RARE ISOTOPE BEAM FACILITIES IN THE UNITED STATES - STATUS AND FUTURE

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Abstract

Several rare isotope beam facilities in the United States provide the basis for a rich Nuclear Physics research program carried out by a large national and international user community. Various production methods are employed for providing rare isotopes beams with different energies for many elements. Facilities using the ISOL and in-flight production technique are complemented by facilities using batch-mode operation or techniques for the production of specific rare isotopes. A major leap in the research with rare isotope beams would be the realization of the proposed Rare Isotope Accelerator (RIA).

INTRODUCTION

There are several laboratories in North America that support a very active research program with rare isotopes, conducted by a community of estimated 700 national and international users. The largest rare isotope beam facilities in the US are the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University (MSU) and the Holifield Radioactive Ion Beam Facility (HRIBF) at Oak Ridge National Laboratory (ORNL). The production techniques are in-flight separation at the NSCL and isotope on-line separation (ISOL) at HRIBF. Smaller facilities are the Argonne Tandem Linac Accelerator System (ATLAS) facility at Argonne Nation Laboratory (ANL), the Cyclotron Institute of Texas A&M University, the Nuclear Structure Laboratory at Notre Dame University, BEARS a the 88-inch cyclotron of Berkeley, and the Nuclear Structure Laboratory at SUNY/Stony Brook. Additional rare isotope research opportunities exist at a number of university-based accelerator facilities.

This paper provides a brief overview of rare isotope beam facilities in the United States with emphasize on the two largest facilities and on the prospects for a next-generation facility, the Rare Isotope Accelerator RIA.

MAJOR RARE ISOTOPE BEAM FACILITIES

National Superconducting Cyclotron Laboratory (NSCL)

The National Superconducting Cyclotron Laboratory (NSCL) has started operation as a user facility in the late eighties. The facility was extended and upgraded several times and has been undergoing a major upgrade during the period 1999-2001. This last upgrade is a big step forward with respect to the number and intensity of rare isotope beams the NSCL can provide. The upgraded facility is based on two coupled superconducting cyclotrons [1] and can produce intense energetic beams of primary heavy ions from hydrogen to uranium. A high-acceptance fragment separator allows efficient production and in-flight-separation of a broad range of secondary rare isotope beams produced by projectile fragmentation or fission reactions.

Research at the NSCL [2] is devoted to nuclear physics, nuclear astrophysics, accelerator physics, and related instrumentation development. A key activity is the investigation of the properties of rare isotopes far away from stability. This includes the measurement of structural and decay properties of nuclei near the drip-lines, determination of astrophysically important data on neutron and proton-rich nuclei that participate in the r and rp (rapid neutron and proton capture) processes, and precision atomic mass measurements. Furthermore, beams at the NSCL allow the creation of nuclei at

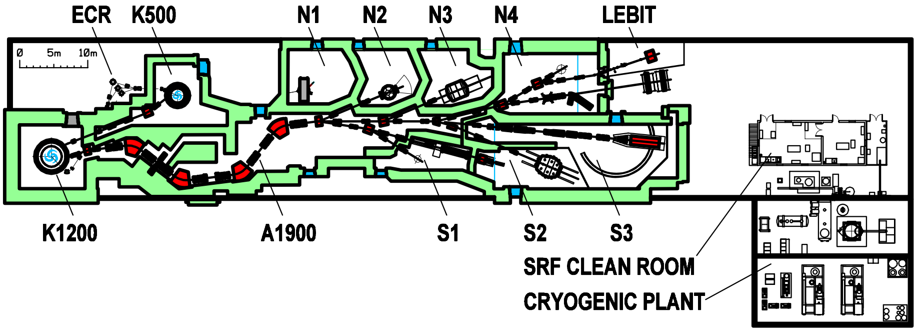

Figure 1: Floor plan of the National Superconducting Cyclotron Laboratory, showing the ECR sources, the two superconducting cyclotrons (K500 and K1200), the superconducting beam analysis system (A1900) and subsequent beam lines, the experimental vaults and areas (N1-4, S1-3, LEBIT), the Superconducting-RF R&D area, and the cryoplant.

temperatures and densities commensurate with the liquid-gas phase transition in the phase diagram of nuclear matter.

Figure 1 shows the floor plan of the NSCL facility. Rare isotope production starts with a set of ECR ion sources that are capable of ionizing essentially any chemical element. Multiply-charged ions are injected into the first of NSCL's two cyclotrons, the K500. Here the ions are accelerated to an energy of about 10 MeV/nucleon and then transferred to the K1200 cyclotron. Inside the K1200 the ions pass a stripper foil that removes most - and in the case of light elements all electrons. In this way maximum beam energies of 200 MeV/nucleon for lighter elements and 90 MeV/nucleon for uranium are achieved after final acceleration. These energetic primary beams can be used directly for experiments, or they can be converted into a broad range of radioactive ions by impinging them onto a thin target, where the choice of material and thickness optimizes the production of the desired isotopes.

To become useful for experiments the rare isotopes produced by projectile fragmentation or fission reactions have to be mass separated. This happens in the A1900 fragment separator/beam analysis system [3], which has a momentum acceptance of $\Delta p/p = 5.5\%$ and a maximum rigidity $B\rho_{max} = 6.0$ Tm. Downstream from the A1900 is a beam switchyard that allows transportation of the radioactive ion beams to several experimental stations.

The largest experimental device connected to the NSCL beam line system is the S800 magnetic spectrograph [4]. The S800 offers the opportunity to perform reaction studies of various type [5] with high resolution and good sensitivity. It is a key instrument for a large part of the experimental program carried out at the NSCL. The 4π-array is a low-threshold "logarithmic" 4π detector that has been successfully used and will be used for intermediate energy heavy ion collision experiments (e.g., Au+Au at $E/A \geq 40$ MeV). A recently commissioned 4-Tm superconducting sweeper magnet serves as a high-acceptance magnetic spectrometer and combined with neutron detectors (neutron walls) will be used for neutron time-of-flight (TOF) spectroscopy. The lab has several large area neutron detectors. A large modular neutron wall (MONA) [6] has been completed and is used in first experiments.

A number of experiments require low-energy beams of high quality as for example available at ISOL facilities. These types of beams are usually not available at projectile fragmentation facilities, which on the other hand provide beams of all elements and have advantages in the production of the most-short-lived isotopes. Providing such low-energy beams and making them available for experiments is the task of the LEBIT (Low Energy Beam and Ion Trap) facility [7]. The key element of this 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. Extracted beams are transported into a low-energy beam area, cooled and bunched in an RFQ ion trap system and captured in a 9.4-T Penning trap system for high-precision mass measurements.

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. An important instrument is a set of 18 segmented germanium detectors (SeGA). This system has been specifically designed for efficient high-resolution detection of γ-rays emitted in flight from fast rare isotopes but it can also be used for on-line decay studies. Experiments that this system is used for are for example intermediate energy Coulomb excitation studies [8].

Holifield Radioactive Ion Beam Facility (HRIBF)

The Holifield Radioactive Ion Beam Facility (HRIBF) [9] at Oak Ridge National Laboratory is the ISOL facility of the US. The ISOL technique relies on light energetic ions impinging on thick production targets where rare isotopes are produced by fission or spallation reactions, depending on the target material used. The targets are kept at a high temperature. The rare isotopes diffuse out of the target material and effuse to an ion source where the atoms are ionized. The ions are accelerated and mass separated. The beams can then be used directly for experiments or post-accelerated.

Figure 2 shows a layout of the HRIBF facility. The driver accelerator is the Oak Ridge Isochronous Cyclotron (ORIC), a multi-species variable energy (K=105) cyclotron. Typical primary beams are protons, deuterons, ^{4}He accelerated to energies of 42-85 MeV per nucleon with intensities between 10^{13} and 10^{14} pps. These beams impinge on a production target/ion source system that is connected to a first-stage mass separator ($M/\Delta M \approx 1000$) followed by a charge exchange cell. In the case the ion

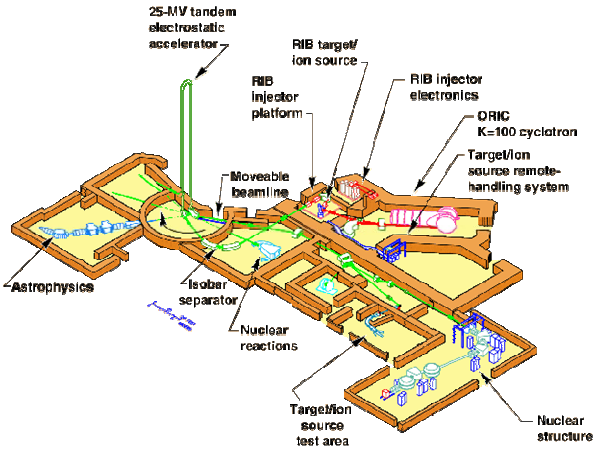

Figure 2: View of the Hollifield Radioactive Ion Beam Factory, showing the ORIC cyclotron, the radioactive ion beam (RIB) target and ion source system of the RIB injector, the 25-MeV tandem accelerator and major experimental installations.

source system provides only positive ions, this charge exchange cell is used to create negative ions, as required for the post-acceleration in the 25-MeV electrostatic tandem accelerator. All these components are installed on a 300 kV high voltage platform to form the radioactive ion beam (RIB) injector of the facility. Prior to entering the tandem the pre-accelerated beam passes a second high-resolution (isobar) separator ($M/\Delta M \approx 20000$). Negative ions are then injected upwards into the tandem and stripped in the terminal. Light positive ions ($A<100$) are accelerated downwards directly to their final energies. In the case of heavier ions an additional stripping step is employed in this acceleration path.

Target development is the key to ISOL beam production and an intense target R&D program is carried out at HRIBF [10]. A number of different target materials and matrices are presently employed at the facility which include hafnium-dioxide coated fiber targets for the production of intense beams of fluorine isotopes, porous carbon matrices coated with uranium carbide for neutron rich isotopes, molten metal targets for As, Ga and Cu production, and various sulfide, carbide and oxide targets for the production of light isotopes of Cl, Al, and Si.

A number of versatile and powerful detector systems are available for the experimental program at HRIBF. The three major experimental stations are the Recoil Mass Spectrometer [11], used mainly for nuclear structure studies, the Daresbury Recoil Separator for nuclear astrophysics investigations, and an Enge split-pole spectrograph for reaction studies. Various detector systems are available to be used with these devices. A recent highlight at the HRIBF was the production of the world's first post-accelerated beams of heavy neutron-rich nuclei. Using these beams Coulomb-excitation experiments in inverse kinematics were performed on neutron-rich tin and tellurium isotopes [12].

A new addition to facility will be a high-power target laboratory served by a second beam line from ORIC. This facility will enhance the ongoing target R&D program. The power densities that can be achieved with the ORIC beams are comparable to those expected for RIA. The facility will therefore also serve as an important facility for testing materials and concepts for high-power targets for the rare isotope accelerator project RIA.

Other facilities

ATLAS at Argonne National Laboratory consists of a superconducting linear accelerator, which is injected by either a 9-MV tandem Van de Graaff or a new positive-ion injector consisting of two ECR ion sources and a superconducting injector linac. Using the positive ion injector, ATLAS routinely accelerates intense beams up to uranium with energies above the Coulomb barriers and with excellent beam properties. In addition to stable-beam acceleration, which is the main mode of operation, long-lived rare isotopes are re-accelerated in batch mode. Furthermore, transfer reactions are employed for in-flight production of beams of a number of light rare isotopes. The facility houses a variety of experimental equipment for an experimental program covering nuclear structure and reaction studies with stable and radioactive beams [13] as well as mass measurements and atomic physics experiments. The equipment includes the Fragment Mass Analyzer (FMA), Enge spectrographs, the CPT Penning trap system [14], and atom trap systems. ANL also houses the gamma detector array Gammasphere [15].

A number of university accelerators serve local faculty and students, but they also are often used by visitors who take advantage of their unique capabilities. Examples are the facilities at the State University of New York at Stony Brook, where one specialty is the study of francium isotopes in magneto-optical traps [16] for fundamental symmetry tests, the tandem laboratory at University of Notre Dame with TWINSOL [17], used for various reactions studies, and Texas A&M University, where a beam-analysis system and the recoil mass separator MARS coupled to the K500 Superconducting Cyclotron provides radioactive-beams for studies of exotic nuclei and astrophysics. A recent addition along this line is the installation of the recoil mass separator SASSYER [18] at the Wright Nuclear Structure Laboratory at Yale University. While no longer a nuclear physics user facility BEARS [19] at the 88" Cyclotron at Lawrence Berkeley National Laboratory continues to be available for the local research program

THE RARE ISOTOPE ACCLERATOR PROJECT

The goal of RIA [20] is to provide the most intense source of rare isotopes for experimental research. This requires a facility that allows for the optimization of production mechanism for each desired isotope. Different production techniques are necessary to achieve this goal as well as a driver that is capable of accelerating all ions up to uranium to at least 400 MeV/nucleon with up to 400 kW beam power.

The scientific program [21-26] and technical concept of RIA, developed by the user community over a period of more than five years, has been thoroughly reviewed by the Department of Energy/National Science Foundation Nuclear Science Advisory Committee, which recommends RIA as its highest priority for new construction in the 2002 Long-Range Plan [27]. In addition, the Office of Science's "Facilities for the Future of Science, A Twenty Year Outlook" [28], identifies RIA as a near-term rank high-priority facility. In this plan, RIA is tied for third place behind ITER and USSCC (UltraScale Scientific Computing Capability). In February 2004 DOE signed the "Critical Decision Zero" (CD0) for RIA, the statement of mission need. A draft request for proposals (RFP) for constructing, building and operating of RIA has been posted and the final RFP is expected to be issued soon.

The development of RIA is subject of a number of technical challenges, which have been and still are addressed in a research and development program involving many institutions in the US. While viable

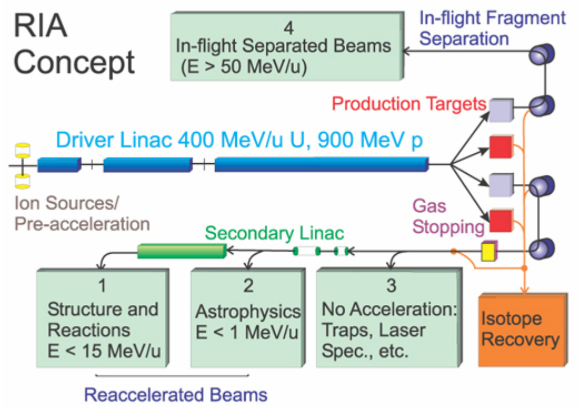

Figure 3: RIA is based on a driver accelerator capable of accelerating beams from protons to uranium up to at least 400 MeV/nucleon. Three production methods (ISOL, in-flight separated beam, and a gas stopping technique) are employed. These rare isotope beams can be used at rest for experiments in Area 3, or they can be accelerated to energies below or near the Coulomb barrier and used in Areas 2 and 1, respectively. Fast beams of rare isotopes can also be used directly after separation in a high-resolution fragment separator (Area 4).

concepts for the driver and post-accelerator have been already developed substantial R&D work is still required to address the high-power levels in the production areas. Both in the case of rare isotope production with the ISOL and via the in-flight technique the major challenge is to cope with the power densities resulting from the high beam power available at RIA. New concepts like liquid metal-based targets [29] are investigated as well as more conventional approaches. Other R&D areas include finding the best concepts for the fragment separators or the validation of the performance of new techniques like the gas stopping [30], where test systems have been developed at ANL and MSU. Gas stopping tests under RIA-like conditions are presently going on with fast beams at the NSCL [31,32] and are planned at GSI.

The Driver

The primary accelerator of RIA will be a continuous wave accelerator capable of accelerating all ions up to uranium. Beam energies of up to 1 GeV for protons and 400 MeV for uranium are foreseen with beam powers up to 400 kW. The design of the driver will be primarily determined by the requirement of a 400 MeV/nucleon uranium beam. For uranium, two charge states (28+ and 29+) will be extracted from the ECR and accelerated through the first linac segment to ≈12 MeV/nucleon. After stripping, the charge state distribution will be truncated to five charge states (73±2) and further accelerated through a second linac segment to ≈90 MeV/nucleon where a final stripping will be performed. The charge state distribution will be truncated to three charge states (88±1) and accelerated through a third linac segment to a final energy of 400 MeV/nucleon.

Production Methods

Rare isotope beam production at RIA will employ three methods. In the first, a thick ISOL-type target will be coupled to an ion source and a mass separator system. This method will provide the most intense beams of those elements with chemistry favourable for rapid release. The other two methods will utilize thinner targets and in-flight fragment separators. In one mode, after mass separation, the ions from the target can be used directly as fast beams for experiments at high energies. In the second mode of thin-target operation, the fast mass separated exotic nuclei will be energy-degraded and then stopped in a gas cell and extracted as low-energy beams. This will provide beams of short-lived isotopes or elements that are difficult to obtain from standard ISOL targets. The beams from the gas stopping cell and the ISOL stations can be reaccelerated up to energies beyond the Coulomb barrier. In all cases, stopped nuclei can also be used for decay experiments, they can be injected into atom or ion traps, or they can be accelerated to low energies suitable for astrophysics studies.

Re-acceleration

The post accelerator for RIA will provide beams of up to about 8 MeV/u for all masses up to A=240 and up to 20 MeV/u for light masses (A<60). These beams will be used for nuclear reaction and structure studies. Lower energy beams (1MeV/u) can be provided for astrophysical reaction studies. The beams to be post-accelerated are delivered either from the gas stopping station or from the ISOL stations.

Experimental areas

Layout of experimental areas and equipment to be installed have been subject of discussions at RIA user workshops on detectors and experimental equipment held at Oak Ridge and MSU in 2003 and 2004. The low-energy beam areas of RIA will house a large fraction of RIA's research program, including fundamental interaction tests, astrophysical reaction studies and the investigation of the properties of nucleonic matter. They will have a non-accelerated beam area for precision experiments and decay studies using the directly the ion beams from the ISOL or the gas stopping stations. An area for astrophysical reaction studies will make use of post-accelerated beams at energies of about 1 MeV/nucleon. An area with beam of at least 8 MeV/nucleon will be used for nuclear structure and reactions studies. The high-energy area, served by one of the in-flight fragment separators of RIA, will be used mainly for nuclear reaction and structure studies and house experimental equipment that can be expected to similar to that presently installed at the NSCL.

In addition to it's main research program RIA will be able to provide isotope for the use in other fields.

There will be large number of isotopes produced during the operation of RIA that could be harvested and used for additional applications. Therefore, a number of isotope-harvesting capabilities will be implemented at RIA.

Conclusions

The United States are home to a very active research program with rare isotope beams, made possible by a number of excellent facilities. The user community has made the case for the construction of the next-generation facility RIA that, once built, will become the world best rare isotope beam facility.

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