{130}Sn, ^{132}Sn and ^{134}Te [Koz07, Jon07, Jon09, Pai07b].

We discuss two major areas: the study of fusion and other reactions where the macroscopic behavior of nuclei is being explored and the study of direct reactions. In both these areas, certain key features of the HRIBF upgrade play an important role. The higher beam intensities and improved reliability are central to the new science that can be addressed. For typical fission fragment beams such as ^{87}Br and ^{132}Sn, the increase in beam intensity with the upgrade is estimated to be a factor of 50. Such increases in on-target beam intensities will have a profound impact on the studies with these beams. With these increased beam intensities, one can chop or bunch the beams (with the concomitant loss of intensity) to allow the introduction of improved measurements of reaction product time of flight, etc. One can also undertake the measurement of sub-barrier fusion and other small cross section processes along with undertaking studies with more exotic n-rich projectiles that are not feasible with today's beam intensities. Another important aspect of the increased beam intensities will be the opportunity to employ auxiliary detectors in various studies to measure the emitted neutrons and other particles. Some detailed scientific drivers for this area of research are given below.

B. Reactions leading to the synthesis of the heaviest nuclei

One can extend and better define the systematics *of fusion enhancement* with n-rich projectiles where existing work [Lov06] indicates that the fusion of n-rich nuclei is substantially enhanced beyond that expected from simple geometric considerations. A recent theoretical paper [Bia09] addressed this issue for all known fusion reactions induced by radioactive beams using a quantum molecular dynamics (QMD) model and satisfactorily described all the known data. In this model, the unusual enhancement of fusion cross sections for neutron-rich systems arises from dynamical effects that enhance fusion when there are large N/Z ratios in the neck of the fusing nuclei. Figure 9 shows the world’s data set for fusion reactions induced by n-rich radioactive beams, the difference between the experimentally deduced barriers and simple models like the Bass model along with the QMD calculations. In this area, one would like to extend these studies to new regions of isospin and to study sub-barrier processes where the most interesting aspects of these reactions surface. These latter studies will require the ability to measure fusion cross sections in the sub-millibarn region. Equally important is the study of the isospin dependence of *fusion hindrance* where current experiments [Vin08] indicate an unexpected hindrance of fusion in the most n-rich systems, a paradoxical result that disagrees with some current models of these processes [Swi81]. However, a dinuclear system model prediction [Gia06] has successfully accounted for the hindrance. Microscopic models such as the time-dependent Hartree-Fock method [Uma09] have made significant advances in heavy-ion fusion calculations, and it is anticipated to shed some light on understanding fusion hindrance in n-rich systems. New studies with smaller experimental uncertainties and more sophisticated detectors to allow separation of similar processes such as elastic scattering, inelastic scattering, damped collisions, fusion-fission, etc. are needed.

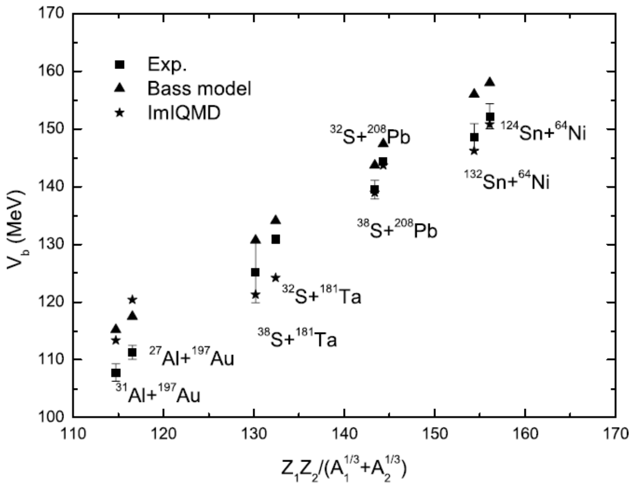

Figure 9: The experimental fusion barriers deduced from reactions involving fusion induced by radioactive and stable beams, predictions of the Bass model and an improved QMD model. (From Ref. [Bia09].)

It has been suggested recently [Zag08] that *multi-nucleon transfer reactions* might be a new path for synthesizing the heaviest nuclei. An upgraded HRIBF can help in exploring these possibilities by extending the range of N/Z available in such collisions leading to an improved understanding of the mechanisms for N/Z equilibration in these reactions. The large N/Z range available in projectiles from an upgraded HRIBF can act as tools to study the sub-saturation isovector equation of state and the role of two neutron transfer processes.

To perform these new studies, one will need to expand the experimental equipment available at HRIBF. The HERCULES detector [Rev05] would seem to offer the opportunity to study sub-barrier fusion utilizing the increased beam intensities of an upgraded HRIBF. The gas-filled Enge spectrometer [Lia99] may also be useful in this regard. A new ion chamber concept under development [Sha09] will prove valuable in separating the similar processes of elastic and inelastic scattering, damped collisions, fusion-fission, etc. There are several types of neutron detectors that measure particle multiplicities and energies, which would be valuable adjuncts to the HRIBF arsenal of detectors. A large gas-filled magnet or solenoid has also been suggested for the study of fusion and transfer reactions. This would replace the Enge spectrometer and increase detection efficiencies.

C. Direct Reactions: evolution of nuclear structure and nucleosynthesis

The beam intensities produced utilizing the new driver at HRIBF will be unparalleled in the US until the FRIB era, enabling the measurement of direct reactions on exotic nuclei that are currently beyond the reach of any US facility. This will extend the reach of the facility in a number of ways. Firstly, it will allow measurements to be performed on nuclei farther from stability, as more intense beams of increasingly exotic nuclei will be available. This will allow for the measurement of reactions on nuclei beyond the N=82 shell closure, such as heavier isotopes of Sn and Te, which are important for freeze-out r-process nucleosynthesis [Sur09], and nuclear structure [Cor08, Kar07], and more neutron rich isotopes around the N=50 shell closure, such as ^{84}Ge. Furthermore, the increased intensity will make possible the measurement of reactions on nuclei farther from the shell closures. For example, it can be seen how quickly the single particle strengths become fragmented by the addition of two protons to the ^{132}Sn core, by considering the levels populated in (d,p) reactions in ^{134}Te compared to ^{132}Sn [Koz07, Pai07b]. At higher level-densities, standard charged-particle measurements in inverse kinematics are typically insufficient to resolve the levels populated. Coincident measurement of de-excitation gamma rays improves the resolving power of the technique considerably [Cat05], but at the expense of detection efficiency. The increased intensity provided by the upgraded facility will allow this technique to be applied to the study of many more nuclei, and will provide opportunity to develop the technique for use with GETINA and GRETA in the long term. Additionally, the higher beam intensities will enable the measurement of (d,n) reactions, utilizing the VANDLE array [Ciz09a] of scintillator detectors currently under development. Such measurements are made challenging by the low efficiencies associated with spectroscopic neutron measurement. The beam intensities available at the upgraded facility will greatly expand the number of nuclei that can be studied effectively with this device.

An additional approach, supplementary to the inverse kinematics measurements, is to make implanted targets of relatively long-lived radioactive species. The implantation would be achieved using the low-energy beam directly from the RIB platform, and be performed at a location where subsequent reactions on these targets could be performed in-situ. These targets could then be used to measure transfer reactions in normal kinematics, by delivering a light ion beam from the tandem accelerator, and utilizing the high resolution obtainable with the Enge magnetic spectrograph for the measurement of reaction products. Such an approach has the additional benefits that it can be used on species that cannot be accelerated by the tandem (as they do not make negative ions). The high intensities required for the implantation would benefit greatly from the proposed upgrade, thus vastly expanding the number of species that could be studied with this technique.

The effective output of any facility is dependent on both the beams and the instrumentation that is available. There are many developments currently underway at the HRIBF that will enable the effective use of the beams that the upgrade will provide. In addition to the ORRUBA detector array [Pai07a], which has made possible many of the measurements in recent years, a second-generation array is under development [Bar09a], which will improve on aspects of the original design by incorporating new ASIC technology. Such silicon arrays will be coupled to high resolution germanium detector arrays (such as GRETINA) to develop the techniques for (d,pγ) measurements which will be important for future studies at FRIB. The use of a magnetic solenoidal spectrometer, such as the HELIOS device at Argonne National Laboratory [Wuo07], would extend the sensitivity for transfer measurements.

Concurrently, it is of paramount importance that attention is paid to the development of nuclear reaction theory [Pan07], which is crucial to the reliable analysis of the measurements that can be performed at HRIBF. In the age of stable-beam nuclear physics, the abundance of facilities allowed for a very systematic approach to reaction theory to be undertaken, resulting in such important achievements as global parameterizations of optical potentials near stability. It is clear that, as one moves into more exotic regions, the extrapolations of these parameterizations is unreliable, and it is necessary that the community endeavor to develop such parameterizations constrained by reactions, such as light-ion elastic scattering, measured away from stability. This, combined with the intense competitive pressure for beam time at RIB facilities, makes reliability a crucial factor if such an undertaking is to be successful. The tremendous boost to facility reliability that will be achieved with the proposed upgrade would be critical to this endeavor.

Nuclear Astrophysics

A. Overview

In stellar explosions, temperatures of millions to billions of degrees and densities of thousands to millions of gm/cm^3 enable unstable nuclei formed by fusion reactions to undergo additional reactions before decaying back towards stability. These thermonuclear reactions involving unstable nuclei generate energy that, in some cases, powers the outburst. These reactions also evolve the isotopic and elemental composition of the system and synthesize the elements of life. Our understanding of these explosions, however, has not kept pace with observations from the Hubble (visible), RXTE (X-rays), INTEGRAL (gamma rays), and other sophisticated orbital platforms. Some of the unsolved puzzles in this exciting research field include: (a) understanding the production and destruction of long-lived radioactive isotopes -- whose decays are the target of gamma ray observatories and can help diagnose the explosion mechanism; (b) accounting for the total energy generated by these cosmic blasts; (c) explaining the total mass ejected from explosions and its detailed composition; (d) understanding the detailed mechanisms – thermonuclear and other -- that cause these outbursts; and (e) correlating models of element burning with their cosmic sites – such as determining the site of the astrophysical r-process that creates the heaviest elements.

Reactions on unstable nuclei play a critical role in addressing these questions, as pointed out in both the RISAC report on *"The Scientific Opportunities with a Rare-Isotope Facility in the US"* [RISAC] and the 2007 NSAC Long-Range Plan "*The Frontiers of Nuclear Science"* [LRP07]. Since its inception, research at HRIBF has made leading contributions in this area – indeed, the first scientific result from HRIBF, and the first measurement in North America with a reaccelerated radioactive beam, was the measurement of ^{17}F + p scattering in 1999 [Bar99] done to elucidate element burning in novae. Another major milestone was our ^{82}Ge(d,p)^{83}Ge experiment [Tho05], which was the first measurement of a transfer reaction on an unstable nucleus in or near the rapid neutron capture process (r-process) reaction path.

The 70 MeV cyclotron upgrade will greatly increase the research capabilities at the HRIBF for the next decade and beyond. With significantly increased beam intensities, greatly improved reliability, and enhanced capabilities for new beam development, this upgrade will enable us to make measurements of reactions on, and structure of, many nuclei not possible at our present facility. In some cases, beam rates at HRIBF with the 70 MeV cyclotron upgrade will be competitive with or surpassing *any* planned future facilities — including FRIB. Below we detail the expected improved capabilities from the 70 MeV cyclotron upgrade for studies in nuclear astrophysics.

B. Neutron-rich beams

In 2001, the National Research Council Committee on Physics of the Universe listed "How were the elements from iron to uranium made" as one of the "Eleven Science Questions for the New Century" [NAS03]. These elements are primarily synthesized by two astrophysical thermonuclear burning processes, the r-process and the slow neutron capture process (s-process). The s-process occurs in distended AGB stars, and involves low energy neutron captures on stable (and a few unstable) isotopes. The r-process mechanism and astrophysical site, on the other hand, remains a topic of intense international study and debate. Observations of galactic chemical evolution indicate that this mechanism is associated with core-collapse supernovae, with merging neutron stars possibly also contributing. With much of the r-process evolution occurring along isotopic chains in (n,γ) - (γ,n) equilibrium linked by beta decays, knowledge of nuclear masses and decay properties is needed to calculate sequences of reactions as far as the neutron-drip line. In addition, sensitivity studies [Sur01, Sur09, Beu09] have indicated that determination of neutron capture rates on unstable nuclei close to the N=50 and N=82 closed neutron shells are also important. In some cases, such as neutron capture on ^{130}Sn [Beu09] and neighboring nuclei shown in Figure 10 [Sur09], capture rates significantly influence final predicted r-process abundances for nuclei with a wide range (over 120 units) of mass.

For nuclei near the N=50 and N=82 closed neutron shells, there is an excellent overlap of data needs for r-process studies with HRIBF radioactive beam intensities. This has enabled us to launch a pioneering series of (d,p) transfer reactions on neutron-rich unstable nuclei in or near the r-process path. The (d,p) reaction "simulates" neutron capture by preferentially populating states that have a strong single particle nature — precisely the levels that are most important for direct neutron capture. Our measurements of (d,p) on ^{82}Ge [Tho05] and ^{84}Se [Tho07] at the N=50 closed shell, and on ^{130}Sn [Koz08], ^{132}Sn [Jon07, Jon09], and ^{134}Te [Ciz09] at the N=82 closed shell, have provided important new level information on these neutron-rich nuclei. They have given us the first glimpse of the evolution of single particle strength of low-lying levels as a function of neutron number.

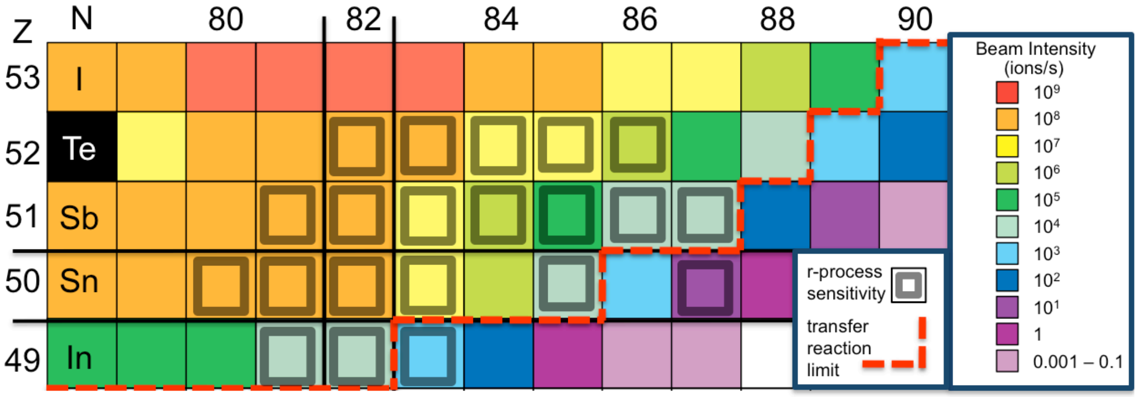

Figure 10: Neutron rich beam intensities with the 70 MeV cyclotron upgrade shown with transfer reaction limit and nuclei identified in a recent r-process sensitivity study [Sur09].

Going beyond the first glimpse, however, requires significantly higher intensities of neutron-rich beams. The 70 MeV cyclotron high-power hadron driver upgrade will provide an immediate intensity gain of a factor of 8 for neutron-rich beams produced by proton-induced fission, and even higher gains for those produced via neutron-induced reactions using a neutron-generating target with (d,n) or (p,xn) reactions. We detail below the exciting physics studies that such intensity gains will make possible.

B.1. Mass and decay property measurements

Our knowledge of the exotic neutron-rich nuclei, including most of the nuclides along the r-process path, is very limited. Experimental information is scarce even for fundamental properties such as masses and half-lives needed to calculate reaction flows in the r-process. With the boosted intensities of neutron-rich nuclei anticipated from the 70 MeV cyclotron upgrade, we will be able to make the first measurements of numerous masses and half-lives of neutron-rich nuclei in or near the r-process path – nuclei inaccessible at our current facility nor anywhere else at present. This includes nuclei such as ^{88}Ge near the $N=50$ closed neutron shell and ^{138}Sn at the $N=82$ closed shell. Typically these measurements require at least 0.1 to 1 particles per second, and the overlap with nuclei relevant for the r-process path can be seen in Figs. 10 and 11.

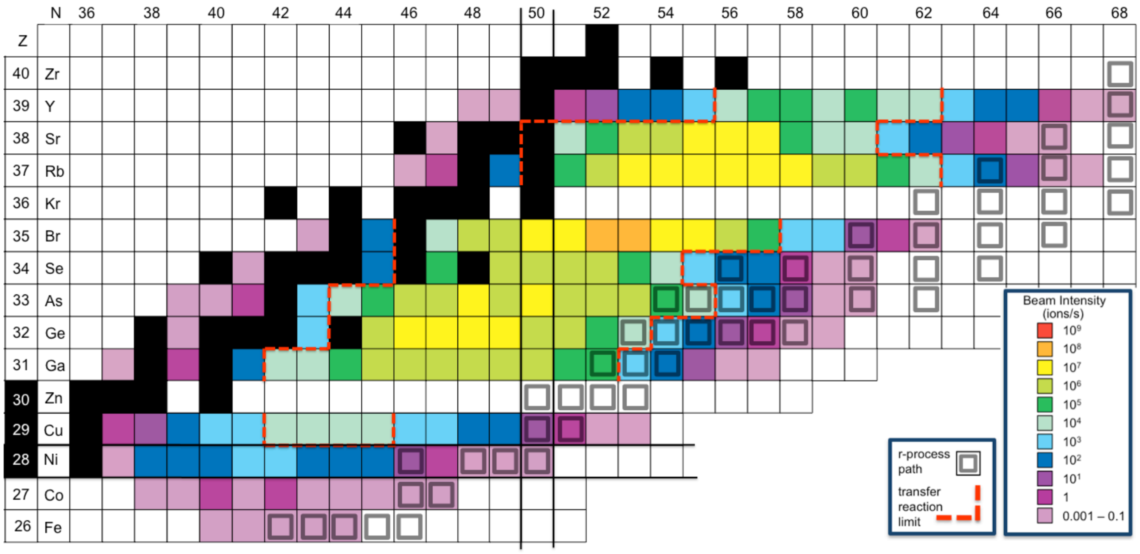

Figure 11: Neutron rich beam intensities with the 70 MeV cyclotron upgrade shown with transfer reaction limit and nuclei typically along the r-process path. Mass and decay measurements can be made for nuclei with intensities greater than 0.1 ions per second.

The instrumentation for such studies either already exists or is being developed at HRIBF. The ORISS system, with its multi-pass-time-of-flight approach, will enable direct mass measurements of many of these nuclides, while we can use transfer reaction Q-value measurements to extend our reach to other exotic nuclei. Some transfer reaction measurements will utilize the upgraded ORRUBA and VANDLE systems, while others will use the Enge Split-Pole spectrograph. In particular, proton transfer reaction measurements at HRIBF provide an approach that is complementary to the Penning trap mass measurements of isotopic chains pursued at numerous other facilities. For example, the masses of Sn isotopes up to ^{134}Sn have been precisely measured at the ISOLTRAP [Dwo08]. With the (d,^{3}He), (t,^{3}He), or (^{10}Be,^{9}B) reactions, new mass values with uncertainties as low as 30 keV could be obtained for several In isotopes, and the (^{4}He,d), (^{4}He,p), (^{6}Li,^{4}He), or (^{6}Li,^{3}He) reactions can be used to determine the masses of several Sb isotopes for the first time, or improve on previous results that have large uncertainties.

Regarding decays, there are certain nuclei such as ^{78}Ni where individual decay lifetimes can have a significant impact on final r-process abundances [Hos05]. The LeRIBSS system will also have the potential to discover and study several new neutron-rich isotopes in the regions critical for the understanding of the r-process at low and high neutron fluxes (see Figure 11). Pushing further out towards the neutron drip line also serves to extend the physics reach of our r-process studies by probing earlier times and higher temperatures.

B.2. Increasing the range

With beam intensities of 10^4 pps required for spectroscopic measurements with the (d,p) reaction, the number of nuclei we can investigate with this technique is limited. The significant intensity increase of beams near the N=50 and N=82 closed shells will enable transfer reactions on r-process nuclei not currently possible. These include ^{134}Sn(d,p)^{135}Sn, ^{84,85}Ge(d,p)^{85,86}Ge, and others. It is likely that the higher currents will enable us to push our measurements by up to four isotopes further away from stability than currently possible. Such new measurements towards the neutron drip line extend the physics reach of our r-process studies by probing earlier times and higher temperatures in the explosion.

B.3. Systematic measurements over a broad range of isotopes

Higher intensity neutron-rich beams from the 70 MeV cyclotron upgrade will enable systematic measurements of quantities such as single-particle strengths, excitation energies, spin/parities, and B(E2) values over a significantly expanded range of isotopes than currently possible. Such systematic measurements would provide strong constraints on nuclear models, and the power of this constraint only increases as nuclei further from stability become experimentally accessible. For example, while we have measured (d,p) on ^{124,130,132}Sn and have approved measurements on ^{126,128}Sn, pushing this to more neutron rich species like ^{134}Sn and beyond will require the higher intensities that the 70 MeV upgrade can deliver.

B.4. Improved quality of measurements

In all of our previous (d,p) measurements, the yield of the lowest energy protons -- corresponding to levels near the neutron threshold – is so low (due to beam intensities) and broad (due to straggling of protons exiting the target) that we cannot distinguish them from the background of detector noise which is independent of beam intensity. Higher beam intensities will likely boost the yields of these low energy protons above the noise. When combined with (funded, in progress) improvements in our detection systems, we will be able to extend our physics reach to higher energy levels in all the nuclei we study.

B.5. Complementary measurements

Higher beam intensities from the 70 MeV cyclotron upgrade will enable us to measure a wide variety of transfer reactions, going beyond our current (d,p) studies. Using multiple reactions to populate levels of interest will give valuable complementary information that will provide strong constraints on nuclear models. For example, with 10^8 pps of ^{132}Sn, we will have the exciting possibility of measuring (d,t), (^{3}He,α), (t,p), (^{3}He,n), (d,p), and (d,^{3}He) at HRIBF – in essence, using this beam as a powerful *spectroscopic tool* to investigate all neighboring nuclei. Such complementary measurements can also greatly aid determinations of level densities and spin distribution functions critical for statistical model calculations of (n,γ) cross sections.

B.6. Coincidence measurements

We have performed two stable beam experiments at the HRIBF to develop the techniques needed to make (d,pγ) coincidence measurements on heavy n-rich unstable nuclei [Ciz07,Pet09]. The high resolution detection of gamma-rays emitted after populating levels with (d,p) is important for determining neutron capture rates that proceed directly via levels with strong single particle nature, as well as for surrogate reaction studies where the reaction mechanism is of a statistical nature. For direct reactions, coincidence measurements promise to provide the highest resolution spectroscopic studies on the final state nuclei – and therefore the strongest constraints on nuclear models far from stability. Level parameter measurements are improved in a number of ways by using (d,pγ): by detecting gamma rays with high resolution Ge detectors; by increasing sensitivity to nuclear levels with higher excitation energies (lower proton energies) that cannot presently be differentiated from background solely using proton detection; and by enabling measurements of nuclei with a higher density of states than possible with (d,p) proton energy measurements. Utilization of the (d,pγ) reaction is also a very promising approach to providing a surrogate for neutron capture via a compound nuclear mechanism [Esc07]. Here, it will be crucial to measure the decay of compound nuclei in order to constrain input parameters (level densities, gamma strength functions) for statistical model (n,γ) cross section calculations.

However, we do not currently have sufficient intensities (~10^7 pps) of unstable beams to carry out such coincidence measurements. The combination of higher intensity beams from the 70 MeV cyclotron upgrade, coupled with GRETINA and the super ORRUBA charged-particle array, will enable us to make the *first ever* use of this powerful new technique with radioactive beams. Possible nuclei of astrophysical interest include the many with intensities larger that 10^7 pps, such as ^{136,137}Te(d,pγ)^{137,138}Te which is important in the r-process. Not only will HRIBF studies of such reactions provide valuable data needed for astrophysics studies, but they will also serve to develop a technique likely to be a mainstay at future facilities like FRIB.

We have outlined above the new physics we can pursue as a result of enhanced intensities of n-rich beams available from the 70 MeV cyclotron upgrade. The new accelerator itself has a unique feature enables a further extension of our physics reach via the production of long-lived neutron-rich radioactive nuclei.

B.7. Radioisotope production

The dual port extraction capability of the 70 MeV cyclotron enables the simultaneous extraction of two beams of deuterons or protons with different energies. While one beam is used for normal RIB production at IRIS1 or IRIS2, the other can be used for the parasitic production of long-lived radionuclides. For species with sufficiently long lifetimes (~ months or greater), these can be implanted into target backings that can be used in separate (d,p) measurements in "normal" kinematics (with a deuteron beam). This approach can yield energy resolutions of ~20 keV, far smaller than the ~200 keV resolution typical of inverse kinematics (d,p) measurements. While the long lifetimes required for this approach preclude direct investigation of short-lived r-process nuclei, it can enable the study of unstable nuclei such as ^{121}Sn, ^{135,137}Cs, ^{147}Nd, ^{154}Eu, and others that form branches in the s-process reaction pathway. Any information on neutron cross sections on branch point nuclei can advance the determination of the temperature and neutron density in s-process burning [Kae99, Cou07]. This work also indirectly advances r-process studies, because the solar r-process abundance "observations" are actually estimates determined by subtracting s-process abundances from solar abundances.

In summary, the increased intensities of neutron-rich beams expected from the 70 MeV cyclotron upgrade will: significantly expand the number of nuclei we can investigate; enable systematic studies over a broader range of isotopes; increase our signal-to-noise and the quality of our results; enable the measurement of numerous complementary transfer reactions; enable the development of (d,pγ) coincidence measurements; measure masses and decays farther from stability; and produce long-lived radioactive targets for separate (d,p) measurements. Collectively, these studies will greatly improve the nuclear physics foundation of astrophysical models of the synthesis of heavy nuclei via the r-process nuclei in supernovae.

C. Proton-rich beams

Proton-induced thermonuclear reactions – "hydrogen burning" – can occur explosively in close binary star systems when hydrogen-rich material from one star is gravitationally drawn (accreted) onto the surface of a compact companion star such as a white dwarf or neutron star. With certain accretion rates, densities and temperatures become sufficiently high so that p-rich unstable nuclei, created by proton captures on stable nuclei, can undergo subsequent p-induced reactions before decaying. Such reactions power a thermonuclear runaway explosion on the surface of the compact star, resulting in a nova (on a white dwarf) or an X-ray burst (on a neutron star). Nova explosions eject ~ 10^{26} kg of accreted material into space, and spectroscopic observations by orbital telescopes of these ashes provide details of the nuclei synthesized during the detonation. Determinations of the rates of reactions on p-rich nuclei are needed so that these observations can be used to constrain models of the nova explosion mechanism. This information is also needed to explain the total mass of ejected material (currently underpredicted by a factor of 10) and the unknown nature of the mixing between the white dwarf and accreted envelope that is needed to initiate a blast [Jos07].

X-ray bursts are the most frequent thermonuclear explosions in space. New detailed observations of the time profile of the X-ray flux (the light curve) generated by nuclear burning promise to enhance our understanding the explosion mechanism [Heg07] – *if* we understand the nuclear reactions on proton-rich unstable nuclei that power these outbursts. We cannot yet explain the thermonuclear trigger mechanism, multiple peaks in the light curve, or what extinguishes the burst (fuel exhaustion or cooling by expansion). It is also important to understand the composition of the ashes of X-ray bursts, since after settling on the surface of the neutron stars they change the thermal and electrical conductivity of the crust and may influence crustal processes [Sch99]. X-ray burst observables depend sensitively on the input nuclear physics of neutron-deficient nuclei in the rapid proton capture process (rp-process) that drives these explosions. To address these issues, proton capture cross sections, positron decay lifetimes, masses, and level structure above the proton threshold are all needed for proton rich nuclei up to mass ~ 100. This is especially true for $N = Z$ waiting-point nuclei where the reaction flow waits for slow positron decays.

At HRIBF, our work with low-mass proton-rich radioactive beams such as ^{17}F, ^{18}F, and ^{26}Al have addressed important problems in explosive hydrogen burning. Our measurements of numerous reactions [(p,p), (d,p), (d,n), (p,α)] with ^{18}F, for example, have significantly reduced the uncertainties in predictions of the production of this long-lived radioisotope in nova outbursts (see, e.g., [Cha06]), and subsequently changed predictions of the sensitivities of orbital observatories searching for gamma rays from ^{18}F decay. We have also studied the important ^{14}O(α,p)^{17}F reaction (via the inverse reaction with a radioactive ^{17}F beam) which is a trigger reaction for X-ray bursts [Bla03]. Our work has addressed two central questions from the 2007 NSAC Long Range Plan for Nuclear Science [LRP07]: *"What are the nuclear reactions that drive stars and stellar explosions?" and "What is the origin of the elements in the cosmos?"*

To carry out this measurement program, we have assembled a world-class experimental endstation with the Daresbury Recoil Separator and windowless H gas target [Bar09] and developed numerous new measurement techniques (e.g., [Moa07]). The 70 MeV cyclotron upgrade will allow us to continue to exploit these developments — and other related ones such as the new IRIS2 platform, the enhanced IRIS1 platform, and a laser ion source — with higher yield and efficiency. Below we detail the possibilities for research with proton-rich beams expected from the 70 MeV cyclotron upgrade.

C.1. Higher beam intensities

The 70 MeV cyclotron upgrade will increase proton-rich beam intensities that will enable measurements of thermonuclear reactions at lower energies. Measurements at the HRIBF have greatly improved our understanding of the ^{17}F(p,γ)^{18}Ne, ^{18}F(p,α)^{15}O, and ^{14}O(α,p)^{17}F reactions. However, important uncertainties remain primarily at lower energies, which are most important for novae. For example, while the most important resonance in the ^{17}F(p,γ)^{18}Ne reaction has been measured directly using the Daresbury Recoil Separator, the direct capture cross section that dominates the reaction rate at nova temperatures remains out of reach at current beam intensities. With the 70 MeV cyclotron upgrade, the intensity of the ^{17}F radioactive ion beam will be increased sufficiently to allow direct measurement of the ^{17}F(p,γ)^{18}Ne direct capture cross section at nova temperatures. Another important example is the ^{18}F(p,α)^{15}O reaction. While the first measurements have been performed at energies corresponding to the highest temperatures in novae, the increased beam intensities provided by the upgrade would allow measurements throughout much of the Gamow window, allowing for a robust determination of the reaction rate over the entire energy range of interest.

When combined with new instrumentation such as the gas jet target, S-ORRUBA, and VANDLE, the expected intensity gains will also enable powerful, complementary investigations of high priority astrophysics puzzles in explosive nucleosynthesis. Specifically, we will be able to measure (d,n) and (^{3}He,d) reactions with low-mass, proton-rich radioactive beams such as ^{25}Al that complement our current (d,p), (p,p), and (p,p') measurements.

For higher mass proton-rich beams, the intensity gains with the upgrade will enable the study of thermonuclear burning in supernovae, such as the νp-process, the p-process, and explosive burning that creates long-lived radionuclides. Specific examples include probing the structure and reactions for nuclei near ^{64}Ge (νp-process), ^{74}As (p-process), and ^{55}Co (radionuclides), none of which is possible with current intensities.

In related work, the 70 MeV cyclotron upgrade will enable systematic nuclear structure measurements along the $N=Z$ line needed for studies of explosive nucleosynthesis in X-ray bursts. Measurements of decay properties and level structure of proton-rich nuclei, not currently possible at HRIBF intensities, are needed to improve our understanding of thermonuclear burning via the rp-process in X-ray bursts. Systematic measurements facilitated by the higher intensity beams from the upgrade will improve nuclear models used to calculate thousands of unmeasured reaction rates using statistical reaction models.

C.2. Proton-rich ISOL beam development

New proton-rich beams, such as ^{25}Al, ^{26,27}Si, ^{29,30}P, ^{30,31}S, and ^{33,34}Cl, are needed for direct and indirect studies of reactions in the rp-process and αp-process in X-ray bursts as well as in the rp-process burning in energetic novae. Heavy p-rich beams near the $N=Z$ line (^{64}Ge, ^{68}Se …^{92}Pd, ^{96}Cd) would greatly aid in studies of waiting points in the rp-process in X-ray bursts, while others closer to stability (e.g., ^{128}Ba) would be helpful for understanding the p-process in supernovae. Our instrumentation for these measurements – SIDAR, ORRUBA, DRS, gas target system – are in place and (in some cases) undergoing funded upgrades; we only need the beams with sufficiently high intensity to make these important studies feasible. Furthermore, development of these and other proton-rich ISOL beams will benefit astrophysics studies at HRIBF and other facilities, and supports a possible ISOL option at FRIB.

The 70 MeV cyclotron upgrade will *significantly accelerate* the development of proton-rich ISOL beams in a number of ways: more production reactions reliably available such as (d,n) and (α, X); higher energy and higher intensity beams available for production reactions will increase yields, such as 70 MeV alpha-induced reactions; higher reliability coupled to two target platforms [IRIS-1 and IRIS-2] will enable rapid, systematic studies of yields from, and high temperature characteristics of, different production target materials; reliability gains will also enable systematic studies of ionization schemes using the laser ion source and target samples at IRIS-2 for pure production of proton-rich species. There is also an exciting possibility for high-power ISOL target development using parasitic beam extraction from the new cyclotron routed to a new target / ion source system coupled to a diagnostic station, which could operate simultaneously with production target bombardment for an experiment.

C.3. Radioisotope production

As described above in Section B.7, the dual port extraction capability of the 70 MeV cyclotron enables one beam to be used for parasitic production of long-lived radionuclides, while the other is used for normal RIB production. This very economical production scheme will allow us to create thick samples of long-lived, proton-rich nuclei such as ^{26}Al, ^{44}Ti, ^{56}Ni, and others that can be put into a traditional sputter source and turned into beams, opening a new avenue for making important measurements. For example, a measurement of ^{56}Ni(d,n) would be very useful in improving the estimate of the destruction rate of ^{56}Ni, the first waiting point in the rp-process in X-ray bursts. These beams can be used to make direct and indirect studies of reactions that destroy these radionuclides in stellar environments, which are needed to improve current predictions of signals from stellar explosions detected by space-based gamma-ray observatories.

D. Summary

We have outlined the exciting new science that can be expected from HRIBF with the 70 MeV cyclotron upgrade. These include advances in understanding novae, X-ray bursts, and supernovae, and involve the utilization of neutron-rich and proton-rich unstable beams coupled to experimental systems including ORRUBA, VANDLE, and the DRS and its gas jet target system.

Applications

Overview

There is a wide range of research and development areas that would benefit from the proposed driver upgrade, as well as activities that would generally enhance the HRIBF research portfolio. The session was attended by participants representing the HRIBF, isotopes, and nuclear physics communities. Specific topics discussed included:

- The proposal for an isotope production R&D facility as an addition to the driver upgrade. The isotope facility was described in an earlier presentation [Sal09].
- The application of the "surrogate reaction" approach for obtaining compound nuclear cross-sections of interest to RIB facilities.
- Opportunities for the use of tritium beams and targets, with particular emphasis on cross-section needs from NIF.
- Accelerator mass spectrometry at extremely high sensitivities.
- Other applications such as implantation of RIBs for material characterization

These topics are summarized in the following five subsections.

The Isotope Facility Proposal

The ORNL Isotope Program is proposing to take advantage of the dual-beam capabilities of the cyclotron upgrade, and the intrinsic operating characteristics of the HRIBF upgrade, to carry out a program of radio-isotope R&D in an adjacent facility [Sal09]. By constructing an isotope irradiation vault external to the upgraded HRIBF facility the isotope program could be provided ~ 4500 hrs/yr of beam time with no significant impact on the HRIBF mission. The proposed addition, shown in outline in Figure 12, would include the irradiation vault; beam lines to transport the cyclotron beams (30-70 MeV protons, 70 MeV alphas, 15-35 MeV deuterons) to the isotope vault; two target stations; transfer systems to move the irradiated targets to an external transfer cell; and the transfer cell where the targets would be disassembled and packaged for transport to the ORNL hot cells elsewhere on site. Because the new cyclotron would already exist, and the fact that ORNL already has the extensive infrastructure required to mount a full isotope production R&D mission, the incremental cost to the isotope program would be modest (currently estimated as 7-10M$).

The proposed isotope program would include:

- Production R&D, exemplified by the current effort to find an accelerator alternative for the production of ^{225}Ac
- Radioisotope production for research and commercial products.
- Education and training for workforce development.

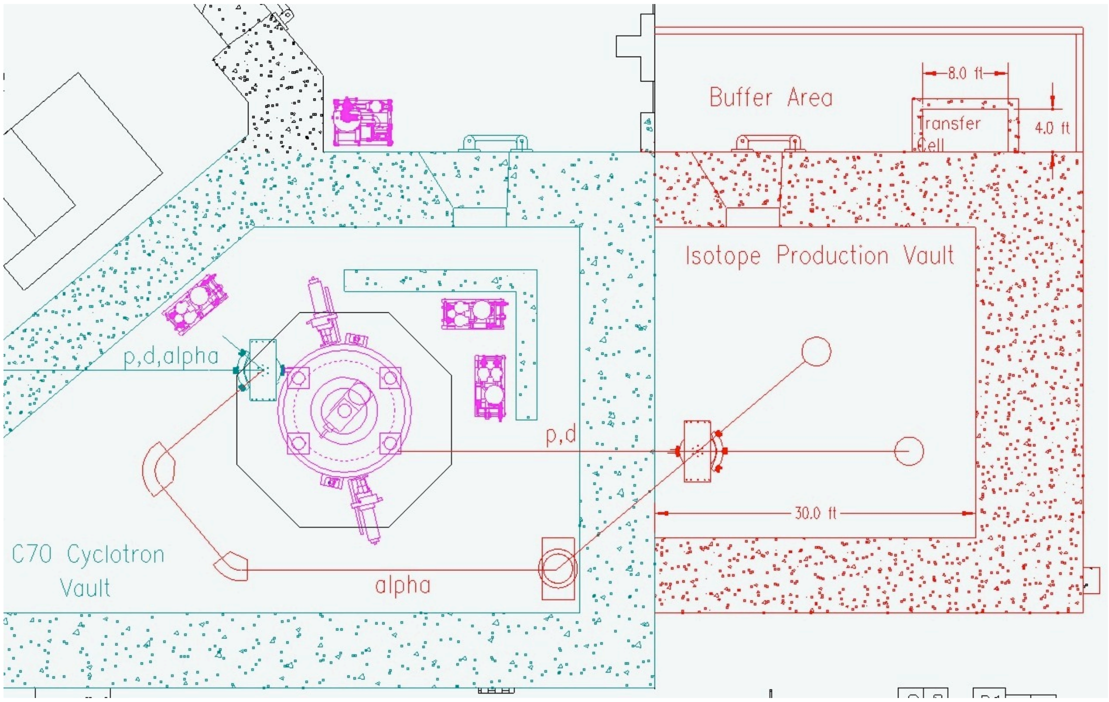

Figure 12: The proposed components of the isotope facility are shown in red.

During the workshop, background was provided by a brief description of the proposed facility [Sal09], and informed by presentations given by two members of the NSACI committee whose final report on the Isotopes Program has just been released [ISO09]. Riedinger (UT) and Ruth (TRIUMF) described the NSACI perspectives. In addition, Riedinger provided an overview of the DOE Isotope Program, and Ruth reported on topics from the Medicine and Biology Working Group at the recent “Accelerators for America’s Future” workshop held in October 2009. Discussion was lively, friendly, and constructive, a common theme was examining how the isotopes and basic science programs could not only co-exist, but complement and enhance each other at HRIBF with the proposed driver upgrade. In addition ideas to strengthen the proposed facility were suggested and noted.

The major consensus item was that the proposed isotope facility addition to the HRIBF upgrade offered significant potential synergies between the HRIBF science program and the isotopes program. Particular examples of such synergy included:

- The production of longer-lived radioisotopes for subsequent “batch-mode” acceleration at HRIBF (^{7}Be production, and extension to other isotopes of interest, e.g. ^{10}Be, ^{26}Al, ^{44}Ti, ^{56}Ni, and ^{59}Fe).
- High power density target technology is needed for both ISOL and isotope production target development.
- Co-location of the two programs provides a bridge between the nuclear physics and radiochemistry expertise needed by both.
- Co-location of facilities and the extensive ORNL isotope infrastructure provide unique opportunities for enhancing workforce development by offering connections for faculty and students in one area to interact and/or practice in the other.

The perspectives from the NSACI review, and operation of accelerator isotope facilities also suggested some ideas to strengthen the proposal. Examples were:

- Explore with manufacturer how to extend the proton minimum energy down to 20 MeV, which is below the advertised minimum of 30 MeV.
- Identify a "niche" isotope production capability, similar to the production at TRIUMF of ^{13}N, used as a tracer.
- Be more explicit about how to accommodate the potentially rigid schedule demands of any medical isotope research and development.
- Are there possibilities for HRIBF mass separation technologies/capabilities to enhance radioisotope purity?
- Are there connections to other fields to be made (NNSA, environmental tracer needs, etc.)
- Be more explicit about the shielding required between target stations to allow adequate access to the target areas for the Production R&D program.

Surrogate Reactions

Compound-nuclear reaction cross sections are required input in various areas of both basic and applied nuclear physics. In general, cross-section needs can be addressed by:

- Direct measurements, where targets can be produced;
- Surrogate measurements, when the compound nucleus can be reached;
- Hauser-Feshbach calculations, if reliable input (level densities, γ-ray strength functions, optical-model potentials) is available.

With the 70 MeV cyclotron upgrade, HRIBF will be able to support all three approaches, by providing:

- Unstable, but sufficiently long-lived isotopes for direct measurements;
- Radioactive beams for surrogate measurements;
- Structure and reaction data on unstable nuclei to improve reaction-theory models and their inputs, and to validate the calculations.

Many compound-nuclear cross sections on unstable isotopes cannot be measured directly, since it is impossible to produce suitable targets; cross-section calculations for these cases are often not sufficiently accurate, since information on the decay of the relevant compound nuclei is not available or insufficient to constrain the calculations. The *Surrogate Nuclear Reactions* method is an indirect approach for determining such cross sections via a combination of experiment and theory (see Ref. [Esc06] for an introduction).

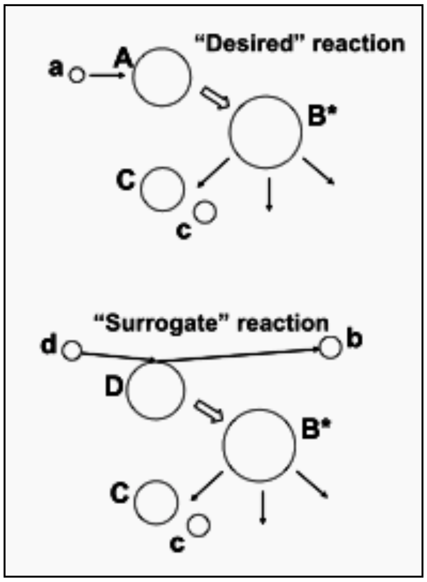

Figure 13: Schematic representation of the “desired” (top) and “Surrogate” (bottom) reaction mechanisms. The basic idea of the Surrogate approach is to replace the first step of the desired reaction, a+A, by an alternative (“Surrogate"”) reaction, $d+D \rightarrow b+B^*$, that populates the same compound nucleus. The subsequent decay of the compound nucleus into the relevant channel, c+C, can then be measured and used to extract the desired cross section. (Taken from [Esc06].)

In a surrogate experiment, the compound nucleus of interest is produced using a light-ion direct reaction on a target that is easier to produce (see Figure 13). The decay of the compound nucleus is measured in coincidence with the outgoing direct-reaction particle and the coincidence probabilities are used to infer the desired cross sections (for a detailed description, see, e.g., [Esc06]). The method is expected to play an important role in future cross-section measurements with RIBs, since inverse-kinematics experiments with radioactive isotopes cannot be performed on a neutron target. For example, if one measures (d,pγ) instead of (n,γ), one carries out a surrogate measurement. To make full use of radioactive-beam capabilities at any RIB facility, the inverse-kinematics surrogate method needs to be developed further. HRIBF is well positioned to significantly contribute to this development effort; it is currently the only facility where inverse-kinematics surrogate experiments are being tested and developed [Ciz09, Pet09]. The proposed upgrade will make it possible to apply the method to unstable isotopes that can presently not be reached with transfer reactions at any other facility, by providing a wider variety of beams (with sufficient count rates). The measurements require experimental equipment that is described in the Instrumentation section of this report. Developing a tritium-beam capability (discussed below) would provide additional enhancements, since, compared to one-neutron transfers, surrogate (t,p) reactions allow one to reach nuclei which are more neutron-rich.

The surrogate method was first used in the 1970s at Los Alamos [Cra70,Bri79] and is now being employed by the Stars/LiBerACE group, a Livermore-Berkeley collaboration, and the CENBG (Bordeaux, France) group, which carries out experiments at INP Orsay. An effort to develop the method with radioactive ion beams in inverse kinematics has been initiated at ORNL by a group led by Cizewski [Ciz07,Pet09]. Typical experiments require both charged-particle and gamma-ray (or fission-fragment) detectors with good energy resolution and high detection efficiency. The surrogate method has been successfully applied to determine a variety of (n,f) cross sections using inelastic scattering, as well as (t,p), (d,p), (^{3}He,α), (^{3}He,t), and other transfer reactions. The agreement with direct measurements, where available, is good. Recently, efforts have been made to determine (n,γ) cross sections, which are much more sensitive to spin differences between surrogate and desired reactions [Boy06, Sci08, Hat08, All09]; theory developments, along with experimental tests, are underway to correct for the spin differences and improve the accuracy of the extracted cross sections [You03, Esc08].

The development of the surrogate method is primarily driven by cross section needs in various areas of applications, as is illustrated in the following (non-exhaustive) list of examples:

- Nuclear astrophysics applications: Cross sections for (n,γ) reactions on specific r-process nuclei in the region near ^{132}Sn have recently been shown to have a significant effect on predicted r-process yields [Beu09, Sur09]. Neutron-capture cross sections for s-process branch points are needed to infer information on stellar conditions (temperature and neutron density) typical of the s process, as well as to deduce isotopic abundances to constrain r-process models [Kae06]. Although target nuclei relevant to the s process are close to stability, they cannot always be reached with stable beam-target combinations. For further information, see the discussion in the astrophysics section of this report.
- Nuclear-energy applications require cross sections for minor actinides, fission fragments, and structural materials [AFC06]. Coordination with scientists modeling nuclear reactors, waste-transmutation scenarios, and alternative fuel cycle scenarios would be useful for determining which cross sections of relevance could be measured at HRIBF.
- Stockpile-stewardship applications require cross sections for a variety of neutron-induced reactions, on selected 'flux monitor' isotopes, actinides (U, Np, Pu), and fission fragments [LRP07]. HRIBF's upgraded capabilities will make it possible to measure many relevant cross sections, either directly using long-lived radioisotopes produced at HRIBF or inverse-kinematics experiments.

In addition to providing enhanced capabilities for surrogate-reaction measurements, the proposed 70-MeV cyclotron upgrade will also contribute to more accurate and reliable cross-section calculations by providing valuable nuclear structure and reaction data that can be used as input and for benchmarking the calculations. Even moderate-resolution information is valuable, as there is currently very little information on unstable proton-rich or neutron-rich species. Furthermore, as one moves closer towards the neutron dripline, current reaction-calculation approaches will need to be modified. Specifically, the level density declines and the statistical-averaging procedures underlying the Hauser-Feshbach formalism may no longer be valid; direct-reaction mechanisms are also expected to contribute to the cross sections. Theory needs to be developed for a proper calculation of the cross sections and HRIBF can provide experimental guidance and tests. HRIBF experimentalists have established collaborations with reaction theorists in order to guide choices for measurements and perform state-of-the-art calculations of cross sections from their data.

Triton beams and targets

There is an increasing interest in reactions that involve tritons from the nuclear structure, the nuclear astrophysics and the fusion communities. The development at HRIBF of both triton beams and triton targets would be highly desirable. Tritium beams are needed for: (i) direct cross section measurements for t-induced reactions; (ii) indirect cross section measurements for compound reactions with the surrogate (t,p) mechanism; (iii) t+t experiments. Hayes (LANL) reported on radiochemical diagnostic tools for the National Ignition Facility (NIF) at LLNL:

- Neutron spectrum from t+t reaction gives information on areal density and ion temperature of fuel in NIF laser-driven fusion experiments.
- Cross sections for t-induced reactions on shell material of NIF capsules are needed to extract information on hydrodynamic instabilities and electron temperatures.
- Results from an old t(t,n)nα experiment, which seem to fit well with theory analysis do not agree with observations of recent t+t fusion experiments at Omega (Rochester). A t+t experiment with tritium beam and tritiated target is needed to resolve the discrepancy.

Galindo-Uribarri reported on the general interest in the reactions and structure community in tritium beams, as well as tritium targets. He laid out a plan for implementing a tritium-beam capability at ORNL. Intense good quality tritium beams with energies up to 50 MeV could be accelerated when other RIBs are not available. Reactions of the type (t,p), (t,n) and (t,alpha) are characterized by a high Q value and therefore able to populate states otherwise not easily accessible. Comparison with ^{3}He induced reactions, charge exchange studies, two nucleon transfer reactions are among the topics of interest in the use of t-beams and t-targets.

The inability of direct-reading instruments to detect tritium and the slight permeability of most materials to tritiated water and tritium requires care in handling to avoid contamination. A tritium beam facility based at the HRIBF would benefit from previous operational experience of other accelerators such as the tandems at McMaster University and Los Alamos. The personnel in charge of the operation of the tritium facility at McMaster have already offered to share their experience. A tritium beam program could also benefit from the tritium handling experience from the fusion energy sciences community (e.g. the confinement and removal of tritium are the key subjects for safety of ITER).

One possible approach for the production of tritium beams at HRIBF could be to implement an independent tritium injector. When the 25 MV Tandem was built provision was made for incorporating a second stable injector. An independent platform would have the advantages of reliable engineered controls designed for handling tritium. The operational procedures would be specific for safe operation of the tritium system minimizing risks. We would use only solid tritium targets (e.g. titanium hydrides) based on sputtering sources.

Accelerator Mass Spectrometry

Renewed interest in Accelerator Mass Spectrometry (AMS) is emerging in connection with RIBs. Isobar separation is one of the main challenges for both AMS and RIB Science. The cyclotron upgrade will extend the range of radioactive species available for experiments. Developing new techniques that improve isobar separation will benefit both fields. HRIBF has equipment for beam transport and analysis that is ideal for AMS. Unique capabilities for performing the highest sensitivity measurements of AMS are: (i) the highest operating voltage in the world, and (ii) folded geometry with 180 degree magnet in the terminal.

The HRIBF tandem accelerator is the most sensitive in the world for the measurement of ^{36}Cl, as illustrated by AMS measurements in seawater samples [Gal07]. This ultra-high sensitivity opens opportunities for applications in a variety of areas: oceanographic tracers, waste disposal, nuclear safeguards, rock erosion, neutron flux monitors, homeland security, and measurement of nuclear cross sections.

One example of a possible application for AMS at HRIBF was presented by Mueller and is related to the neutron Electric Dipole Moment (nEDM) experiment at the Spallation Neutron Source (SNS). The nEDM experiment, a $30 million project managed by the Physics Division of ORNL, requires ultra-pure liquid helium with a 3He/4He ratio of 1 part per trillion (ppt) or less. Naturally occurring helium contains at least 0.1 part per million (ppm) ^{3}He. Using a superfluid heat flush (phonon wind) technique, liquid helium can be purified to less than 1 ppt ^{3}He. Measurements with a Residual Gas Analyzer (RGA) are only sensitive down to 0.01 ppm ^{3}He. Therefore, Accelerator Mass Spectrometry (AMS) measurements are needed to ensure the required helium purity. Initial AMS measurements at ATLAS at ANL using an Electron

Cyclotron Resonance (ECR) ion source, a linear accelerator, and a gas-filled ENGE split-pole spectrograph measured 0.27 +/- 40% ppt ^{3}He in a helium sample produced in a heat flush apparatus that has since been moved from LANL to ORNL. Similar measurements could be made at HRIBF using a 100 MHz rubidium charge-exchange (Alphatross) ion source, a tandem electrostatic accelerator, and either a gas-filled ENGE split-pole spectrograph or a separate ion chamber and silicon detector hodoscope. Readily available ^{3}He AMS measurements at HRIBF will be essential throughout the several year duration of the nEDM experiment. Another potential fundamental neutron physics experiment at SNS requires even lower levels of ^{3}He and will, therefore, benefit from further AMS development at HRIBF.

Other ongoing and potential applications at HRIBF

A proof-of-principle experiment has been done at HRIBF showing the usefulness and practical potential of the use of ^{7}Be implantation as a radiotracer for wear studies using a ^{7}Be implantation setup developed at the Colorado School of Mines [Gre09]. Further analysis and experiments have to look at improvements in the activity measurements (to reduce scatter and systematical error), the influence of radiation dose on mechanical properties (will provide upper limits on allowable ^{7}Be implantation dose) and the possibilities of extending the method to natural materials. A program for wear studies using ^{7}Be will benefit from the isotope program, as ^{7}Be can be produced on site.

The availability of a broad range of isotopically clean radioactive ion beams with the possibility to implant the isotopes on-line offers opportunities for studies to characterize materials. Radioactive ion beams offers opportunities for emission channeling studies for the characterization of defects in semiconductors.

ISOL Technology

ISOL technology encompasses a wide variety of topics from basic science to training to practical considerations. Understanding ISOL physics and chemistry is the key to delivering the rare isotopes required for the experiments of a RIB physics program. For a successful program the physics and technology must also be firmly anchored with experienced personnel that understand the radiological and engineering aspects of ISOL technology and the training of young researchers in this important area. In addition, a crucial component for a production facility is the network of commercial suppliers both of materials and services that are capable of providing the radiation hard, high temperature components for target ion sources. At HRIBF all these capabilities are currently implemented and operating smoothly as a team. As a result, the HRIBF is already a leading ISOL facility, as illustrated by the comparisons in Table 1 [But09].

FACILITY	**DRIVER**	**POWER**	**USER BEAMS ACCELERATED**	**MAX ENERGY**
HRIBF **Oak Ridge** **(USA)** **1997**	50-100 MeV p, d, α *(-ve ion source)*	1.5 kW	^{7,10}Be, ^{17,18}F, ^{26g}Al, $^{76-79}$Cu, $^{67,83-85}$Ga, $^{78,80,82-87}$Ge, ^{69}As, ^{83,84}Se, ^{92}Sr, ^{117,118,120,122,124,126}Ag, $^{126,128,130-136}$Sn, ^{129}Sb, ^{129,132,134,136}Te **(45)**	5-15 MeV/u tandem
ISAC **TRIUMF** **(CANADA)** **2000**	500 MeV protons	50 kW	^{8,9,11}Li, ^{10,11}Be, ^{18}F, ^{20,21,25,29}Na, ^{23}Mg, ^{26}Al **(12)**	14 MeV/u linac
SPIRAL **GANIL** **(FRANCE)** **2001**	100 MeV/u heavy ions	6 kW	^{6,8}He, $^{14,15,19-22}$O, ^{18}F, $^{17-19,23-26}$Ne, $^{33-35, 44,46}$Ar, $^{74-77}$Kr **(25)**	10-25 MeV/u cyclotron
REX **ISOLDE** **(CERN)** **2001**	1.4 GeV protons	3 kW	^{8,9,11}Li, $^{10-12}$Be, ^{10}C, ^{17}F, $^{24-30}$Na, $^{28-32}$Mg, $^{61-63}$Mn, ^{61,62}Fe, ^{66,68}Ni, $^{67-71,73}$Cu, ^{74,76,78,80}Zn, ^{70}Se, ^{88,92,94,96}Kr, ^{96}Sr, ^{108}In, $^{106-110}$Sn, ^{100,102,104,122,124,126}Cd, ^{138,140,142,144}Xe, ^{140,142,148}Ba, ^{148}Pm, ^{153}Sm, ^{156}Eu, ^{182,184,186,188}Hg, ^{200}Po, ^{202,204}Rn **(72)**	3 MeV/u linac

Table 1: Current status of world ISOL accelerated beams [But09]. The total number of isotopes accelerated by each is given in parentheses.

For the future, in this section we show that HRIBF personnel are researching ways to provide the research community with almost any beam via the ISOL method and with purity and intensity unparalleled in today's ISOL community. This combination of existing capabilities and active, forefront ion source/target research programs guarantees that the investment of funds for an HDU at HRIBF will provide the US with a state of the art production-ISOL facility.

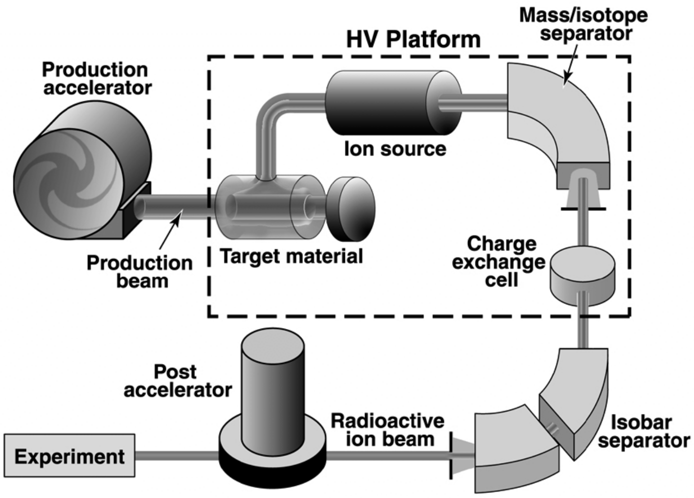

Figure 14: Schematic view of the existing HRIBF facility. All ISOL related components, e.g., targets, ion sources (including laser ion source), mass separator, HV platform, and target ion source module handling and storage are brand new and laid out for high power operation.

The HRIBF currently has research personnel involved both in off-line target and ion source development as well as on-line rare isotope beam production and delivery. This combination and expertise is unique in the DOE portfolio, as all other proposed or funded US rare isotope facilities would have to build up expertise in at least one of these areas already established at HRIBF.

It is clear that the benefits of a proton driver upgrade (50 MeV and higher, several ×10 μA protons or deuteron beams) would boost rare isotope beam delivery to both existing and new experiments, as well as provide additional beam time for on-line development of high power, high density uranium targets – all developments that are also key to a possible FRIB-ISOL upgrade. Even with an FRIB upgrade, the HRIBF would be needed to supply the RIBs for a majority of the ISOL experiments in the nuclear physics community. This is owing to the fact that each experiment usually requires dedication of the experimental infrastructure for one whole facility, and the performance of experiments is thus limited worldwide by the (scarce) availability of intense ISOL RIBs. Typically, this results in a huge backlog of approved experiments waiting to be conducted.

Other than the nearly half-century-old cyclotron, proposed to be replaced, all of the components for Radioactive Ion Beam production at the HRIBF are state of the art. This is especially true of the target and ion source front end and the mass separators, shown in Figure 15. The target modules are 2nd generation, derived from the proven CERN-ISOLDE ISOL target enclosures and ion sources. The high voltage platforms and mass separators are newly installed. Target material and ion source technology development and testing are ongoing. HRIBF has at its disposal the complete set of on-line ion sources to make best use of the isotopes produced:

- Electron Beam Plasma Ion Source (EBPIS)
- Kinetic Ejection Negative Ion Source (KENIS)
- Multi-sample, Cs-sputter ion source for ^{7}Be, ^{10}Be, ^{26g}Al beams
- Surface Ionization Source (positive and negative)
- Laser Ion Source (producing beams in 2011)

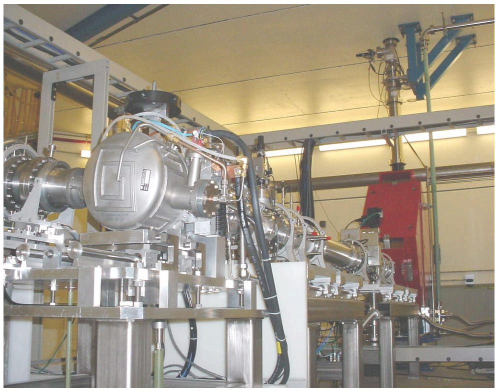

Figure 15: Photograph of the new HRIBF target ion source front end with mass separator on a high voltage platform.

Continuous ion source and target development are carried out at HRIBF. Two off-line ion source test facilities (ISTF1 and ISTF2) are in operation. They are optimized for positive and negative ion studies and laser ion source development. An on-line ion source and target test facility also exists at HRIBF. Worldwide, this online test facility is a unique facility dedicated primarily to developing radioactive beams. The value lies in the ability to test prototypes of targets and ion sources using actual experimental conditions with radioactive ion beams.

Development activities aimed at solving two key problems of ISOL facilities are under way at the HRIBF. The two key problems are: 1) Chemistry dependent ion sources, i. e., not all beams are available, especially refractory elements. 2) Cocktail beams – typical RIBs contain a number of different elements. To address 1) a group has begun development of an ion source using gas stopping techniques. In this technique, ideally the radioactive element never touches a surface, so chemically dependent effects, wall sticking times, are effectively eliminated. An active program has begun to develop such an ion source that would extend the number of elements available as beams for both low energy as well as re-accelerated beams. The other problem of "cocktail" beams is being addressed by the use of laser ion sources, chemical separation techniques, and a chemically independent technique that utilizes a multi-pass time-of-flight technique. Such a time-of-flight device would provide ultra pure beams.

In summary, the HRIBF staff and facilities serve to provide strong leadership in the development of ISOL technology. Existing personnel and laboratories at HRIBF have developed and are now developing the technology necessary to carry out forefront ISOL-type experiments. With the technology being developed, it is expected that the HRIBF, within a very few years, will be capable of providing a beam of almost any element and will also be capable of providing pure beams. Upgrading HRIBF to its full potential would provide the US nuclear physics community with intense beams of crucial rare isotopes and create the only US development facility for high power ISOL targets for next generation RIB facilities. With the addition of the HDU to provide reliability and increased primary beam intensities, the HRIBF will enhance its already strong position among the world's leading ISOL RIB facilities.

Instrumentation

The HRIBF is a mature facility with a large variety of instrumentation well optimized for research with radioactive ion beams. As such, it is well situated to take immediate advantage of the new beams and intensities after the upgrade. The wide range of equipment consists of spectrometers, silicon detectors, Ge detectors, and micro-channel plates (MCP). Many systems, e.g., Ge detectors and MCPs, can be used at every target location and are readily adapted to a wide range of experiments. Below, we list the major experimental systems and their primary or originally intended research focus. More information may be found on the HRIBF web site at http://www.phy.ornl.gov/hribf/.

Nuclear structure - decay spectroscopy

Research in decay spectroscopy is based on identifying the decay of relatively long-lived states of exotic nuclei through γ-ray and particle detection. These studies are able to use the weakest beams from the RIB ion source and the research concentrates on nuclei at the extremes of nuclear stability. Typically half-lives, energy levels, and beta-delayed neutron branching ratios are measured in these studies. These measurements take place at the low-energy radioactive ion beam spectroscopy station and the existing general-purpose beam line. In addition the recoil mass spectrometer can use fusion-evaporation reactions to access extremely proton-rich nuclei.

Low-energy Radioactive Ion Beam Spectroscopy Station (LeRIBSS): Located beneath the tandem but above the rotating beam line, RIBs with either positive or negative charge at energies below 250 keV are deposited onto a moving tape collector (MTC). CARDS and ^{3}Hen were designed for this station. An ultra-thin-foil MCP has been constructed to provide implantation timing signals for activities with extremely short half-lives (< 200 ms).

Clover Array for Recoil Decay Spectroscopy (CARDS): This is a subset of the CLARION clover Ge detectors used in a close-packed, high efficiency geometry for the detection of γ-rays following radioactive decay. Typically, RIBs are deposited on the MTC and transported to CARDS for long-lived activities or, for short-lived activities, the implantation point is the center of CARDS and the MTC removes the daughter activity. Plastic beta-counters surround the activity on the tape and provide a trigger for the Ge detectors.

Moving Tape Collector (MTC): A thin tape many meters long used to transport radioactivity to or away from the measuring station that is typically CARDS although ^{3}Hen and MTAS will also require an MTC. Three versions exist with various sizes of tape and movement speeds.

Ranging out ionization chamber: Placed on the general-purpose beam line together with CARDS, mixed isotope RIBs can be analyzed and, for neutron-rich beams, purified by taking advantage of the differences in energy loss of each isotope.

Recoil Mass Spectrometer (RMS): A zero-degree mass separator optimized for fusion-evaporation reactions. It has a large target-quadrupole distance that allows large devices such as GRETINA to be installed without compromise. It has superior beam rejection allowing the use of symmetric reactions with little primary beam reaching the focal plane. The focal plane is compatible with all the detectors for decay spectroscopy and has an ionization chamber for energy loss measurements useful for in-beam γ-ray spectroscopy. It is most often used with stable beams to study the proton drip line and alpha-decay near ^{100}Sn.

^{3}He Neutron Detector Array (^{3}Hen): The new ^{3}He ionization detector array for beta-delayed neutrons has a high and nearly constant efficiency for detecting low energy neutrons (1 keV – 1000 keV) that will enable the measurements of absolute beta-neutron branching ratios for a wide variety of neutron-rich nuclei that often emit low-energy neutrons.

Digital signal processing (Pixie): HRIBF users have pioneered the use of digital signal processing for decay spectroscopy. Isotopes with the shortest half-lives and unusual decay paths such as rapid daughter decay (resulting in a double pulse signal) have been identified through flexible software within the modules and in off-line analysis.

Double-sided Silicon Strip Detectors (DSSD): Located after the ranging-out ion chamber or the focal plane of the RMS, heavy ions are implanted into the pixelated silicon detector. Radioactive decay produces a signal in the detector that can be correlated with the implantation event.

VANDLE: A high efficiency detector for measurements of neutron energies from beta delayed neutron emission. A partial array for decay spectroscopy is to be available in 2011. It will consist of straight plastic scintillator bars and use time-of-flight to determine neutron energy and discriminate between γ-rays. It will be also applicable to nuclear reaction studies.

Modular Total Absorption Spectrometer (MTAS): The MTAS is a large NaI detector array weighing approximately 850 kg that surrounds smaller detectors such as silicon beta counters and a tape system. It detects nearly all gamma radiation from a beta-decaying nucleus and provides a measure of the beta strength distribution. It will be available in 2013.

Oak Ridge Isomer Spectrometer and Separator (ORISS): ORISS is an ion separator with an ultimate mass resolving power of 400,000 to 1 that transmits 50% of the desired isotope. It consists of a Multi-turn Time-of-Flight spectrometer (MTOF), a radio-frequency gas-filled beam cooler, and an electrostatically controlled gate. RIBs are injected into the cooler where they are cooled and prepared into a bunched beam of ions with extremely low emittance. The ions are then separated in time in the MTOF and then released to a decay spectroscopy measuring stations such as CARDS or MTAS. Given enough time in MTOF, the decay of different isomers within a given isotope may be studied. It will be available in 2013.

Nuclear structure - in-beam spectroscopy

In-beam nuclear structure research is primarily concerned with discovering new and unusual properties of nuclei by characterizing the excited states of the nucleus through γ-ray detection and determining the properties of these states such as level energy, lifetime, spin, parity, magnetic moment, etc. Typical locations of experiments include the recoil mass spectrometer and the existing general-purpose beam line.

CLARION: An array of 11 Compton-suppressed clover Ge detectors located at the RMS target station. The device has 2.2% photopeak efficiency at 1.33 MeV. When the Ge detectors are used without the BGO Compton suppressors in a close-packed geometry of 4 or 5 detectors the system is called CARDS for decay spectroscopy experiments.

HyBall: An array of CsI(Tl) charge-particle detectors consisting of 95-elements in a 4π geometry. The full array is covered with absorbers to protect it from scattered beam and used primarily for fusion-evaporation reactions. Another array, Bare HyBall, is a 55-element array without absorbers used for Coulomb excitation and transfer reactions to detect scattered target nuclei and provide a clean reaction trigger for CLARION.

Neutron detector array: A little used liquid-scintillator neutron detector that fits into the forward section of the CLARION support structure. Together with HyBall, it provides complete evaporation particle detection for fusion-evaporation reactions using proton-rich RIBs such as ^{56}Ni.

BaF$_2$: The BaF$_2$ array consists of more than 150 hexagonal crystals, 20 to 25 cm long, that can be packed into several configurations such as a large wall or packs of 19 or 37 detectors. The array is highly efficient particularly for high-energy γ-ray detection and has been used for Coulomb excitation measurements of double-magic ^{132}Sn (with a first 2+ state at more than 4 MeV). In addition, Coulomb excitation of weak RIB beams such as ^{134}Sn with intensity around 3000 ions/sec was possible with this high efficiency device.

Hercules: A scintillator detector array based on energy and time-of-flight identification of reaction products. It can be used in conjunction with CLARION and GRETINA to provide an efficient γ-ray trigger. In addition, it can be used to measure cross-sections of fusion, fusion-fission, and similar reactions. This device is based at Washington University and may be used at HRIBF for the first time in 2010.

Spin Spectrometer: The venerable 70-element NaI array for gamma-ray detection. It should be an optimal device for (d,pγ) reactions and Coulomb excitation measurements where 7-9% energy resolution is not a problem. This device is in storage and is presently planned to be available at the target position of the RMS once modifications necessary for GRETINA are made.

GRETINA: A γ-ray tracking detector array with 1π solid angle coverage. The HRIBF is expected to host GRETINA around the start of FY13 for approximately 6 months which will make a great improvement in experiments with γ-ray detection. It will be placed at the RMS target position replacing CLARION but is expected to be compatible with auxiliary detectors similar to those found at HRIBF or GAMMASPHERE and includes the RMS. GRETINA should be able to take advantage of the driver upgrade in the second rotation cycle starting around 2015.

Nuclear reactions

Nuclear reactions research is primarily concerned with understanding the mechanisms of processes that occur when two nuclei collide. Data critical to these processes include cross-section measurements, product identification, and angular distributions. In addition, light ion spectroscopy such as (d,p) reactions are used to derive nuclear structure information such as spectroscopic factors and spin-parities of states. Users have begun exploring using (d,pγ) reactions as a surrogate reaction for (n,γ) reactions on radioactive isotopes. Typical locations of experiments include the time-of-flight station, general-purpose beam line, Enge spectrograph, DRS target area, and the future ORRUBA/Scattering chamber beam line.

Time-of-flight station: A micro-channel plate (MCP) based time-of-flight system typically used for RIBs with intensities less than 1 million ions/s. When paired with an ionization chamber this system is used to measure fusion evaporation residue cross-sections at incident rates of less than

50,000 ions/s. When paired with an annular silicon strip detector the system is used to detect binary reactions such as fusion-fission and operates at the higher beam intensities.

Enge Magnetic Spectrograph: A rotating magnetic spectrograph that can operate in two modes: vacuum and gas-filled. In vacuum mode it is designed for particle spectroscopy from transfer reactions at tandem energies for angles from 0° to 30°. In gas-filled mode, it is a 0° evaporation residue transport device for fusion evaporation cross-section experiments. It can rotate away from the beam axis for angular distribution measurements

1-meter scattering chamber: A generic scattering chamber with movable detector mounts is built on a platform and can be easily rolled into place on the general-purpose beam line.

ORRUBA: A position sensitive silicon detector array optimized for detecting the products from light ion transfer reactions in inverse kinematics. Typically placed around 90° with respect to the beam, it is compatible with other equipment such as SIDAR and the DRS.

ORRUBA-S: Improvements will be made to the existing ORRUBA silicon detector array that is used for light ion spectroscopy in inverse kinematics. The position-sensitive silicon detectors (resistive strips) will be replaced by double-sided silicon strip detectors to create distinct pixels. Preamps and processing electronics will also be upgraded. It will be available in 2013.

ORRUBA/Scattering Chamber Beam Line: The facility has developed several compact detector systems that compete for use of only one general-purpose beam line. The addition of another beam line to house the ORRUBA detector and the 1-meter scattering chamber is necessary. It will be available in 2011.

Fusion-Fission Detector: Fusion-fission, quasi-fission, and deep-inelastic collisions become dominant for heavy systems formed in the nucleus-nucleus capture process. In order to study these processes with beams less than 500,000 ions/sec a detector needs to be highly efficient and able to differentiate the various binary reactions (e.g. deep inelastic) that can occur. This gas ionization detector will have a solid target placed inside its volume, contain tracking wires for determining ion trajectories, and be lined with Si and scintillator detectors. It will be available in 2012.

VANDLE: A time of flight detector for measurements of neutron energies from direct reactions. Expected to be available in 2012 for reaction experiments, it will consist of 200 or more straight plastic scintillator bars. It most likely will require pulsed beam from the tandem though other methods using MCPs could be used for RIBs with intensities around 1 million ion/s or less.

Spin Spectrometer: See Instrumentation section on Nuclear structure - in-beam spectroscopy above.

Radioactive Targets: The location of the RIB injector line near the Enge Spectrograph provides the opportunity to make implanted radioactive targets in-situ while bombarding the same target with light stable ions from the tandem. A beam line and electrostatic optical elements would connect the RIB injector beam line with the target chamber of the Enge. Light ion spectroscopy could then be done using a deuteron beam from the 25 MV tandem accelerator. Long-lived targets can be made elsewhere and moved to the Enge for initial proof-of-principle experiments. This work is looking for funding.

Polarized Target: A cryogenic polarized hydrogen and deuterium target is being considered for HRIBF. It would enable critical scattering experiments in inverse kinematics of many radioactive neutron-rich beams.

Hercules: See Instrumentation section on Nuclear Structure - In-beam Spectroscopy above.

Nuclear astrophysics

Nuclear astrophysics research is primarily concerned with understanding the underlying nuclear physics that drives the processes that occur in stellar environments including explosive events. Data critical to these processes include reaction rates and masses as well as nuclear structure data such as half-lives, energy levels including resonances, and decay branching ratios. Typical locations of experiments include the Daresbury recoil separator, the existing general-purpose beam line, and the future ORRUBA/Scattering chamber beam line.

Daresbury Recoil Separator (DRS): The DRS is a mass separator based two velocity filters. It is optimized for proton capture reactions using the windowless gas cell. It has versatile target chambers that can accommodate many set-ups including various silicon detector arrays.

Windowless gas cell target: The target is 10 cm in length with the gas contained by apertures and differential pumping. It is used primarily for proton capture reactions although parts of the cell can be used to contain a large chamber of gas that has also been used as a target.

SIDAR: A silicon strip detector array often used with ORRUBA for charge-particle detection.

ORRUBA: See Instrumentation section on Nuclear reactions above.

ORRUBA-S: See Instrumentation section on Nuclear reactions above.

VANDLE: See Instrumentation section on Nuclear reactions above.

DRS Gas Jet Target: The conversion of the DRS windowless, differentially pumped gas target to a gas jet target will enable measurements of transfer reactions (e.g., (^{3}He,d)) and scattering measurements by localizing the target nuclei. It will utilize existing components supplemented with a new central chamber, pumps, and a recirculating/purification system. It will be available in 2012.

Fast Ion Chamber: A multi-segmented ion chamber is proposed to increase the count rate capability in experiments requiring >50,000 ions/sec. It functions by making the distance between anodes and cathodes smaller reducing the drift time of electrons and the slower positive ions. It will be available in 2013.

Nuclear applications

Most applications involve equipment and techniques which were originally designed and developed for basic research. For example, the use of (d,pγ) as a surrogate reaction for (n,γ) on radioactive targets requires equipment described above.

Enge Magnetic Spectrograph: See Instrumentation section on Nuclear reactions above. Operated in vacuum and at 0° ions are separated and transported to the focal plane where they are detected with silicon detectors or a Bragg detector that can discriminate between isobars for accelerator mass spectrometry (AMS).

Spin Spectrometer: See Instrumentation section on Nuclear structure - in-beam spectroscopy above. It will be used to determine the spin and energy distributions of the compound system. These studies will aid theorists in connecting the compound nucleus of the surrogate to the desired reaction.

Tritium beams: Beams of radioactive tritium will help research materials used in light ion fusion environments such as the National Ignition Facility and ITER. HRIBF is presently exploring what is necessary to offer these beams.

General-purpose beam line: A location where small set-ups can be staged for implantations of radioactive isotopes into materials. One example given is implanting ^{7}Be for medical wear studies of material used in artificial joints.

General-purpose equipment and future improvements

General-purpose equipment available within the facility is listed below. During the process of preparing this white paper, several improvements to the facility have been identified as well as suggestions for new equipment. In addition, the implications of hosting GRETINA will offer an opportunity to make the RMS target area more flexible so that it could be used by additional detector systems, e.g., the Spin Spectrometer.

Isobar separator: HRIBF has a very good high resolution isobar magnet capable of separating isobars when the beam has good emittance. Separation on the order of 7000:1 (FWHM) is achievable and 10,000:1 may be possible. Experiments have demonstrated six orders of intensity reduction of a contaminating isobar with the device.

General-purpose beam line: A beam line with enough room for users to set-up experiments that do not have their own station. Experiments include transient field g-factor measurements, Coulomb excitation using the BaF_2 array, projectile break-up using the 1-meter scattering chamber, decay spectroscopy using the ranging-out technique, (d,pγ) surrogate reactions, nanosecond isomers populated through multi-nucleon transfer reactions, etc..

Gas detectors: HRIBF has several gas detectors such as Bragg detectors and ionization chambers that can be used to diagnose beam composition and to supply data useful for normalization. These detectors are often used as beam samplers and under low counting rates (<50 kHz) in event-by-event data.

Micro-channel plate detectors (MCP): HRIBF has several versions of MCP-plus-thin foil detectors that provide timing, beam counting, and even position of heavy ions passing through the thin foils. These detectors provide sub-nanosecond timing and can withstand upwards of 1 MHz counting rates although position is not available at such rates.

Computer Infrastructure: The new computer cluster will aid in simulations, data analysis, and theoretical computations. In addition, network improvements will allow the new computer cluster to function as data acquisition hosts.

Tandem pulsing: A project to refurbish and improve the tandem's capability to deliver a pulsed beam to improve timing and detection efficiency for experiments. New system available in 2013.

RMS target area: GRETINA will require the removal of the CLARION support structure as well as the target chamber support. GRETINA will be supported from the floor and we intend to reuse that support concept for a method of supporting the CLARION hemispheres. In addition, a platform can be constructed to support the large Spin Spectrometer. The RMS target room has the space necessary to store each device when it is not installed at the target position. This should also allow this target station to be of more general use.

New LeRIBSS: The present LeRIBSS beam line is supported below the tandem and CARDS, when fully installed, blocks access to the time-of-flight station and the general-purpose beam line. In addition, the MTAS is a 1-ton device that should be in a better-controlled environment than what is possible at the present LeRIBSS location. Therefore, we envision extending the beam line into the adjoining room at a height similar to the existing high-energy beam lines.

Compact Efficient Radioactive Decay Array (CERDA): A Ge double-sided strip detector array coupled with Clover Ge and scintillator detectors for complete decay spectroscopy measurements. Such a device is portable and can be used at HRIBF, NSCL, and other RIB facilities. This is only a proposal at this time.

Laser spectroscopy: The use of laser ionization techniques in producing RIBs at HRIBF brings new possibilities for decay studies in the future. Spins, charge radii, and moment measurements are all possible through the use of laser spectroscopic techniques. Expansion of LeRIBSS into the west experiment room may provide HRIBF with an opportunity to participate in this field of research.

Storage ring: A recirculating storage ring has been suggested to be possible for use in (d,p) experiments in inverse kinematics. It is believed that technology has progressed such that RIBs can be recycled and the same ions can be used to bombard the target again and again. A number of significant and detailed studies are needed to evaluate this suggestion.

Large acceptance spectrometer: A large gas-filled magnet or solenoid has been suggested for fusion and transfer reactions. This would replace the Enge and improve detection efficiency.

Education and Outreach

The education of young scientists must be an integral part of any vision of the future of nuclear science, as well as being central to the mission of the Department of Energy [Cer04]. Well-designed education programs, ensuring a stable supply of nuclear scientists – as well as a scientifically literate society – are essential not only to the fertility of academic research, but also to the needs of medicine, defense, industry, and government. It is more important than ever that the public be informed about science and technology in general, and nuclear technology is an important component. As more lives are saved through nuclear medicine, it is critical that we continue to invest in the nuclear scientists that drive these innovations. As global climate change becomes a more and more compelling reality, it is clear that nuclear power will become more important to this country's future energy needs. Only with a scientifically literate society can well-founded decisions on these important topics be made. Moreover, education in Scientific, Technology, Engineering, and Mathematics (STEM) is essential to maintaining the Nation's competitiveness both technologically and economically. This section discusses how the HRIBF impacts society through the education of young scientists and by the outreach efforts from the laboratory. These activities form the broader reach of the HRIBF.

Graduate and Post-Graduate Education

Graduate education is at the heart of educational activities in nuclear science. From today's corps of graduate students will emerge the young scientists who will provide tomorrow's intellectual leadership in experimental and theoretical nuclear science, and the talent to help address the needs of the nation in defense, medicine, energy, and industry. HRIBF plays host every four years to the Summer School on Exotic Beam Physics. The primary goal of the summer school is to nurture future exotic beam scientists. The school provides a unique opportunity for graduate students, senior undergraduates, and young post doctoral researchers to attend lectures from world-leading nuclear physicists, participate in "hands-on" activities and present their own research.

Oak Ridge National Laboratory, and the HRIBF in particular, have fostered many partnerships with national and international educational institutions, either directly or through intermediary bodies such as Oak Ridge Associated Universities (ORAU), the Oak Ridge Institute for Science and Education (ORISE), the University Radioactive Ion Beam Consortium (UNIRIB), the Joint Institute for Heavy Ion Research (JIHIR), and more recently the Japan-U.S. Theory Institute for Physics with Exotic Nuclei (JUSTIPEN). These provide vital conduits linking students to research opportunities throughout the laboratory. Since 1982 the JIHIR [http://scialli.org/jihir/] has supplied critical research assistance and dormitory space to more than 1,000 scientists from all over the world and been host to more than 4,000 scientists who have attended 60-plus international conferences and workshops. The UNIRIB consortium [http://www.orau.org/university-partnerships/unirib/default.aspx] also provides local support for UNIRIB students, supports experimental expertise and equipment at the HRIBF, and supports workshops and locally organized conferences.

At the HRIBF, graduate students participate in the complete spectrum of activities that characterize experimental nuclear science. They typically play active roles in the design, construction, calibration, and maintenance of experimental equipment, in addition to exploiting these instruments for research. They are actively involved in data-taking, analysis, and interpretation of results. On the theory side graduate students work with some of the world's leading nuclear theorists to develop new theories of the nucleus as well as performing calculations on world-leading computers. During 2009, 52 graduate students from 19 institutions participated in research at the HRIBF, as well as another 51 postdoctoral associates from 29 institutions. The education of these young scientists is not only a measure of success for the field, but an important contributor toward addressing national needs. Based on a survey of Ph.D.s granted in nuclear science "5-10 years out" in 2004, over 40% of scientists who receive Ph.D. degrees eventually work in professions outside the field of nuclear science, contributing broadly to the nation's scientific and technical needs [Cer04].

Figure 16: Members of Center of Excellence for RIBSSS meet with Thomas P. D'Agostino (center), Deputy Administrator for Defense Programs in the NNSA, at the SSAA Symposium held at the Carnegie Institution in Washington D.C. They are graduate students Cara Jost (Mainz), Travis Bray (Auburn), Kelly Chipps (Col. School of Mines), Steven Padgett (U. Tennessee), Patrick O'Malley (Rutgers) and postdoctoral fellows Sean Liddick (U. Tennessee), Catalin Matei (ORAU), William Peters (Rutgers), and PI Jolie Cizewski (Rutgers).

One important contributor to graduate and postgraduate education at the HRIBF is the Center of Excellence for Radioactive Ion Beam Studies for Stewardship Science (RIBSSS) (Figure 16). The National Nuclear Security Administration within DOE is committed to recruiting a highly talented workforce ready to solve the most challenging scientific problems associated with ensuring the safety, reliability, and performance of the nuclear stockpile in the absence of nuclear weapons testing. To realize this goal, the NNSA initiated the Stockpile Stewardship Academic Alliance program to support the U.S. scientific community in the critical areas of low-energy nuclear science, materials science, and high-energy density physics. The Center of Excellence for RIBSSS, centered at the HRIBF, is an example of one of these projects. The consortium of nuclear scientists, led by Jolie Cizewski of Rutgers University, is developing and using radioactive beams of fission fragments for reaction and structure studies. The center provides direct support for undergraduate and graduate students and postdoctoral scholars and facilitates the participation of other students and postdoctoral scholars. As of fall 2007, 22 undergraduate students, 25 graduate students, and 16 postdoctoral fellows from 19 universities have participated in the activities of this center. Many of these participants have been heavily involved with the development, construction, and use of two large detector arrays that have been developed by the center: the Oak Ridge Rutgers University Barrel Array (ORRUBA) [Pai07a] of silicon strip detectors and the Versatile Array of Neutron Detectors for Low Energy (VANDLE), an array of plastic scintillator detectors. To date, four former postdoctoral fellows associated with the center are performing research at Livermore National Laboratory, with others considering such opportunities as they complete their studies and research. Finally, let us mention that some discussion of education and training for workforce development can be found in other sections of this Report. For instance, unique opportunities can be opened up by building an isotope facility at HRIBF, see Applications section.

Undergraduate Education

To meet the national need for a citizenry with a strong scientific background, the nuclear science community nurtures the development of future scientists by offering undergraduate students a number of opportunities to experience the excitement of research. Such experiences have proven to be a strong enticement for students to consider pursuing careers in science. Nuclear science research groups at the HRIBF routinely involve bright and eager undergraduate students in their activities, often starting in the freshmen year. One example is the nuclear astrophysics group (Figure 17), which typically hosts 5-7 undergraduate students each summer from many institutions including Tennessee Technological University, Rutgers University, the University of Tennessee, and the Colorado School of Mines.

Figure 17: Undergraduate students Kyle Thomson (Tenn. Tech.), Brett Manning (Col. School of Mines), Irena Spassova (Rutgers), Will Martin (U. Tenn.), Belinda Loi (Pellissippi State), Eric Hannah (Tenn. Tech.), graduate students Enrique Merino (Rutgers), Stephen Pittman (U. Tenn.), postdoctoral fellows Eric Lingerfelt (U. Tenn.), Kelly Chipps (Rutgers), William Peters (Rutgers), Catalin Matei (ORAU), Andy Chae (U. Tenn.), Steve Pain (ORNL), high school teacher Randall Dunkin, professor Ray Kozub (Tenn. Tech) join HRIBF staff Dan Bardayan, Caroline Nesaraja, and Michael Smith at the start of a busy summer period.

Outreach

The technological developments of the future will require an increasingly science-literate and well-informed populace. In addition to their roles in undergraduate and graduate student education, many HRIBF researchers, working alone or as part of interdisciplinary outreach programs, have made significant efforts to enhance the scientific literacy of the public at large and to engage K-12 students and teachers in scientific endeavors.

Examples include the HRIBF's Michael Smith who has participated in a variety of outreach activities such as engaging 6th grade students at Clinton Elementary School [Bri09] in scientific discussions via live video conferencing, participating in the Adopt-A-Physicist Program with follow up lectures at the Webb School of Knoxville, and conducting a seminar series for 24 Tennessee Governor's Academy students. For his efforts, Michael was awarded the ORNL Mentor and Education Champion Award in February 2008 and ORNL Top Science Communicator Award in November 2006. Other examples include the effort led by HRIBF researcher Lee Riedinger to establish Farragut High School's Science Academy, a practical-experience program placing students in ORNL labs [Whi09], and the construction of outreach websites by HRIBF researchers that target the general public with animations describing nuclear physics [http://www.phy.ornl.gov/hribf/science/abc/].

It is clear the HRIBF staff play a vital role in educating and developing this country's next generation of nuclear scientists. To maintain and expand the number of Ph.D. students, it is essential that HRIBF can support world-class research projects. The greatly increased reliability and reach of the scientific program offered by the cyclotron upgrade ensures that this important pipeline remains viable, active, and growing. Only with investments in scientific research, education, and outreach can our country continue to thrive and remain competitive.

HRIBF Driver Upgrade in the context of the 2007 NSAC Long Range Plan

The proposed cyclotron upgrade of HRIBF is consistent with the most recent NSAC planning exercise for the field, i.e., 2007 NSAC Long Range Plan [LRP07]. This Plan gave priority to FRIB, of course, but also quite clearly noted the need for productive use of our other facilities, including the necessary modest upgrades that are needed to keep them world class. The LRP stated:

> "To launch the field into this new era requires the immediate construction of FRIB with its ability to produce ground-breaking research, and effective utilization of current user facilities, NSCL, HRIBF and ATLAS." (FRIB recommendation)
>
> "... it is critical: (...) to optimally operate NSCL, taking advantage of its world-leading capabilities with fast rare-isotope beams; and to invest in the ATLAS and HRIBF user facilities with their unique low-energy heavy-ion and rare-isotope beams." (p. 9)
>
> "Especially critical are experiments with rare-isotope beams. Pioneering efforts in this field have provided impressive first results and have temporarily put the United States in a world leadership position. Yet, the field is still in its infancy and is limited by no access to the rarest isotopes and the beam intensities available today. To address this limitation, physicists have begun planning a next-generation Facility for Rare Isotope Beams (FRIB), which will deliver the highest intensity beams of rare isotopes available anywhere. But FRIB will not be available for a decade. So in the meantime, physicists hope to continue developing a comprehensive picture of atomic nuclei by strengthening operations and carrying out modest upgrades at the National User Facilities (at ANL's ATLAS, ORNL's HRIBF, and MSU's NSCL)" (p.58)

The National Academy of Sciences - National Research Council RISAC report [RISAC] also emphasized the importance of low-energy facilities on the road to, and in support of, FRIB. Concerning HRIBF, the RISAC report has explicitly stated that:

> "The current U.S. program is world-leading, with the highest intensity fast exotic beams available at the NSCL and a unique set of beams from actinide targets at HRIBF."
>
> "Clearly, the major national user facilities in the United States (NSCL at MSU, and HRIBF at ORNL) are now competitive with the world's other leading facilities and, thus, are extremely important."
>
> "HRIBF has demonstrated the ability to accelerate approximately 175 radioactive isotopes including 140 neutron-rich species; more than 50 of these, including ^{132}Sn, are available at intensities of 10^6/s or greater. The post-accelerated neutron-rich beams are unique worldwide."

Of course, these sentiments had been strongly endorsed by the low energy community itself en route to the Long Range Plan. They were perhaps best captured by the White Paper "Nuclear Astrophysics and Study of Nuclei Town Meeting" [NSA07] prepared for the 2007 NSAC Long Range Plan. The main recommendation of the Town Meeting was devoted to FRIB:

> “The highest priority in low-energy nuclear physics be the construction of a heavy-ion linac based rare isotope facility, including the capabilities for stopped, re-accelerated and in-flight beams to realize the scientific potential defined by the community and endorsed by the National Academies of Sciences in their recent RISAC report.”

However, the upgrades of existing low-energy facilities were also discussed at the Chicago Town Meeting. In particular, a plan was presented to improve RIB production capability at HRIBF by installing a turnkey accelerator that would replace ORIC. The second recommendation of the Town Meeting stated, in fact, that

> “In support of this science goal (FRIB), we must continue forefront research at existing facilities to make new discoveries, train new people and develop new detector and accelerator technologies. Hence, we also recommend that
>
> Appropriate funds for operations and near-term upgrades of existing rare isotope and stable beam research capabilities at ANL, NSCL, ORNL, and other national and university facilities be supported together with a strong theory program and interdisciplinary initiatives. In particular, it is critical that funding be increased immediately to allow the effective utilization of the U.S. national user facilities.”

The HRIBF upgrade plans were presented at the meeting of NSAC Long Range Plan Working Group in Galveston. It is important to recall the context of the Galveston discussions. The main priority was to launch the FRIB initiative. To push for smaller-scale upgrades of existing facilities through secondary recommendations might have impacted this goal and were not at the funding level to warrant major LRP recommendations. Hence the lack of explicit recommendations on upgrades of HRIBF, ATLAS, NSCL, and other facilities. In spite of this, the Long Range Plan 2007 report [LRP07] did provide strong support for such upgrades as noted in the quotes given above.

In summary, the proposed cyclotron upgrade of HRIBF is fully aligned with the long-range plan of the U.S. nuclear physics community. This investment will provide this community with unique rare-isotope beams, it will produce groundbreaking research, and it will provide opportunities for important societal applications. As mentioned in the next Section, the upgraded HRIBF will provide training of the next generation of scientists in nuclear physics and nuclear astrophysics and in the techniques for exploiting exotic nuclei, and will also improve and develop the instrumentation that will ultimately be used at and will improve the capabilities of FRIB itself.

Relationship of the HRIBF Upgrade to FRIB

The upgrade at HRIBF will be important for maintaining and developing programs based on ISOL technology, and is the only U.S. center where such activities are currently performed. Given the emphasis on in-flight separation for the initial operation of FRIB, it is unlikely that developments for an ISOL program can be made at the FRIB facility. Hence, these developments must be accomplished at existing ISOL facilities such as HRIBF.

ISOL operation at FRIB was acknowledged as important to the long-term science program by the Rare Isotope Science Assessment Committee of the National Academies [RISAC], where they listed heavy-element studies and tests of fundamental symmetries in nuclei as two of the FRIB science drivers. Both programs require the highest possible intensities and will likely require ISOL capabilities. In light of these scientific opportunities, the 2007 NSAC Rare Isotope Task Force [Sym07] recommended that an ISOL program be made an option for future implementation at FRIB: "… 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."

The future FRIB user community has also continued to express an interest in a future ISOL capability at FRIB. One of the consensus statements from the ANL FRIB Workshop in May 2009 stated: "We support including space to implement an ISOL option."

In light of the expert panel and user recommendations, the FRIB design must consider the option of ISOL production [She09]. Figure 18 shows a possible co-location of the ISOL targets with the in-flight target.

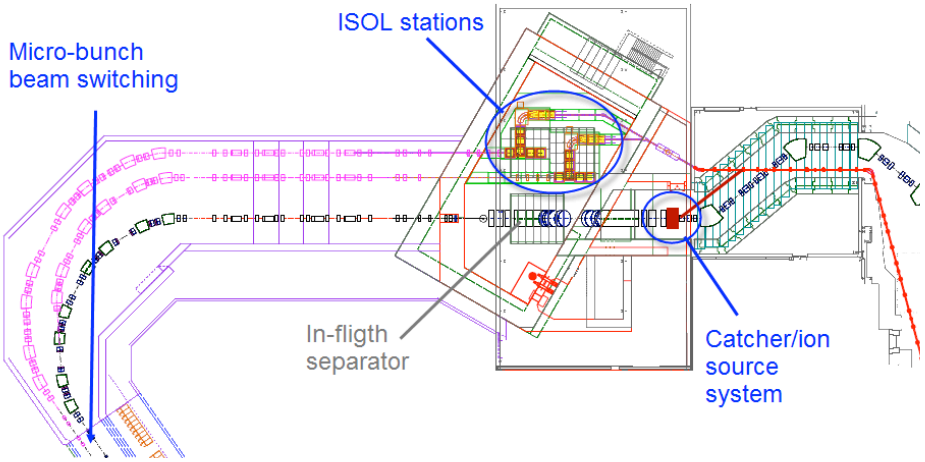

Figure 18: Schematic layout of the FRIB target area showing a possible location for two ISOL target stations. The current plan is to include the civil infrastructure in the initial construction including shielding to allow ISOL operation with up to 400kW of 1 GeV protons. Locating the ISOL station in the same area as the in-flight target with the remote handling, air, and water handling will reduce the additional cost of an ISOL addition.

The timescale of the HRIBF upgrade is likely consistent with the time frame of the developments at FRIB. The start of ISOL operation at FRIB is uncertain, since the baseline project includes in-flight production, but does not include day-one ISOL stations. The current CD-4 range for FRIB is Oct. 2017 to February 2019, although this is a proposed range since the project has not yet been baselined. Hence it is likely that ISOL operation at FRIB many not be available until after 2020.

The HRIBF driver upgrade will also provide, in a cost-effective manner, continued scientific resources for the community of researchers using rare isotopes, allowing them to develop scientific programs and answer important scientific questions in preparation for, and in helping guide the first generation of experiments at FRIB. For example, research at HRIBF in the near term will stimulate development of the theoretical tools needed to interpret transfer and fusion reactions with exotic, rare isotopes. Study of key isotopes near ^{132}Sn and ^{100}Sn will guide the experimental program, pointing to the most important measurements at FRIB and allowing the facility to be used more efficiently. While FRIB will produce thousands of new isotopes, equally important will be the guidance to determine the most important measurements to perform.

Hence, both scientifically and technically the Driver Upgrade at HRIBF fits well into the overall low-energy program in the FRIB era. The upgrade will advance science and enhance the value of research at FRIB, while preparing the community and providing the technical advances to make an ISOL program at FRIB possible.

Other ISOL facilities

HRIBF in the world context

The main niche of HRIBF remains in its ability to provide high-quality radioactive ion beams for research. The facility delivers a large range of isotopes with tandem energies and beam quality – this is unique worldwide and reflects the outstanding contributions from the target-ion source group. In this respect it is superior, in terms of range of radionuclides that can be post-accelerated to Coulomb barrier energies, to any other ISOL facility worldwide.

The replacement of ORIC by a high intensity driver such as the HDU is important to the future provision of intense beams of neutron-rich radionuclides for the US and international user community. This will build upon the existing strength of the facility and complement FRIB by accessing mass regions vital for studies of shell evolution and the astrophysical r-process.

The main competition for high-intensity neutron-rich beams comes from the TRIUMF e-driver (photo-fission) and SPIRAL2 (deuteron driver for n-induced fission), but there is a window of opportunity if the upgrade can be implemented soon, optimally by the middle of the next decade. Given the technological challenges facing the two competitors in the areas of handling actinide targets, charge-breeding and beam purification, HRIBF is in a strong position to retain its world-leading capability well into the next decade. This is nicely illustrated in Table 2 that shows measured and projected post-accelerated yields (per second) of neutron-rich doubly magic ^{132}Sn at current and planned fission factories worldwide [But09].

HRIBF	10^5	4.5 MeV/u	(now)
REX-ISOLDE	10^6	3 MeV /u	(now)
CARIBU	$5\cdot10^4$	10 MeV/u	(2010)
TRIUMF p-driver	10^7	5 MeV/u	(2010)
CARIBU phase 2	10^6	14 MeV/u	(2013)
HRIBF HDU	**$2\cdot10^8$**	**4.5 MeV/u**	**(2015)**
HIE-ISOLDE	10^8	10 MeV/u	(2015)
TRIUMF e-driver	$5\cdot10^8$	5 MeV/u	(2015)
SPES	$5\cdot10^8$	9 MeV/u	(2015)
SPIRAL-2	$2\cdot10^9$	7 MeV/u	(2015)
EURISOL	10^{11}	150 MeV/u	(2025)

Table 2: Accelerated ^{132}Sn yields (per second) at present and planned fission factories worldwide

Europe

The ISOLDE facility at CERN, based on a 1.4 GeV proton driver, has operated for four decades and pioneered many of the techniques for ISOL beam production for both non-accelerated as well as reaccelerated beams. The HIE-ISOLDE upgrade conditionally approved by the CERN management in the fall 2009 provides more intense proton-driver beams and improved post-acceleration capability to increase the current energy from about 3 MeV/u to 10 MeV/u within a few years to come. Its strengths lie on a wide range of ion beams from lightest to heaviest elements both for neutron-deficient as well as neutron-rich isotopes that are produced in spallation, fragmentation and fission reactions; its weakness lies in the present lack of instrumentation for reaction studies.

The SPIRAL2 facility at GANIL in France is expected to be completed in about 2015. SPIRAL2 has the potential to become the world's most powerful ISOL facility for neutron-rich (fission fragment) beam production. The driver beam for fission fragments will be a linac capable of delivering 5 mA of 40 MeV deuterons to a carbon neutron-production target. The present goal is about $5\mathrm{x}10^{13}$ fissions per second induced by ~20 MeV neutrons, but it will take some years to achieve this target.

The SPES facility under planning in Legnaro, Italy is based on a 70 MeV cyclotron driver, similar to the HDU driver of HRIBF. It will employ a direct target approach with the objective to reach 10^{13} fissions/s in the target. The post accelerator to be used is the existing superconducting linac ALPI. There is considerable uncertainty in the construction schedule as the host laboratory has no experience of RIB production.

North America

The ISAC facility at TRIUMF in Canada is based on 500 MeV proton driver beams. ISAC I has produced accelerated radioactive beams up to 1.5 MeV/u for nuclear astrophysics and nuclear structure studies for several years, and its extended version ISAC II has begun operations with the additional superconducting linac reaching its full potential of 5 MeV/u energy in 2010. It is pursuing operations with actinide targets allowing in the future production of neutron-rich (fission product) beams. ISAC has enormous potential for production of beams of proton-rich species. The facility has a scientific reach similar to that of HIE-ISOLDE. Recently, in the context of its next five-year plan (2010-2015) TRIUMF has submitted a proposal for a high-power electron-beam driven photofission facility to add additional neutron-rich capability.

A major advance at the ATLAS facility at Argonne National Laboratory in rare-isotope capabilities is the Californium Rare Ion Breeder Upgrade (CARIBU). In full operation (summer 2010), rare isotopes will be obtained from a one-Curie ^{252}Cf fission source located in a large gas catcher from which they will be extracted, mass separated, and transported to an ECR source for charge breeding prior to acceleration in ATLAS. This will provide accelerated neutron-rich beams with intensities up to 10^6/s at energies up to 12 MeV/nucleon for a few hundred isotopes, many of which cannot be readily extracted from ISOL-type sources. An energy and efficiency upgrade of ATLAS is currently under way up to 15 MeV/u. ATLAS also produces a limited number of proton-rich, light isotopes through the in-flight method. The upgrade will increase the intensity of these beams by one order of magnitude.

Asia

TRIAC (Japan) is a facility jointly developed by JAEA and KEK. Radioactive beams are produced by 30MeV, 1-3μA Tandem proton driver beam inducing fission in a 330mg/cm^2 UC$_x$ targets, as well as a variety of other nuclear reactions. An ECR charge breeder is used to create multi-charged ions, which are accelerated to energy of 1.1A MeV by two linear accelerators. It is proposed to accelerate RIBs up to 8A MeV by injection into the existing SC-booster linac.

VECC (India) is an ISOL facility using a K=140 MeV cyclotron to produce proton and alpha driver beams. Ions from irradiated targets are passed through a 6.4 GHz ECRIS to produce multiple charge ions. An accelerator chain, including RFQ and linear accelerator sections, is scheduled to be commissioned soon; the energy range will be up to 460A keV. A proposal to accelerate RIBs up to 1.3A MeV and to construct an electron driver has been submitted to Government of India for funding.

BRIF (China) is a proposed ISOL facility based on a 100 MeV, 200μA cyclotron proton driver. The radioactive beams will be injected into the HI-13 tandem facility at the Chinese Institute for Atomic Energy (CIAE).

CYRIC (Japan) is based on an existing k=130 AVF proton cyclotron. This facility can accelerate proton beams to 300μA. Implanted radioactive ions produced with this beam are currently used to study β-decay properties of exotic nuclei, but a proposal to accelerate the ions is under discussion.

KoRIA (South Korea) is a proposed ISOL (and later in-flight) facility based on a K=100, 1mA cyclotron driver and 10 MeV/u post-accelerator linac.

From this brief survey it is clear that there is considerable interest in Asia concerning the production of RIBs by the ISOL method. However, these facilities are still being developed so their full potential will not be realized for several years. Thus, due to the accumulated expertise in RIB production at HRIBF and provided a new cyclotron can be installed on a relatively short time scale, there is good reason to believe that Oak Ridge could retain its lead in RIBs from fission production well into the next decade.

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Workshop Schedule

(modified to accommodate a Friday evening power failure)

Friday, November 13
Main auditorium

08:30 Welcome (Ray Kozub, HRIBF Users Executive Committee Chair)
08:40 Welcome (Michele Buchanan, Director ORNL Physical Sciences
08:50 Welcome (Jim Beene, Physics Division and HRIBF Director)
09:00 HRIBF Upgrade Project (Jim Beene, Alan Tatum, Dan Stracener

10:45 Break

11:15 FRIB (Brad Sherrill)
11:45 Other ISOL facilities (Juha Äystö and/or Peter Butler)
12:15 Isotopes (Mike Saltmarsh)
12:40 Working group goals and schedules (Ray Kozub)

Breakout parallel sessions

13:00 Decay Spectroscopy, Reactions, Applications

18:00 Adjourn

Saturday, November 14

Breakout parallel sessions

8:00 In-beam spectroscopy, Astrophysics, ISOL technology

10:30 Break

Main auditorium

11:00 Session summaries
13:00 Lunch (provided by ORAU)

14:00 Close of workshop