Rare Isotope Research Capabilities at the NSCL Today and at RIA in the Future

C. Konrad Gelbke
National Superconducting Cyclotron Laboratory, Michigan State University,
East Lansing, Michigan 48824-1321, USA

Abstract

The new (2002) Long Range Plan for Nuclear Science in the U.S. finds that "the exciting new scientific opportunities offered by research with rare isotopes are compelling." The NSCL's recently completed coupled cyclotron upgrade can provide fast beams of rare isotopes with intensities higher by about 3 orders of magnitude than previously available in the U.S. Large additional gains, especially for medium-mass and heavy elements, will be possible with the Rare Isotope Accelerator (RIA), the highest priority recommendation for major new construction in the 2002 Long Range Plan for Nuclear Science.

Overview

The National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) is a national user facility for rare isotope research and education, with over 270 employees (including over 60 undergraduate and 45 graduate students) and serving a user community of over 500 researchers. Research at the NSCL is primarily in basic experimental and theoretical nuclear physics, nuclear astrophysics, accelerator physics, related instrumentation development, and applications to meet specific societal needs. Located on the campus of a major research university, the NSCL offers an ideal synergy of research and education and plays a major role in the training of the next generation of scientists.

The Laboratory has a history of technical innovation. It has been a pioneer in applying superconducting magnet technology to the design and construction of cyclotrons, magnetic spectrographs, and beam transport systems. The NSCL has recently completed an upgrade to a coupled cyclotron facility (CCF) capable of producing intense beams of primary heavy ions from hydrogen to uranium with maximum beam energies of 200 MeV/nucleon for lighter elements and 90 MeV/nucleon for uranium. A high-acceptance superconducting fragment separator immediately downstream of the coupled cyclotrons allows efficient production and separation-in-flight of a broad range of secondary rare isotope beams produced by projectile fragmentation or fission, opening new opportunities for basic nuclear physics and nuclear astrophysics research.

Insight and experience gained at MSU and other laboratories in producing radioactive beams via projectile fragmentation and in-flight separation has helped open new vistas for nuclear structure physics and nuclear astrophysics research, and NSCL faculty played a seminal role in developing the concept for the new Rare Isotope Accelerator (RIA). RIA will allow large additional gains in rare isotope intensities, and MSU has offered a particularly attractive option of siting RIA on its campus.

The Nuclear Science Advisory Committee (NSAC) for the Department of Energy and the National Science Foundation has recently submitted a new Long Range Plan for Nuclear Science in the U.S., which states in its two top priority recommendations: *it is imperative to increase support for facility operations – especially our unique new facilities RHIC, CEBAF, and NSCL – which will greatly enhance the impact of the nation's nuclear science program (and) increase investment in university research and infrastructure… The Rare Isotope Accelerator (RIA) is our highest priority for major new construction…*

In this talk I will briefly discuss the NSCL's CCF facility, its scientific reach, and the additional gains made possible by RIA. Ongoing activities at the NSCL in support of RIA will be summarized, and a possible layout of the facility will be presented.

NSCL Facility

Located on the MSU campus, the NSCL offers a true synergy between research and education. The NSCL is adjacent to the Department of Chemistry building and MSU's new Biomedical and Physical Sciences Building. The College of Engineering is within 5 minutes walking distance. Formal classroom education and hands-on research are naturally integrated into a first-class education and research experience that *U.S. News and World Report* has ranked as the #2 nuclear physics Ph.D. program in the United States.

The floor plan of the experimental high bay area is shown in Figure 1. The NSCL's two cyclotrons, beam line and spectrometer magnets are based on superconducting technology and were designed and built in house.

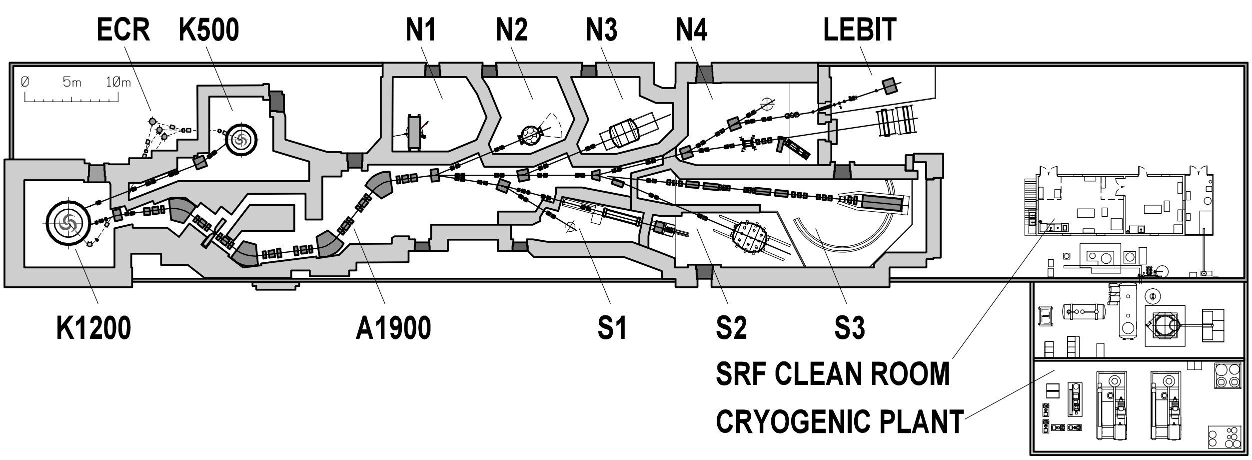

Figure 1: Floor plan of the NSCL high bay experimental area showing the two superconducting cyclotrons (K500 and K1200 on the left), the superconducting A1900 beam analysis system and subsequent beam lines, the various experimental vaults, the SRF R&D area, and the new cryoplant.

Two electron cyclotron resonance (ECR) ion sources produce the ions needed for acceleration. A beam switchyard allows injection from either ion source into either cyclotron allowing both coupled-cyclotron (CC) and K1200 stand-alone operations. For CC operations, intense beams of low-charge state ions accelerated in the K500 pass through a coupling line to the K1200 cyclotron where they are stripped and accelerated to full energy. The NSCL facility can accelerate ions of essentially any chemical element to energies from approximately 10 to 200 MeV/nucleon (the exact energy range depends on the A/Z ratio of the isotope). Energetic primary beams can be used directly, or they can be converted into a broad range of nuclear species by means of projectile fragmentation or fission. The resulting fragments are then separated in-flight and delivered to one of the experimental vaults.

The new A1900 beam analysis system (momentum acceptance $\Delta p/p$ = 5.5%, maximum rigidity $B\rho_{max}$ = 6.0 Tm) is currently the largest-acceptance fragment separator in the world and the only one based on superconducting technology. Compared to the NSCL's previous fragment separator, the A1900 has about an order of magnitude higher acceptance and a 50% higher bending power.

Downstream from the A1900 is a beam switchyard that allows transportation of all radioactive ion beams to any experimental station at the NSCL.

The S1 vault contains the Reaction Product Mass Separator (RPMS) and a multi-purpose beam line primarily devoted to studies of Single-Electron-Events (SEE) in semiconductors under a beam-time purchase agreement. The RPMS consists of a Wien velocity filter followed by a magnetic dipole for mass separation; it achieves a mass resolution of 10^2 and a primary beam suppression factor of approximately 10^8. The RPMS is used for low-background studies of nuclei far from stability, with its Wien filter providing additional purification particularly for studies with proton-rich nuclei. An experimental station for measuring nuclear magnetic moments is situated in S1 just upstream from the RPMS.

The "Superball" in the S2 vault is a high-efficiency neutron multiplicity meter built by a University of Rochester group. The Superball contains approximately 17 m^3 of Gd-doped scintillator for the detection of neutrons in 4π geometry. Its large internal scattering chamber can accommodate the Miniball/Miniwall 4π charged-particle-detector array or other charged-particle detection equipment.

The S800 in the S3 vault is a superconducting high-resolution magnetic spectrograph with energy resolution $E/\delta E = 10^4$, maximum rigidity $B\rho_{max}$ = 4 Tm, momentum acceptance $\Delta p/p$ = 5%, and solid angle $\Delta\Omega$ = 20 msr. The S800 beam line can deliver dispersion-matched beams to the S800 magnetic spectrograph; alternatively, it can be used as a fragment separator with momentum acceptance $\Delta p/p$ = 6%, maximum rigidity $B\rho_{max}$ = 5.35 Tm, momentum resolution $p/\delta p$ = 2000, and solid angle $\Delta\Omega$ = 6 msr. Both the S800 spectrograph and the S800 beam line deflect the ions vertically.

The 4π array in the N2 vault is a low-threshold "logarithmic" 4π detector consisting of successively layered shells of parallel plate multiwire detectors, segmented Bragg ionization chambers, and fast-slow plastic scintillator phoswich detectors. A number of forward arrays were built by outside user groups for experiments requiring higher resolution and/or granularity at small angles.

The N3 vault is the major general-purpose vault in the NSCL facility. It contains a large cylindrical multi-purpose scattering chamber (diameter: 231 cm, length: 271 cm). The chamber shell can be lifted from the vault to provide a large free space.

The N4 vault will be the normal location for a large-gap superconducting "sweeper" magnet (4 Tm), a high-acceptance magnetic spectrometer constructed by the High Magnetic Field Laboratory at Florida State University. The sweeper magnet can be combined with large-area neutron detectors for neutron time-of-flight (TOF) spectroscopy at very small angles. The N4 shielding wall behind the sweeper magnet can be opened to allow long flight-paths for the forward emitted neutrons.

The central beam line in N4 will feed the new LEBIT (Low Energy Beam and Ion Trap) facility [1]. The key element of the LEBIT facility is a high-pressure (up to 1 bar) helium gas cell for slowing down and collecting energetic rare isotopes from the A1900 fragment separator. Ions stopped in the gas cell remain singly charged and can be extracted with good efficiency. Electric fields guide the ions through an exit nozzle into a radio-frequency quadrupole (RFQ) system that provides transport through a differential pumping system. The continuous ion beam is then injected into a linear RFQ ion trap, which acts as a beam accumulator, cooler, and buncher. The energy for the extracted ion bunches can be varied between 5 - 60 keV by means of a pulsed drift tube in order to satisfy the requirements of a variety of envisaged experiments. The first experiments at the LEBIT facility will use a 9.4 T Penning trap for precision mass measurements of rare isotopes with half-lives as short as 10 ms.

A future addition to the LEBIT facility will be a setup for laser spectroscopy. The high-quality pulsed low-energy beams of the LEBIT facility will make it feasible to perform highly sensitive atomic spectroscopy experiments to measure nuclear moments and charge radii. Laser light can also be used to create polarized atom and ion beams for NMR-type measurements. In addition, atom trap experiments with rare isotopes will become feasible.

In addition to the fixed major equipment described above, a number of special purpose detector arrays exist for the coincident detection of γ-rays, neutrons, and charged particles. A set of 18 segmented germanium detectors with associated electronics and cryogenic support is well matched to detect gamma-rays emitted in flight from fast rare isotopes. The detectors can also be closely packed for on-line decay studies. A pair of neutron time-of-flight walls (2m x 2m, position sensitive in two dimensions, and liquid-scintillator filled) is used for studies of nuclei with loosely bound neutrons, primarily at lower energies. A modular neutron array (MONA), of comparable area and an efficiency of about 70% for neutron energies above 50 MeV, is built by a collaboration of several universities and undergraduate colleges.

Scientific Reach of the Coupled Cyclotron Facility (CCF)

To illustrate the scientific reach of the coupled cyclotron facility (CCF), Figure 2 depicts the predicted intensities after separation in flight with the A1900. For orientation, the approximate paths of nucleo-synthesis via the astrophysical rapid proton (rp) and rapid neutron (r) processes are indicated. Since most rare isotope production rates are unknown, most intensities must be extrapolated from existing empirical models. Hence, the intensities in Figure 2 have considerable uncertainties that generally increase for isotopes more distant from the line of beta-stability.

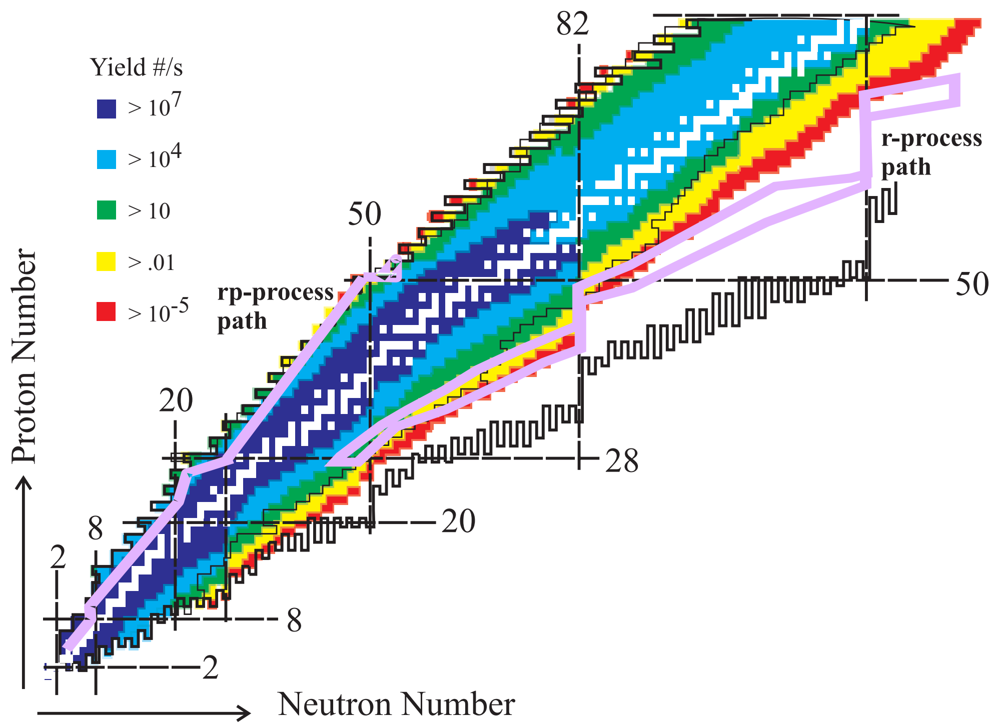

Figure 2: The scientific reach of the NSCL Coupled Cyclotron Facility is illustrated in terms of the projected intensities for fast beams of rare isotopes. Note of caution: Far from stability, the predicted intensities become increasingly uncertain due to a current lack of experimental data.

With beams from the CCF it may be possible to extend our knowledge of the neutron drip line from oxygen to silicon or even sulphur. It will be possible to study a large number of rp-process nuclei and r-process nuclei up to $A \approx 140$. However, investigation of the heavy r-process nuclei is beyond the reach of the CCF, and will require construction of a dedicated high-intensity facility such as RIA.

When discussing the scientific capabilities of various rare isotope facilities, the beam intensity is not the only important figure of merit. Other important issues come into play, such as back-ground suppression, efficient coincidence detection, thick target utilization, or short development times for beams of specific isotopes. In this context, it is noteworthy to point out that energetic beams of rare isotopes (E/A > 50 MeV) produced by projectile fragmentation (or fission) and in-flight separation offer a number of attractive features that allow studies of many very short-lived, neutron-rich nuclei even at rather low production rates, namely

- Economic production of medium-energy (E/A ≥ 50 MeV) beams of rare isotopes, without re-acceleration;
- Increased luminosity from the use of thick secondary targets (by up to a factor of 10,000);
- Reduced background from in-flight tracking and identification of individual isotopes in the beam on a particle-by-particle basis;
- Efficient particle detection from strong forward focusing;
- Short beam development times and low losses due to fast (sub-microsecond) and chemistry-independent separation and transport to the experiment.

The combination of these features often results in large gains in sensitivity when experiments can be performed at high energy. For example, Coulomb excitation and nucleon knock out studies can be performed with rare isotope beam intensities of 1 particle/second or less.

RIA – A Vision for the Future

In developing plans for a next generation rare isotope research facility in the U.S., NSCL faculty proposed to build a high-power heavy-ion facility capable of accelerating all elements up to energies per nucleon of at least 400 MeV. A high-acceptance fragment separator similar to the NSCL's A1900 would be used for in-flight separation of rare isotopes produced by projectile fragmentation or fission. After separation from the primary beam, the fragments could either be used directly for experiments or they could be stopped in a medium suitable for fast and efficient extraction and further manipulation, such as trapping or re-acceleration. After proving the viability of this approach with its inherent advantages, MSU faculty and colleagues from Argonne National Laboratory and several other laboratories in the U.S. refined these ideas into the Rare Isotope Accelerator (RIA) concept [2,3], schematically illustrated in Figure 3. RIA has been enthusiastically embraced by the U.S. nuclear science community [4] and is now the highest priority for new construction in the new (2002) Long Range Plan for Nuclear Science of the DOE/NSF Nuclear Science Advisory Committee.

Most of the science at RIA is the logical extension of the NSCL's ongoing rare isotope research program. Naturally, MSU strongly supports the construction of RIA and is offering to host RIA on the MSU campus. The MSU site is sufficiently large to allow a fully optimized layout that is unconstrained by existing legacy buildings and has ample space for future upgrades. A possible layout is shown in Figure 4. The example shown depicts a stretched driver linac with chicanes at the stripping stations. (Of course, a folded driver linac option is also possible if this should prove advantageous.) The layout provides for beam sharing between two experiments, but the site is sufficiently spacious to allow the incorporation of additional beam splits in the early design (at some additional cost) if this if this should be desirable.

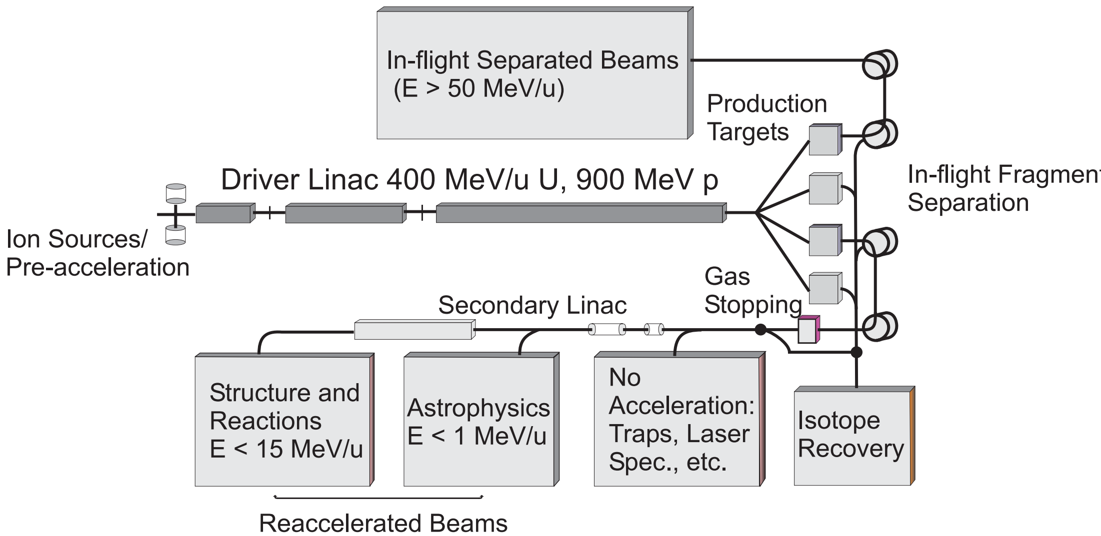

Figure 3: Simplified schematic of the RIA facility. Rare isotopes can be produced at rest via target fragmentation (or fission) or in flight via projectile fragmentation (or fission). Fast fragments, separated in flight, can be used directly for experiments, or they can be stopped in a gas cell from where they can be extracted for experiments at rest or for re-acceleration. Re-acceleration is also available for isotopes produced at rest. At least two experiments can be performed simultaneously.

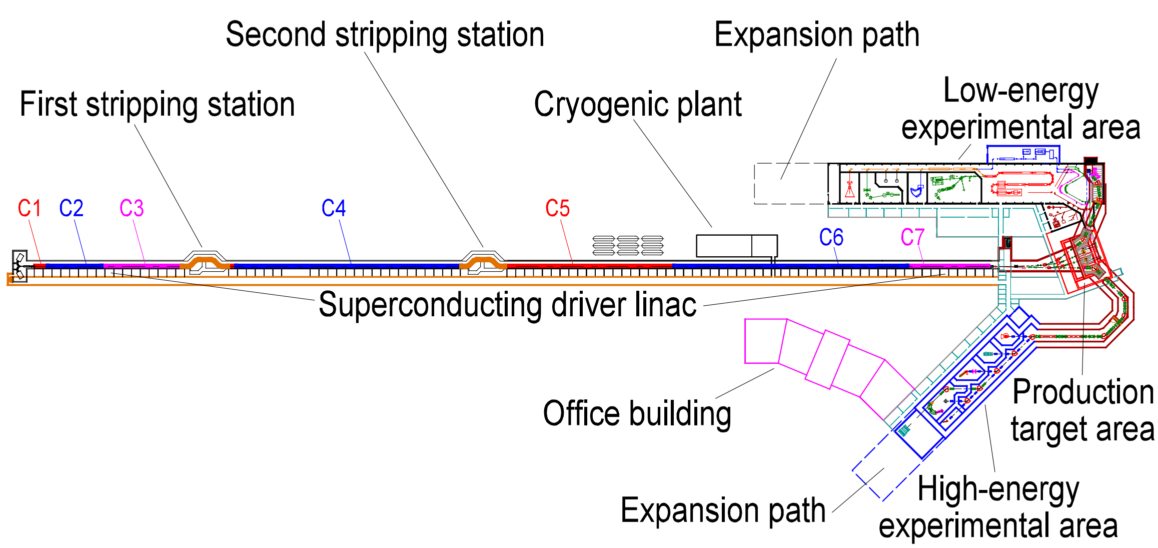

Figure 4: Optional layout of the RIA facility at MSU. Key elements of the facility are indicated in the figure. The site as MSU is sufficiently large to allow construction of a stretched driver linac (approximate length: 0.5 km), but a folded driver linac is also possible. The MSU site offers ample space for upgrades.

Figure 5 gives a comparison of rare isotope intensities produced by projectile fragmentation or fission at RIA and the NSCL. For lighter masses RIA provides gains of one to two orders of magnitudes, but for heavier masses gains of four orders of magnitude and more can be realized. Nearly all r-process isotopes can be studied with fast beams at RIA, whereas research at the NSCL will be limited to the lighter r-process elements. This illustrates the paramount importance of RIA's fast beams capability and the ability to accelerate very heavy beams, including uranium.

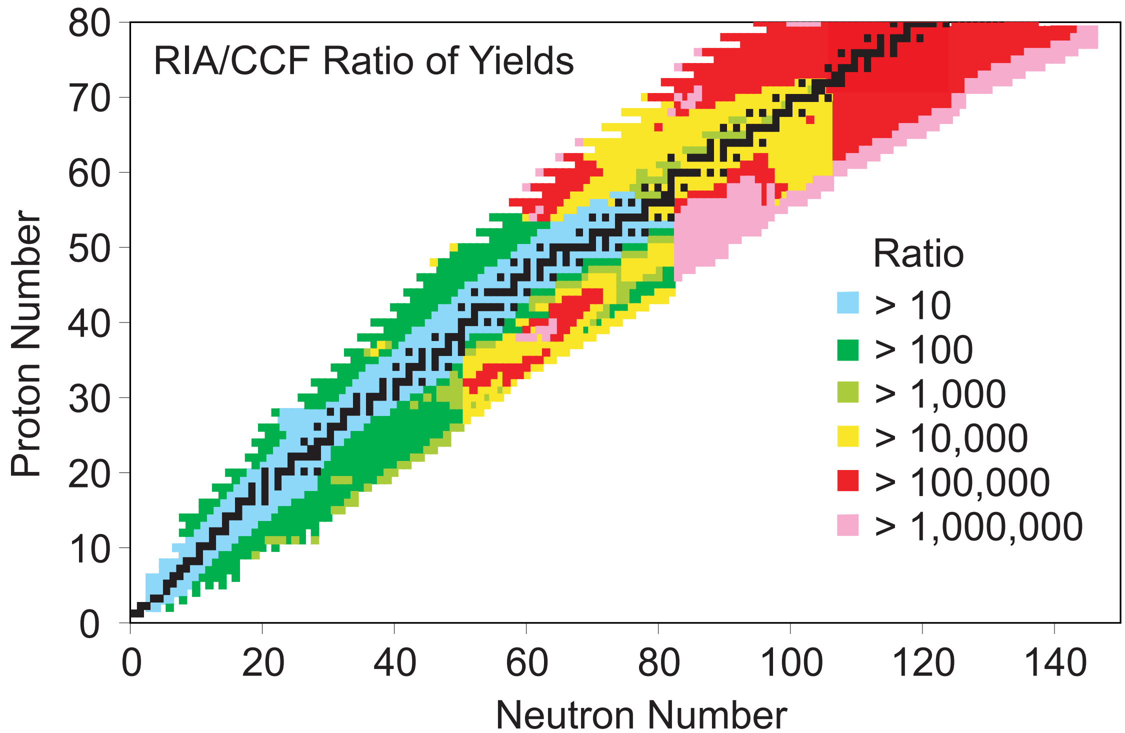

Figure 5: Comparison of fast beam rare isotope intensities at MSU's coupled cyclotron facility (CCF) and the proposed RIA facility. Fast beams allow achieving the large efficiency gains needed for reaching most r-process nuclei.

The scientific importance of RIA has been documented in a number of white papers [2-6], including NSAC's 2002 long-range plan for nuclear science [7]. In short, RIA is:

—Essential for maintaining cutting-edge research in basic nuclear science
—Essential for understanding how the elements that exist on earth were formed
—Essential for interpreting many of the high-quality astronomical observations made available from earth- and space-based observatories
—Essential for developing and testing theoretical models that can reliably predict rare isotope behavior, e.g., during stellar explosions

In addition, RIA will contribute to reliable nuclear weapons stockpile stewardship, and produce new radioisotopes for medical and materials sciences research and other applications.

Accelerator Physics and Beam Dynamics

MSU is one of a few academic institutions with graduate programs in accelerator physics and beam dynamics. Traditionally, the hardware-related part of the accelerator physics program at MSU has been centered on cyclotron accelerators, beam line magnets, and magnetic spectrographs. Quite naturally, emerging needs and opportunities of MSU's nuclear physics research program have often provided a stimulus for progress and innovation in accelerator physics and vice versa. As this traditional strength in cyclotron technology continues to be maintained, RIA has stimulated new programs and initiatives at MSU. Perhaps the most important new initiative is the development of superconducting radio-frequency (SRF) structures for use in linear accelerators and the RIA facility. After building the needed infrastructure (clean rooms, chemical treatment and high-pressure rinse facilities, plus a variety of magnetically shielded liquid helium Dewars), the NSCL now collaborates with several institutions in the U.S. and Europe to test, improve, or develop a variety of low- and medium-velocity structures suitable for heavy-ion acceleration.

Existing low-velocity ($\beta = v/c \approx 0.02$ - 0.5) structures typically have lower performance and lower efficiency than state-of-the art high-velocity ($\beta \approx 1$) elliptical structures. One goal of the NSCL's SRF R&D program is to develop higher performance low-velocity structures by making use of existing know-how for building high-performance $\beta = 1$ structures. This strategy will include the use of high-purity niobium and maintenance of an ultra-clean environment during cavity fabrication and operation to reduce performance limits from field emission and thermal breakdown.

Virtually all advanced high-velocity cavities ($\beta \approx 0.5$ - 1) consist of elliptically shaped multi-cell structures. When these cells are designed to accommodate lower velocity values, the cell-to-cell distance must be decreased and the walls of the cells become more planar, which makes the structures more susceptible to microphonics. A number of options are being pursued to mitigate this problem. First, the microphonic response of various geometrical designs is numerically simulated, and a preferred geometry is selected for prototyping. Second, various options for isolating the accelerating structure from external vibrations will be explored. Third, the use of active feed-forward systems to reduce or eliminate the external driving forces will be studied. The first multi-cell $\beta=0.47$ structure has recently been completed and shown to exceed design specifications. (This work is done in collaboration with Jefferson Laboratory.)

The NSCL is studying an alternative design for the low velocity section of the driver linac that would operate on the 10-th harmonic of the agreed upon base frequency of 805 MHz. Beam dynamics studies performed so far indicate no intrinsic limitations for the required 80 MHz RFQ and subsequent low-energy driver sections. Use of the 10-th harmonic option explored at MSU would require only four different cavity types. Because of the higher frequency, these cavities would be smaller in size and promise improved microphonic characteristics as compared to cavities that would, e.g., operate at the 14-th harmonic frequency. The needed half-wave (spoke) resonator has been built and shown to exceed design specifications. Construction of the needed quarter-wave resonators in progress and performance tests should be completed before the end of 2003. (This work is done in collaboration with the University of Lagnaro, Italy).

I would like to acknowledge the many excellent contributions of my colleagues, the faculty, students, and staff at the NSCL. Without their dedication and work there would be nothing to talk about. Operation of the NSCL as a national user facility is supported by the National Science Foundation under Grant No. PHY 01-10253.

References

[1] S. Schwarz, M. Baird, G. Bollen, D. Lawton, P. Lofy, D. Morrissey, J. Ottarson, R. Ringle, P. Schury, T. Sun, *The LEBIT project at NSCL/MSU*, Proceedings 'Exotic Nuclei and Atomic Masses', July 2-7, 2001, Hämeenlinna, Finland, in print

[2] ISOL Task Force Report, November 22, 1999, a copy can be downloaded from: http://srfsrv.jlab.org/isol/ISOLTaskForceReport.pdf

[3] Scientific Opportunities with Fast Fragmentation Beams from RIA, March 2000, a copy can be downloaded from: http://www.nscl.msu.edu/future/ria/process/whitepapers/opportunitiesffbeam.pdf

[4] OPPORTUNITIES IN NUCLEAR ASTROPHYSICS, Conclusions of a Town Meeting held at the University of Notre Dame, 7-8 June 1999, a copy can be downloaded from: http://www.nscl.msu.edu/future/ria/process/whitepapers/nuclearastrophysics.pdf

[5] RIA Physics White Paper, summary of the town meeting held at the RIA 2000 Workshop in Durham, North Carolina, July 24-26, 2000, a copy can be downloaded from: http://www.nscl.msu.edu/future/ria/process/whitepapers/durham2000meeting.pdf

[6] RIA Applications Workshop held at Los Alamos National Laboratory, October 30-31, 2000, a copy can be downloaded from: http://www.star.bnl.gov/STAR/nsac/papers/ApplicationWorkshopy.pdf

[7] OPPORTUNITIES IN NUCLEAR SCIENCE -- A Long-Range Plan for the Next Decade, prepared by the DOE/NSF advisory committee, April 2002, a copy can be obtained from the U.S. Department of Energy, and can also be downloaded from: http://www.nscl.msu.edu/future/ria/process/whitepapers/lrp_5547_final.pdf