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Prospects for exotic beam facilities in North America

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Abstract. There are several nuclear physics laboratories in North America that have on-going research using energetic and stopped radioactive beams. These include the large ISOL-type programs ISAC at TRIUMF and HRIBF at Oak Ridge and the in-flight fragmentation program at the NSCL of Michigan State University. There are also smaller, more specialized, programs using a variety of techniques at the 88-inch cyclotron of Berkeley, ATLAS at Argonne, the Cyclotron Institute of Texas A&M University, the Nuclear Structure Laboratory at Notre Dame University, and the Nuclear Structure Laboratory at SUNY/Stony Brook. There are also three projects on the horizon in North America for new capabilities in both the near term and more distant future. The intensities of the in-flight fragment beams at the NSCL will be increased dramatically very soon as the Coupled Cyclotron Project will be completed and commissioned for research by mid-2001. A new project, ISAC-II, has been approved in Canada. For the longer term, the United States is considering construction of a major new facility, the Rare Isotope Accelerator (RIA), which would have a very high-intensity heavy-ion driver linac. The RIA facility is proposed to utilize both ISOL and in-flight production mechanisms.

PACS. 29.17.+w Electrostatic, collective, and linear accelerators – 29.25.Rm Sources of radioactive nuclei – 29.20.-c Cyclic accelerators and storage rings

1 Introduction

This paper describes the existing and planned exotic beam facilities in North America, with emphasis on their capabilities rather than their specific science programs. Reports on physics results and future scientific programs of these facilities have been given at this and other recent conferences.

2 Existing facilities

There are eight nuclear physics laboratories in North America, which currently do research with radioisotopes and/or radioactive beams. They are listed briefly in table 1 below along with an indication of the production mechanisms used at each. They are separately discussed in sub-sections below, sorted according to the production mechanisms used. Three of the facilities have active research programs with atom or ion traps for radioisotopes; these are also indicated in table 1 and described briefly below.

Table 1. Summary of existing facilities.

Location and name	Type
TRIUMF/ISAC	ISOL & Traps
ORNL/HRIBF	ISOL (accelerated)
LBNL/88″/BEARS	Batch & Traps
ANL/ATLAS	Batch, In-flight & Traps
UND/TWINSOL (UND/UofM)	In-flight
TAMU/K500-MARS	In-flight
SUNY, Stony Brook/SC Linac	Traps
MSU/NSCL/K1200	Fragmentation

2.1 Current ISOL facilities

There are two active ISOL facilities in North America, one at TRIUMF in Vancouver, BC, and one at Oak Ridge National Laboratory in Tennessee.

2.1.1 TRIUMF/ISAC

The new ISAC complex [1] at TRIUMF is a high-intensity ISOL facility. ISAC occupies one of several beam lines from the TRIUMF 500 MeV, H^- cyclotron and will use up to 100 microamperes of continuous-wave primary proton beam current. To date tests have been carried out at production currents of up to 20 microamperes. Since 1998 radionuclides have been mass separated at ion source energies of 60 keV and delivered to experimental apparatus for research. Beta-decay studies related to nuclear astrophysics and fundamental symmetry studies in an atom trap, TRINAT [2], comprise one area of research currently being pursued. An accelerator is also currently being commissioned for radioactive beams at ISAC; it is described

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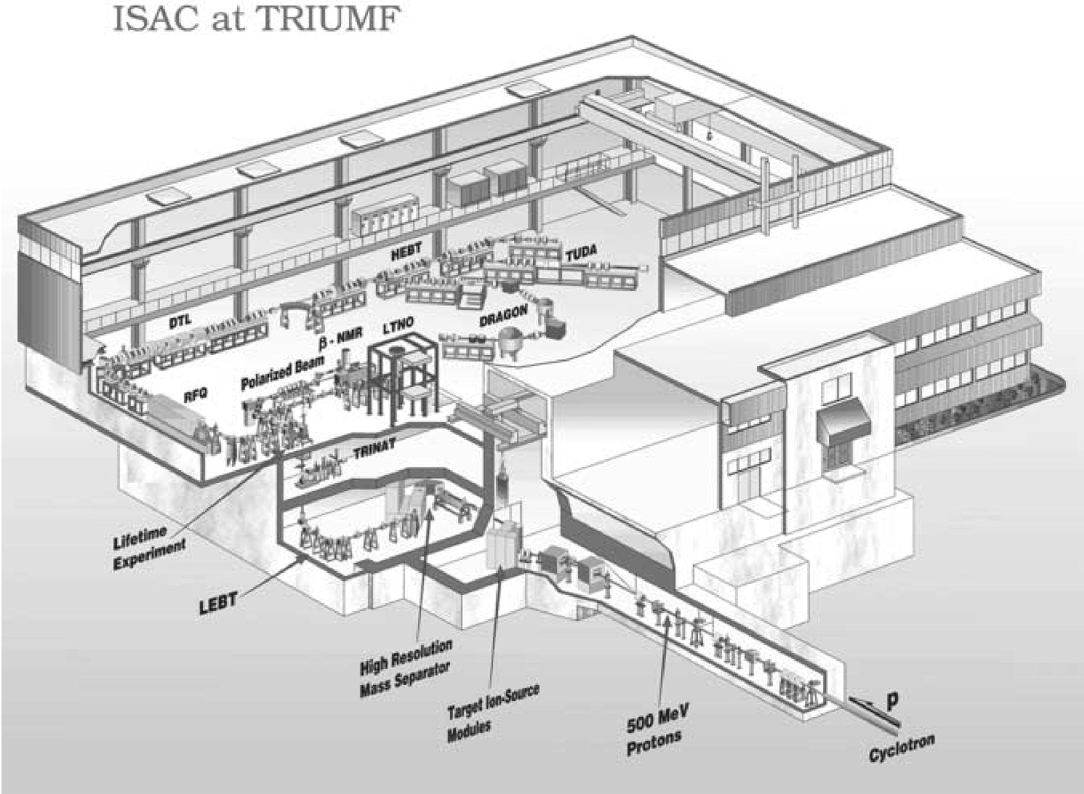

Fig. 1. A perspective overview of the ISAC facility at TRIUMF.

briefly below in sect. 3. An overview of the ISAC facility is shown in fig. 1.

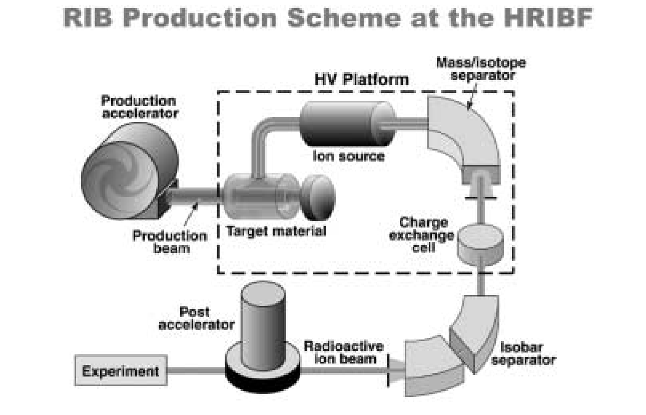

Fig. 2. A schematic layout of the Holifield Radioactive Ion Beam Facility at Oak Ridge.

2.1.2 ORNL/HRIBF

The Holifield Radioactive Ion Beam Facility [3] at Oak Ridge uses the $k = 160$ MeV ORIC cyclotron as the driver and a 25 MV tandem as the post accelerator. Radionuclides are produced using primary beams such as p, d, and ^{3,4}He from the cyclotron at energies of 42 to 85 MeV and with currents of 3–12 microamperes. The production target/ion source complex produces negative ions as required for the tandem post accelerator. A schematic layout of this facility is shown in fig. 2. Beams developed and used to date include ^{67}Ga and ^{69}As at intensities on the order of 10^5–10^6/s on target, and beams such as ^{17,18}F with intensities of 10^4–10^7/s. These beams have been used for research in nuclear astrophysics and nuclear structure using various experimental apparatus such as the Daresbury Recoil Separator (DRS), the Recoil Mass Separator (RMS), and a silicon detector array/gas-filled ionization chamber setup [4]. A batch mode of operation for relatively long-lived isotopes such as ^{56}Ni is currently being developed. Neutron-rich fission products have been produced via proton-induced fission of ^{238}U. Beams such as ^{118}Ag have been produced, accelerated and delivered to targets at intensities of $\sim 10^6$/s. Experiments with such neutron-rich beams are planned for the near future. A summary of recent developments and research at the HRIBF was presented at this conference by C. Baktash [5].

2.2 Current "batch-mode" facilities

The superconducting heavy-ion linac ATLAS at Argonne has been doing research with accelerated radioactive beams since 1994. Both the batch mode and in-flight production mechanisms are used; they are described separately in this subsection and the next one below. A group at the LBNL 88″ cyclotron has recently developed a batch-mode radioactive beam capability.

2.2.1 ANL/ATLAS

In 1994 a ^{18}F ($T_{1/2} = 110$ min) beam was developed and used for nuclear astrophysics measurements at ATLAS. The radionuclide was produced and prepared for the ion source at the University of Wisconsin medical cyclotron and flown to Argonne where ^{18}F(p, α) cross-section excitation functions were measured [6]. More recently, a ^{56}Ni beam was developed and used to measure spectroscopic factors via the (d, p) reaction in inverse kinematics [7]. The ^{56}Ni ($T_{1/2} = 6$ days) was produced at the 50 MeV proton linac of the ANL pulsed neutron source (IPNS) and transferred to the ion source of the tandem at ATLAS for ionization and acceleration [8]. Beam intensities on target were 3×10^6/s at 0.6 MeV/u for ^{18}F and 3×10^4/s at 5 MeV/u for ^{56}Ni. The experimental apparatus used at ATLAS included the split-pole magnetic spectrograph in the gas-filled mode and the Fragment Mass Analyzer (FMA) in conjunction with a large-area silicon detector array near the target. Recently similar methods were used to produce a ^{44}Ti beam for a measurement of the ^{44}Ti(α, p) reaction in inverse kinematics [9].

2.2.2 LBNL/BEARS

A project called Berkeley Experiments with Accelerated Radioactive Species (BEARS) has been implemented at the LBNL 88″ cyclotron [10]. The project has the capability of producing radioactive isotopes such as ^{11}C, ^{13}N, and ^{14}O at the LBNL medical cyclotron that is located 350 meters from the 88″ cyclotron. The activity is carried through a tube via a carrier gas from the medical cyclotron to the 88″ cyclotron. Early tests with activity created at the 88″ cyclotron demonstrated that ^{11}C and ^{14}O can be separated from the carrier gas in a liquid nitrogen trap and subsequently delivered slowly into the ECR ion source. Ionization and transport efficiencies of over 11% of the trapped ^{11}C into the 4+ charge state were measured after the ion source analyzing magnet. With the two cyclotrons coupled via the transfer line, a beam of ^{11}C with an intensity of 10^8/s was used to study the ^{197}Au(^{11}C$, x$n) reaction over an energy range from 5 to 10 MeV per nucleon [11]. The 8π-detector array, large-area silicon detectors, and the new Berkeley Gas-filled Separator (BGS) are available for future research with BEARS.

2.3 Current in-flight-production facilities

There are three nuclear physics laboratories in North America that are currently doing research with radioactive beams produced via direct reactions in inverse kinematics. Their capabilities are summarized below.

2.3.1 Notre Dame/University of Michigan

For several years a University of Notre Dame and University of Michigan collaboration has been doing research using superconducting magnetic solenoids with large solid angle to capture and refocus radionuclides produced via reactions on targets located in the beam line [12]. Their current project is based on a pair of superconducting solenoids known as TwinSol [13]. TwinSol was used to provide a radioactive beam of ^{6}He at over 10^5 ions per second for the study of sub-barrier fusion with ^{209}Bi [14]. Recent work by this group was also presented at this conference [15].

2.3.2 ANL/ATLAS

An in-flight production system has been developed at ATLAS to supplement the capabilities of the batch-mode method discussed above. The system consists of gas cells with thin Havar windows operating at about 600 T of H_2, D_2, or ^{3}He. Inverse (p, n), (d, n), or $(^3\mathrm{He}, \mathrm{n})$ reactions are induced by primary heavy-ion beams with intensities of roughly 250 particle nanoamperes. The reaction products are collected and focussed by a superconducting solenoid. A superconducting resonator following the solenoid is used to debunch the time structure of the secondary beam to reduce its energy spread [16,17]. Excitation functions of the cross-section for the fusion of ^{17}F+^{208}Pb [18], as well as, excitation functions of the reaction p(^{17}F$, \alpha$)^{14}O [19] have been measured at beam energies between 70 and 100 MeV with ^{17}F intensities of 3×10^5 to 3×10^6/s on target.

2.3.3 Texas A&M/MARS

Groups at the Texas A&M Cyclotron Institute have been using primary heavy-ion beams from the K500 superconducting cyclotron to initiate reactions in gas targets in the beam line. Radioactive ^{7}Be beams have been used to study the (^{7}Be$, ^8$B) reaction on ^{10}B and ^{14}N to determine parameters relevant to the ^{7}Be(p, γ) capture reaction rate [20]. The experiments used the recoil mass separator, MARS, to achieve a 99.5% pure ^{7}Be beam at a rate of about 10^5/s at the focal plane, where the secondary reaction targets were located. Other research involves the use of radioactive beams to study the isospin dependence of nuclear reactions.

2.4 Current facilities for trapping radioactive ions or atoms

There are four facilities in North America with programs that use atom or ion traps for research with short-lived radioisotopes. The neutral atom trap, TRINAT [2], at TRIUMF was mentioned above as part of the present ISAC facility. There are also neutral atom traps at the 88″ cyclotron at LBNL and at the superconducting heavy-ion linac at SUNY Stony Brook. The LBNL atom trap has been used to trap and study the decay of ^{21}Na [21]. The trap at Stony Brook has been used for several studies of the optical spectroscopy of francium isotopes [22,23]. The Canadian Penning Trap [24] has been installed and commissioned at the ANL ATLAS facility and is currently being used to study short-lived isotopes along the $N = Z$ line. The isotopes are produced via heavy-ion–induced fusion reactions, separated by a gas-filled magnetic spectrograph, and stopped as 1^+ ions in a helium gas catcher. They are cooled and accumulated in a linear quadrupole ion trap and subsequently transferred to the precision trap.

2.5 Current fragmentation facility

The only fragmentation facility in North America is at the National Superconducting Cyclotron Laboratory (NSCL) at Michigan State University.

2.5.1 Michigan State/NSCL

The NSCL K1200 superconducting cyclotron [25] produces primary beams of heavy ions in the 100 to 200 MeV per nucleon energy range. Energetic radioactive beams produced via the fragmentation mechanism have been used for nuclear physics research at the NSCL for about 10 years. The primary beam, with currents up to approximately 100 particle nanoamperes, interacts with a target at the front of a Projectile-Fragment Separator, the A1200 [26,27]. Studies of reaction mechanisms, nuclear structure, and nuclear astrophysics have been carried out using the A1200 itself or downstream in other apparatus. The instruments available include magnetic spectrographs (the old S320 or the new S800), recoil separators (the RPMS), large-acceptance charged particle, gamma, and neutron detector arrays, the University of Michigan superconducting solenoid (BIGSOL), and general-purpose scattering chambers. A measurement using the S800 to study the Coulomb breakup of a radioactive ^{8}B beam was done recently [28]. The NSCL facility was shut down in 1999 for an intensity upgrade, the Coupled Cyclotron Project described below.

3 Facilities under construction

The two major radioactive beam construction projects currently underway in North America are listed in table 2 and described in the sections below.

Table 2. Facilities with upgrades currently in progress.

Location and name	Construction status
TRIUMF/ISAC	Commissioning in 2000-2001
NSCL/K500⊗K1200	Commissioning in 2001

3.1 TRIUMF/ISAC

The ISAC (Isotope Separation and Acceleration) facility at TRIUMF has been operating with radioactive beams at ion source energies since 1998, as described above. The construction of a linear accelerator to deliver radioactive beams at higher energies for research is now underway [1, 29]. An overview of the entire facility was given in fig. 1 above. The accelerator comprises an 8 m long RFQ and an IH-type drift-tube linac. The accelerator will run CW and can accept ions with m/q up to 30. The RFQ has been assembled and tested successfully with stable beams including N^+ and N_2^+. It operated CW at the required voltage and the energy gain and acceptance efficiency agreed with design calculations. The drift-tube linac section is nearing completion and is expected to be tested with stable beams by the end of 2000. The output energy of the completed accelerator will be continuously variable from 150 keV/u up to 1.5 MeV/u. The construction of a recoil-mass separator, DRAGON, optimized for measuring capture-reaction cross-sections is also nearing completion. DRAGON will be used with a windowless gas target apparatus for (p, γ) and (α, γ) measurements.

3.2 Michigan State/K500 ⊗ K1200

A major project involving the coupling of the K500 and K1200 superconducting cyclotrons at the NSCL is nearing completion [30]. This intensity upgrade also involves replacing the A1200 beam analysis system by an improved A1900 beam analysis system which will have more bending power and a higher capture efficiency to enable research with very neutron-rich secondary beams. A schematic layout of the new A1900 fragment separator is shown in fig. 3 along with a photograph of one of the large-acceptance superconducting quadrupole triplets. Large gains in radioactive beam intensity, often by two-to-three orders of magnitude, and significant gains in maximum energy for very heavy beams will be achieved. Primary beam intensities of up to 1 particle microampere at energies of 200 MeV/u for light, $N = Z$, ions will be available. For the heaviest beams, such as ^{238}U, the intensities and energies

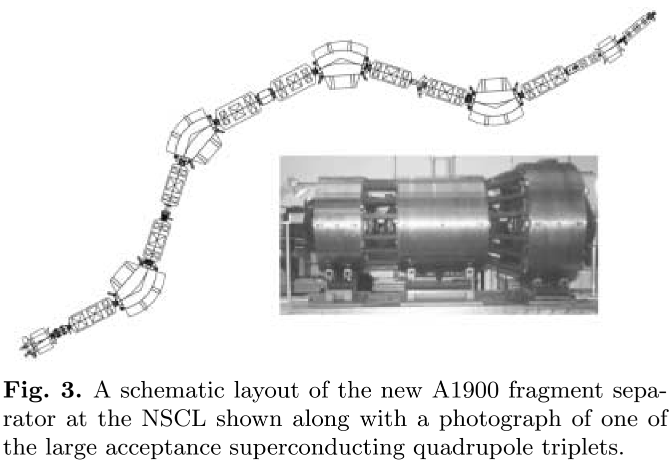

Fig. 3. A schematic layout of the new A1900 fragment separator at the NSCL shown along with a photograph of one of the large acceptance superconducting quadrupole triplets.

Table 3. Future exotic beam facilities.

Facility proposals	Time scale
Canada: ISAC-II	Approved/completion ∼ 2005
U.S.: RIA	Design/construction ∼ FY 2003–2009

will be approximately 10^9/s and 100 MeV/u, respectively. The construction is scheduled for completion by the end of 2000 with system commissioning occurring during the first half of 2001.

4 Future new exotic beam facilities for North America

In North America there are two projects for advanced exotic beam facilities in Canada and the United States. A proposal to increase the radioactive beam energy and mass range at ISAC (ISAC-II) has been approved at TRIUMF [29]. In the U.S., a sub-committee of the Nuclear Science Advisory Committee has recommended construction of an advanced RNB facility known as the Rare Isotope Accelerator (RIA). This project is designed to address the scientific goals spelled out in the RIA Physics White Paper [31]. R&D and prototyping for RIA is currently being addressed at several laboratories in the U.S. The time scales of these two projects are listed in table 3.

4.1 TRIUMF/ISAC-II

The ISAC-II project to greatly extend the range of the radioactive beams available for research has been approved for construction during the current 5-year plan at TRIUMF. The project will increase the maximum energy and mass range of the post accelerator to 6.5 MeV per nucleon and $A = 150$, respectively [29]. The front end of the post accelerator will be redesigned to extend its mass range. One option for this is to introduce a charge breeder to increase the charge states of 1^+ ions from the ISOL-type ion sources to be compatible with the present RFQ mass-to-charge ratio limit. A new drift-tube linac for the high-energy end will use short, independently phased superconducting resonators. A major building addition will provide space for new experimental apparatus.

4.2 RIA

In 1995 the Physics Division at Argonne National Laboratory proposed a concept for an advanced ISOL-type exotic beam facility based on ATLAS [32,33]. The concept featured a 100 MeV per nucleon, 100 kW beam power, conventional heavy-ion driver linac and a radioactive beam post accelerator with an injector capable of accelerating very heavy ions from 1^+ ISOL-type ion sources. The proposed radionuclide production mechanisms included light-ion–induced spallation and compound-nucleus reactions,

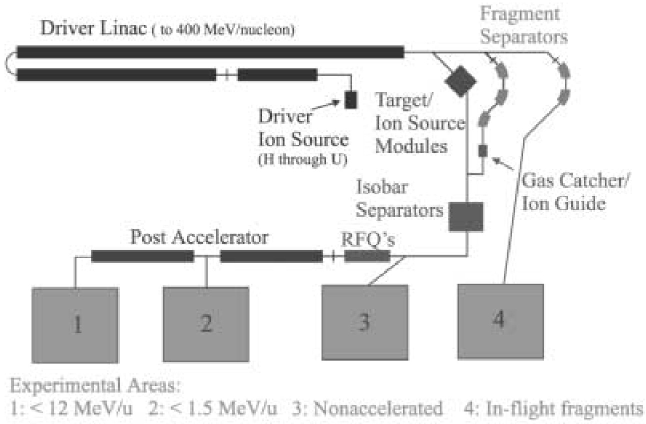

Fig. 4. A schematic layout of the proposed RIA facility. The superconducting driver linac, radionuclide production areas including two high-acceptance fragment separators, and four distinct experiments areas for research at different secondary-beam energies are indicated.

the two-step neutron-generator method [34], and stopped heavy-ion fragmentation products. By 1998 the concept had evolved to using a CW superconducting driver linac and the new fast-gas-catcher method [35]. The switch to independently phased superconducting resonators in the driver increased the energy of the light-ion beams while keeping the linac voltage fixed. Some critical components of the facility, such as the intermediate-velocity superconducting, spoke-type resonators for the driver and the high m/q, CW RFQ for the post accelerator, were demonstrated as prototypes [36,37]. The fast gas catcher was developed in conjunction with the Canadian Penning Trap program at ATLAS and had the great benefit of eliminating the strong chemical dependence of the standard ISOL technique. The ISOL Task Force, a subcommittee of the Nuclear Science Advisory Committee of the U.S., was formed in late 1998 to evaluate the technical options for a next-generation exotic beam facility. The Task Force recommended a facility of this type, but with the driver energy increased to 400 MeV per nucleon for primary beams as heavy as uranium. The Task Force also recognized the additional opportunity of adding experimental instrumentation for physics with secondary beams of fragments or fission products separated in flight. A schematic overview of this larger facility, RIA, is shown in fig. 4. With the combination of high beam power, relatively high beam energies, a wide variety of production mechanisms, high-acceptance fragment separators, and high-efficiency secondary-beam formation and post-acceleration, RIA will deliver a broad variety of intense exotic beams. RIA will be particularly well suited for the studies of very neutron-rich nuclei, especially in the $N = 50$ and 82 regions, that are fundamental for an understanding of the astrophysical r-process.

The present version of the RIA driver linac [38] has a nominal beam power of 400 kW and is designed to accelerate two charge states of uranium from the ion source and up to five charge states following the stripper foils to

Table 4. Summary of the driver linac simulations for selected beams. The assumptions for the ECR ion source charge states and currents are indicated.

Mass (A)	$I_{\rm source}$ (pμA)	$q_{\rm out}$	$I_{\rm out}$ (pμA)	Energy out (MeV/u)	Power (kW)
1	556^a	1	445	899	400
3	232^a	2	186	717	400
2	416^a	1	333	600	400
18	54^a	8	40.3	551	400
40	29^b	18	18.0	554	400
86	15^b	36	8.8	515	390
136	12^b	53–54	6.2	476	400
238	3^b	87–90	1.6	403	152

[a] Limited by RF power in linac.
[b] Limited by ion source.

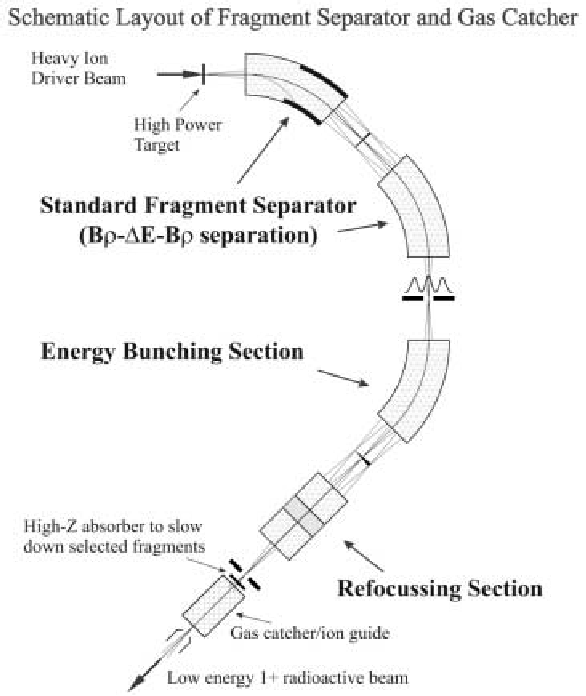

Fig. 5. A schematic of the fast-gas-catcher method for separating, stopping, and rapid extraction of 1^+ radionuclides with chemical independence.

achieve high beam power for the heaviest beams [39,40]. The driver beam list for a variety of ions between protons (900 MeV) and uranium (400 MeV/u) is given in table 4.

One of the critical components of RIA, the high-acceptance fragment separator/fast-gas-catcher subsystem, is shown schematically in fig. 5. The power density in the production target for in-flight fission of 100 kW uranium beams is well over 1 MW/cm^3, assuming a 1 mm diameter beam spot as required by the optics of the fragment separator. A windowless liquid-lithium target concept is being pursued to address this problem [41]. A third-generation prototype of the fast gas catcher is currently being tested at Argonne, prior to the construction and testing of a full-scale RIA prototype by an international collaboration at GSI. Tests with heavy-ion fusion reactions at ATLAS have produced efficiencies of over 45% and extraction times of less than 10 ms [42].

The development of concepts and prototyping of critical components of RIA is continuing under the guidance of a national coordinating committee set up by the Department of Energy Nuclear Physics Division. At this time seven laboratories (ANL, JLAB, LANL, LBNL, LLNL, NSCL and ORNL) are participating. The relative priority of RIA within the U.S. nuclear physics program will be determined by the long-range planning exercise that is now in progress. Currently MSU and ANL are interested in hosting the RIA facility.

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