ISOL Task Force Report to NSAC

November 22, 1999

The Isotope Separation On-Line (ISOL) Task Force is requested to provide a technical analysis of the various options for subsystems of ... a new facility for a research program along the lines indicated by the benchmark experiments outlined in the 1997 physics report "Scientific Opportunities with an Advanced ISOL Facility." It should assess the advantages and disadvantages of these options, identify preferred technologies, and prioritize needs for R&D. Consideration should be given to the maximum effective use of U.S. accelerator facilities, of major detector facilities, and of technical expertise.

—From the charge to the ISOL Task Force.
(See Appendix 1.)

Contents

Executive Summary
Overview and Recommendations
- Opportunity: Rare-Isotope Accelerator (RIA) Facility
- RIA Facility Recommendations

Scientific Motivation
- Nuclear Astrophysics
  - Studies of nuclei involved in the r-process
  - Explosive nucleosynthesis via the rp-process
- Fundamental Physics
  - Challenging the Standard Model of particle physics
  - Search for fundamental symmetry violations in atoms
- Nuclear Structure
  - Nuclei near the extremes of nuclear existence
  - Amplifying subtle aspects of the nuclear force

Unprecedented Rare-Isotope Yields Required
Technical Solution
- Driver Beam Requirements
- Driver System Description
  - Multiple-charge-state beams
  - ECR ion source and LEBT
  - RFQ component of the injector
  - Room-temperature IH structures
  - The superconducting linac
- Target Concepts for RIA
  - ISOL target: refractory metal foil
  - ISOL target: compressed powder
  - Liquid-lithium-cooled two-step ISOL targets
  - Liquid-lithium targets for heavy-ion fragmentation
- In-Flight Isotope Separation
  - RIA fragment separator
  - Gas catcher/ion guide system
- Post-Accelerator
- Fast Beams of Rare Isotopes

Experimental Equipment
Radiation Handling
The RIA Facility in Worldwide Context
- RIKEN RI Factory vs. RIA
- ISAC-II vs. RIA

Preconstruction R&D
Appendices
1. Charge to the Task Force
2. Task Force Activities and Participants
3. Driver Working Group Process, Findings, and Recommendations
4. Driver Beam Energy Choice for RIA [Added March 1, 2000]

Acronym List

Single-Page, Nontechnical

Executive Summary

The ISOL Task Force has unanimously concluded that developments in both nuclear science and its supporting technologies make building a world-leading Rare-Isotope Accelerator (RIA) facility a scientific imperative for the United States. RIA would substantially advance our understanding of the atom's nucleus, and therefore of matter itself.

Much remains to be learned about the nucleus, the atom's dynamic core of nucleons—protons and neutrons. Fewer than 300 stable kinds of nuclei account for 99.9% of Earth's matter, but thousands of unstable kinds can and do exist. They usually decay nearly instantly—part of the challenge for RIA. In stars, such nuclei help generate the stable nuclei that we know. In RIA, such nuclei will be artificially produced to help generate essential new knowledge.

These short-lived nuclei are the rare isotopes referred to in RIA's name. Most have never been accessible for experiments. RIA will reveal previously unobserved aspects of nuclear behavior, and will probe the limits of nuclear existence. It will advance our understanding of stellar evolution and the origins of the elements. It will support tests of fundamental theories.

With strong support from universities and national laboratories, the Task Force studied rare-isotope production methods and unanimously chose the solution that best combines available technologies. RIA will exploit accelerator-related advances to build on pioneering work in techniques called *isotope separation on-line* (ISOL) and *in-flight fragmentation*. It will enable the richest variety and highest possible quality of experiments, advancing the state of the art by several orders of magnitude through a combination of greatly increased intensities and an enormously widened variety of high-quality rare-isotope beams.

The Task Force recommends a highly flexible superconducting linear accelerator to "drive" RIA with beams of all the stable isotopes from hydrogen, with its single-proton nucleus, to uranium, containing 238 nucleons. In power, these drive beams should reach 100 kilowatts, in energy, 400 million electron volts per nucleon. This performance has no precedent in existing or planned facilities worldwide. The drive beams will be used to produce a broad assortment of short-lived rare-isotope beams via a combination of techniques: projectile fragmentation, target fragmentation, fission, and spallation. Maximizing access to the rare-isotope beams for the large community of nuclear physics users will require simultaneous operation of multiple experiment stations.

To enhance performance and reduce costs, the Task Force recommends conducting modest preconstruction research and development (R&D) on RIA's key elements. Efforts from several laboratories will be needed to complete the R&D, to develop a comprehensive conceptual design report (CDR), and ultimately to construct the facility itself. To extend RIA's scientific reach still further, the design should provide for the addition of a capability for fast in-flight separated beams of rare isotopes.

The Task Force recommends commissioning a CDR in the immediate future to prepare for the earliest possible construction start. Strong coordinating leadership is required. It will be vital for DOE to ensure continuity of the CDR team in the construction of RIA.

For a Fiscal Year 2002 construction start and operation in Fiscal Year 2007, the Rare-Isotope Accelerator facility's projected cost is about $500 million.

Overview and Recommendations

Of the wide variety of nuclei that nature has used to build the universe, only a small fraction are stable. The systematic study of this broad range of nuclear species has been a core aspect of nuclear physics for many decades, with the goal of deepened understanding of nuclear matter in both our terrestrial environment and the more extreme conditions in stars and other astrophysical settings. Today the cutting edge of this research is the study of very short-lived nuclei which may have features quite different from those of more stable isotopes. Figure 1 shows the immense breadth of such study.

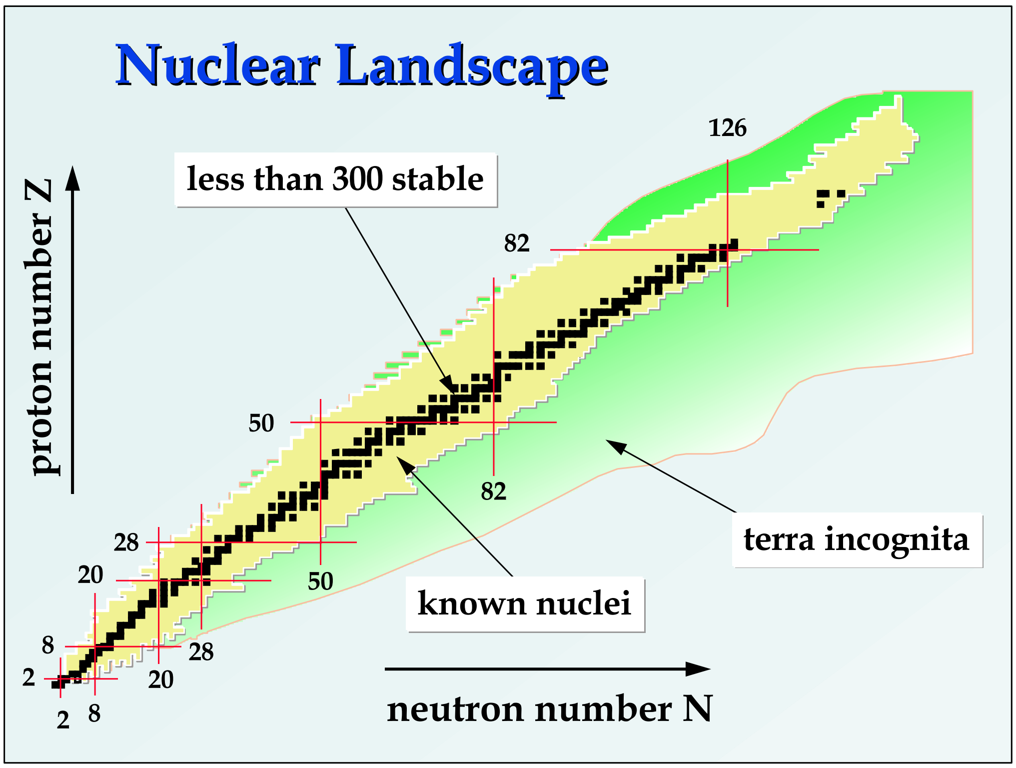

Figure 1. Map of bound nuclear systems as a function of the proton number *Z* (vertical axis) and the neutron number *N* (horizontal axis). This nuclear landscape forms the territory of rare-isotope beam physics. The black squares show the nuclei that are stable—that is, long-lived—with half-lives comparable to or longer than the age of Earth. Fewer than 300 such species exist. These nuclei form the "valley of stability." The yellow color indicates man-made nuclei that have been produced in laboratories and that live a shorter time. By adding either protons or neutrons, one moves away from the valley of stability, finally reaching the drip lines where the nuclear binding ends because the forces between neutrons and protons are no longer strong enough to hold these nuclei together. The nuclei beyond the drip lines emit nucleons very quickly to form nuclei with combinations of protons and neutrons for which the strong interaction is able to cluster these nucleons together as one nucleus. Many thousands of nuclei with very small or very large *N*/*Z* ratios are yet to be explored. In the (*Z*,*N*) landscape, they form the terra incognita indicated in green. Note that the neutron drip line is far from the valley of stability, and thus hard to approach. The red lines show the magic numbers known around the valley of stability. However, since the structure of nuclei is expected to change significantly as drip lines are approached, we really do not know how nuclear shell structure evolves at the extreme *N*/*Z* ratios.

The U.S. nuclear physics community has recognized the rich developing opportunities in this science, and in the technologies needed to pursue them. Technologies for the production and utilization of high-power beams of ions have positioned the field for a significant leap in capability directed at exploring nuclei very far from stability. In the 1996 Long Range Plan for Nuclear Physics, this thrust was identified as the field's highest priority for the next major facility. Accordingly, this Task Force was charged (Appendix 1) to analyze the requirements and the technical feasibility issues for implementing a facility that would serve this need at the cutting edge of science by exploiting on-line isotope separation techniques.

Appendix 2 lists Task Force activities and participants. The Task Force convened on October 30, 1998. Through a series of eleven meetings and site visits, it reviewed the technical options for a facility for producing and using rare isotopes via Isotope Separation On-Line (ISOL) and related techniques. With strong support from the community of U.S. national laboratories, which contributed numerous consultants, the Task Force characterized the strengths of several rare-isotope production methods and was drawn to a solution that combines the advantages of each. The Task Force examined all of the technical subsystems and found them to be sufficiently ready to proceed toward construction. A subgroup formed to examine options for the driver accelerator—a major portion of the facility costs—recommended a preferred technical option and produced a first cost estimate. To assess options for maximizing yields of the desired rare species, a study was commissioned which identified significant opportunities for progress in the effectiveness of ISOL targets.

Opportunity: Rare-Isotope Accelerator (RIA) Facility

We have unanimously concluded that the coming decade presents an important opportunity to construct a world-leading facility for the study of short-lived isotopes, which we call the Rare-Isotope Accelerator (RIA) facility. Such a facility will enable a program of experiments with the potential to revolutionize our understanding of the production of nuclei in stellar environments, to advance our knowledge of the structure of nuclei far from stability, and to make stringent tests of the standard model of elementary particles and their interactions.

This RIA facility's projected cost is about $500 million. RIA will be driven by a highly flexible superconducting linear accelerator (linac), which will provide a high-power, 400 MeV/nucleon beam of any stable isotope from hydrogen to uranium onto production targets. The energy of the linac is determined based on the desire to optimize the facility cost versus rare-isotope yield. The broad assortment of short-lived secondary beams needed for the experimental program will be variously produced by the most effective combination of a number of techniques: projectile fragmentation, target fragmentation, fission, and spallation. After separation, the selected rare isotopes will, in many instances, be accelerated and directed to fixed-target experiments. Experiments with stopped and trapped isotopes will also make up a major component of the scientific program. An attractive opportunity open for addition to this facility will be to use the projectile fragment beams directly while in flight.

The RIA facility will include several experimental areas and a suite of instrumentation that will allow the community of facility users to perform the forefront experiments needed to shed light on the most important scientific issues. The user community, which now numbers over 600 in the U.S. and perhaps 1000 overseas, is extremely supportive of the goals of this facility and has actively participated in setting the end-use requirements.

RIA Facility Recommendations

The RIA facility can be built based on modest extrapolations of existing technologies. No technical showstoppers exist, and only a relatively modest amount of R&D must be completed before a comprehensive conceptual design can be prepared. With construction beginning in FY 2002, the facility could be ready to begin operations in FY 2007. In support of this goal, the Task Force recommends:

- The design and construction of a Rare-Isotope Accelerator (RIA) facility that provides unprecedented beams of a diverse assortment of nuclei. The scientific potential of the RIA facility will be maximized by integrating multiple techniques for producing and separating, then accelerating and utilizing, these rare isotopes. RIA will be based on a highly flexible superconducting linac driver capable of providing 100 kW, 400 MeV/nucleon beams of any stable isotope from hydrogen to uranium. The broad assortment of short-lived secondary beams needed for the experimental program will be produced by a combination of techniques: projectile fragmentation, target fragmentation, fission, and spallation.
- That an additional important opportunity be provided: fast in-flight separated beams of rare isotopes. This will extend the scientific reach of the RIA facility. We recommend that the RIA design accommodate this capability.
- Complete preconstruction R&D on key elements of the sources, targets, driver linac, and experimental equipment. Specific systems where R&D will provide opportunities for cost reduction and enhanced performance are identified later in the report. Significant efforts from several national laboratories will be needed to complete the preconstruction R&D, to develop a comprehensive conceptual design report (CDR), and to construct RIA.
- Timely commissioning of a CDR to prepare the project for the earliest construction start. Strong coordinating leadership is required. It will be vital for DOE to ensure continuity of the CDR team in the construction of RIA.

In addition to these recommendations, the Task Force notes that in the next phase the diverse user community must increasingly participate in the evolution and execution of RIA planning to ensure a successful RIA facility that best serves forefront research.

Scientific Motivation

Studies of nuclei far from stability promise to improve radically our understanding of atomic nuclei—the cores of all atoms, and the building blocks of the universe. Many of these nuclei have never before been accessible in the laboratory. Such studies will advance our theoretical models of nuclei, search for new manifestations of nuclear behavior, and probe the limits of nuclear existence. They will also have profound impact on nuclear astrophysics, which utilizes descriptions of the processes of nucleosynthesis to test our understanding of the evolution of stars and the origins of the elements in our universe. They will allow tests of fundamental theories of particle physics, and may provide applications of technology to other disciplines and to practical realms such as electronics and medicine.

Nuclear Astrophysics

Studies of nuclei involved in the r-process. Half the nuclei heavier than iron are synthesized in the rapid-neutron-capture process, or r-process. It occurs in a few seconds, possibly just outside the core of a massive star after it has collapsed to nuclear density (which is one hundred trillion times that of ordinary matter), at a temperature greater than one billion Kelvin, as the star explodes as a supernova. However, the site of the r-process is not known with certainty. It may also occur when two neutron stars collide. The nuclei through which the r-process passes are so neutron-rich that most have never been studied; the constraints on nuclear astrophysics experiments are considerably more stringent than those to which nature is subjected! RIA will make it possible to measure many new masses and half-lives, allowing a new level of precision in our understanding of r-process nucleosynthesis. The observed r-process abundances, coupled with these new nuclear physics constraints on its theoretical description, will provide a vastly improved understanding of some of the most cataclysmic events in the universe.

Explosive nucleosynthesis via the rp-process. The rapid-proton-capture process, or rp-process, occurs in several stellar environments, but dominates when matter is accreted from a companion star onto a compact star—a white dwarf or neutron star. In such situations, the accreted matter is heated as it falls to the surface of the compact star, where it undergoes thermonuclear runaway. The energy suddenly released produces novae or x-ray bursts, which are observed by astronomers with space-borne observatories. Studies of the nuclear reactions relevant to the rp-process require intense beams of very proton-rich nuclei; RIA will produce beams of many of the crucial nuclei at the required intensities. Study of the reactions involving the proton-rich nuclei through which the rp-process passes will allow unprecedented understanding of these explosive cosmic events, and of the nucleosynthesis that they produce.

Fundamental Physics

Challenging the Standard Model of particle physics. The β-decays of special nuclei can provide precise information on one of the elements in the "CKM matrix," by which the basic constituents of matter are related in the Standard Model of particle physics. Combination of these elements produces a test, called a *unitarity test*, of the basic assumptions of the model. At present this test appears to fail, although the evidence is not yet sufficiently definitive to justify revision of the model. If this evidence is reinforced by results of new RIA experiments which help to refine the previous results, new physics will have to be added beyond that of the Standard Model.

Search for fundamental symmetry violations in atoms**.** Parity, or mirror symmetry, violations in atoms can be sought in a special class of elements, the heavy alkalis, particularly cesium and francium. Observation of parity violation allows determination of the incredibly small electroweak coupling that results from the exchange of Z^0 bosons between the electrons and the nucleus. The effect has been demonstrated in cesium isotopes, but should be eighteen times larger in francium. However, there are no stable francium isotopes, so no beams are possible from an ordinary accelerator facility. RIA will produce beams of about a dozen francium isotopes with sufficient intensity to perform these measurements.

Nuclear Structure

Nuclei near the extremes of nuclear existence. Experiments using RIA on very neutron-rich nuclei, especially along iso-chains such as the isotopes of nickel, will provide critical data from which to forge a new understanding of the nucleus. Studies of nuclei near both the proton-rich and neutron-rich limits of stability will yield new information on the structure and quantum states that characterize them. Studies to date, including recent work on "halo" and other neutron-rich nuclides, have suggested that the standard form of the Shell Model—the microscopic model of the nucleus that has reigned for half a century—may not be generally applicable to nuclei far from stability, and is but a part of a more general class of models. The cornerstones of the Shell Model, the concepts of closed shells and magicity, are now recognized as quite fragile. Beams of exotic nuclei may also be used to probe a third frontier—the heaviest elements that may exist—where recent dramatic advances offer promise for future work. RIA presents opportunities for dramatic extensions of the nuclei accessible for study, and hence for improvements in the understanding of nuclear structure.

Amplifying subtle aspects of the nuclear force. Exotic nuclei can often produce large amplifications of certain components of the nuclear force, by which atomic nuclei exist. Protons and neutrons can interact in the nucleus in two ways, which go by the names T=0 and T=1 interactions. Although the T=0 interaction is inherently stronger, its effects in normal nuclei are usually masked by the accumulated effects of many T=1 interactions. Yet the T=0 interaction is extremely important. It accounts for the existence of the simplest nucleus, the deuteron, and plays a key role, albeit a hidden one, in all nuclei. The formation of deuterons in Big Bang nucleosynthesis was a precondition for the subsequent synthesis of heavier nuclides; human existence therefore depends on the T=0 interaction. In nuclei with equal numbers of protons (Z) and neutrons (N), where the protons and neutrons are filling similar orbits, the importance of the T=0 interaction is greatly amplified. Studies of such nuclei with RIA, ranging from mass measurements to studies of regularities in the energies of low-lying states, and transfer reactions, can elucidate this force in heavier nuclei than are currently accessible. Moreover, in some N=Z nuclei with odd numbers of each type of nucleon, a new form of theoretically predicted correlation of nucleon motions, called T=0 pairing, may be observed.

Unprecedented Rare-Isotope Yields Required

For exploration on the broad frontiers of nuclear study that are summarized above, RIA must provide a diverse selection of isotopes both near and far from the stable isotopes found in nature. Figure 2 and Table 1 are keyed to each other to show examples of specific types of investigations and the corresponding beam requirements. In sum, these examples outline the overall RIA performance characteristics needed to explore the new science opportunities. Generally, the facility should provide access to as many as possible of the nuclei that participate in astrophysical processes, such as the r-process. It should allow nuclei at or near the limits of stability to be studied over the whole range of proton-rich nuclei and perhaps up to mass 60–100 for neutron-rich nuclei. It should provide high-intensity beams near stability for the measurement of astrophysical reaction rates, nuclear reaction studies, and the synthesis of more exotic nuclei. It should provide sufficiently intense neutron-rich beams to address the production of superheavy elements. Finally, RIA should provide beams with sufficient intensity to allow nuclear structure to be studied over widely varying proton-to-neutron ratios, if possible, ranging from the proton to the neutron drip lines, in both isobaric and isotopic sequences.

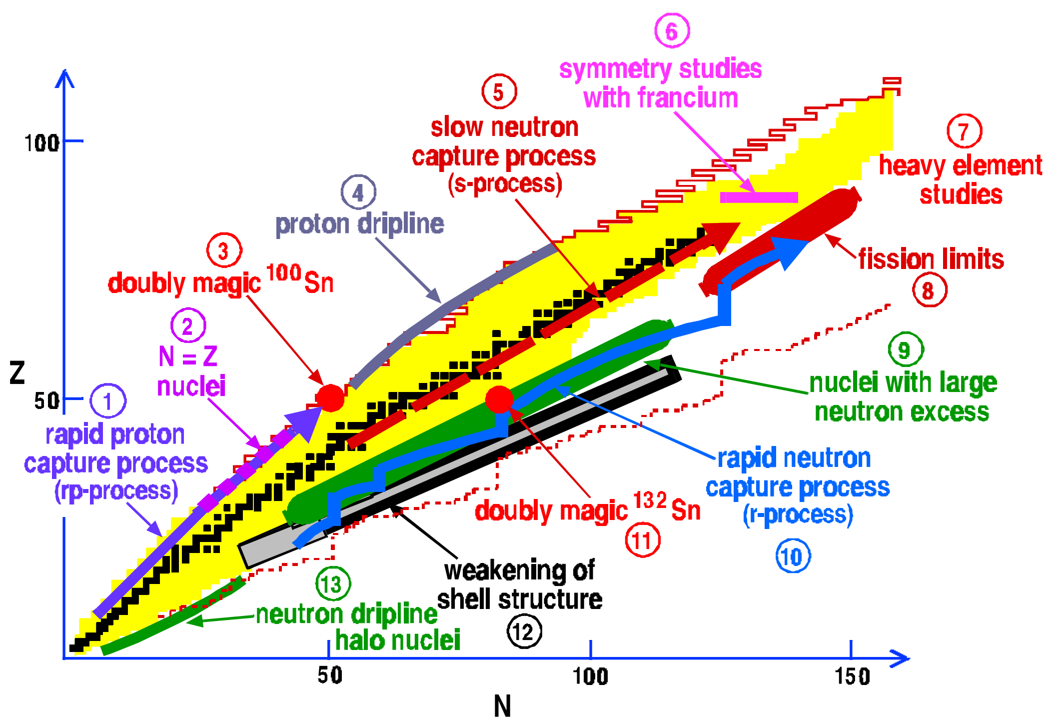

Figure 2. Example RIA research opportunities. The circled numbers correspond to the physics topics enumerated in Table 1, which in turn link the example opportunities to actual beam requirements. (Figures 1 and 2, and Table 1, are taken from the 1997 White Paper, “Scientific Opportunities with an Advanced ISOL Facility,” referenced in the charge to the Task Force.)

Table 1

Beam Requirements for Example RIA Research Opportunities

Physics Topics*	Reactions and Techniques	Beams	Desired Intensities [particles/sec]	Energy Range [MeV/nucleon]
1. Rapid proton capture (rp-processes)	Transfer, elastic, inelastic, radiative capture, Coulomb dissociation	^{14}O, ^{15}O, ^{26}Si, ^{34}Ar, ^{56}Ni	10^{8}–10^{11} 10^{5}–10^{11}	0.15–15
2. Reactions with and studies of *N*=*Z* nuclei, symmetry studies	Transfer, fusion, decay studies	^{56}Ni, ^{62}Ga, ^{64}Ge, ^{68}Ge, ^{67}As, ^{72}Kr	10^{4}–10^{9}	0.1–15
3. Decay studies of ^{100}Sn	Decay	^{100}Sn	1–10	Low energy
4. Proton drip-line studies	Decay, fusion, transfer	^{56}Ni, ^{64,66}Ge, ^{72}Kr	10^{6}–10^{9}	5
5. Slow neutron capture (s-process)	Capture	^{134,135}Cs, ^{155}Eu	10^{8}–10^{11}	0.1
6. Symmetry studies with francium	Decay, traps	^{A}Fr	10^{11}	Low energy
7. Heavy-element studies	Fusion, decay	$^{50–52}$Ca, ^{72}Ni, ^{84}Ge, ^{96}Kr	10^{4}–10^{7} 10^{6}–10^{8}	5–8
8. Fission limits	Fusion-fission	$^{140–144}$Xe, $^{142–146}$Cs, ^{142}I, $^{145–148}$Xe, $^{147–150}$Cs	10^{7}–10^{11} 10^{4}–10^{7}	5
9. Rapid neutron capture (r-process)	Capture, decay, mass measurement	^{130}Cd, ^{132}Sn, ^{142}I	10^{4}–10^{9}	0.1–5
10. Nuclei with large neutron excess	Fusion, transfer, deep inelastic	$^{140–144}$Xe, $^{142–146}$Cs, ^{142}I, $^{145–148}$Xe, $^{147–150}$Cs	10^{7}–10^{11} 10^{2}–10^{7}	5–15
11. Single-particle states/effective nucleon-nucleon interactions	Direct reactions, nucleon transfer	^{132}Sn, ^{133}Sb	10^{8}–10^{9}	5–15
12. Shell structure, weakening of gaps, spin-orbit potential	Mass measurement, Coulomb excitation, fusion, nucleon transfer, deep inelastic	^{A}Kr, ^{A}Sn, ^{A}Xe	10^{2}–10^{9}	0.1–10
13. (Near) neutron-drip-line studies, halo nuclei	Mass measurement, nucleon transfer	^{8}He, ^{11}Li, ^{29}Ne, ^{31}Na, ^{76}Cu	10^{6}–10^{8} 10^{3}–10^{6}	5–10

***The numbers 1 to 13 correspond with the circled numbers in Figure 2 on the preceding page.** Only a few typical ion species are shown for each entry to exemplify the intensity and energy ranges needed for conducting experiments in those areas.

Technical Solution

Comprehensive study of nuclei far from stability will require a Rare-Isotope Accelerator (RIA) facility that is best driven by an SRF linac (a superconducting radio-frequency linear accelerator). Because the driver accelerator is by far the major cost component in any approach, the Task Force commissioned a focused RIA Driver Working Group—chaired by Christoph W. Leemann of the Thomas Jefferson National Accelerator Facility—to examine design options. Appendix 3 summarizes the process whereby the working group concluded that the RIA requirements are most effectively met by an SRF linac, which has an order-of-magnitude advantage over a cyclotron, regardless of how the driver ion source (Figure 3) is developed.

Figure 3 is a simplified schematic of the RIA layout. The driver linac, based on SRF accelerating structures, will accelerate arbitrary ions—up to and including uranium—to energies as high as 400 MeV/nucleon, and in some cases beyond. Each desired isotopic species will be produced via the most effective combination of target fragmentation, projectile fragmentation, fission, and spallation. The selected species will be separated and variously accelerated or used directly for experiments. Figure 4 presents yields for the RIA facility. Table 2 itemizes the project cost, approximately $500 million.

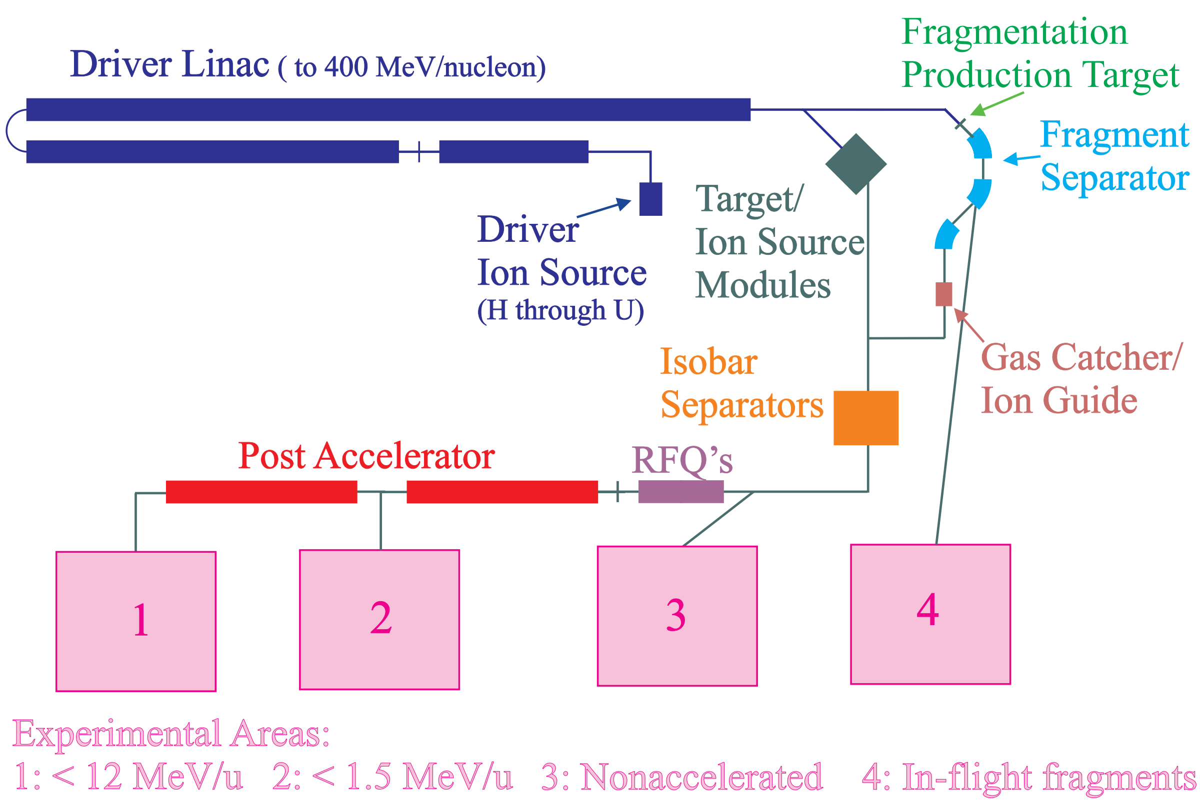

Figure 3. Simplified schematic layout of the Rare-Isotope Accelerator (RIA) facility. (Note that while highly recommended, the in-flight fragmentation experimental area (4) is beyond the scope of this Task Force.)

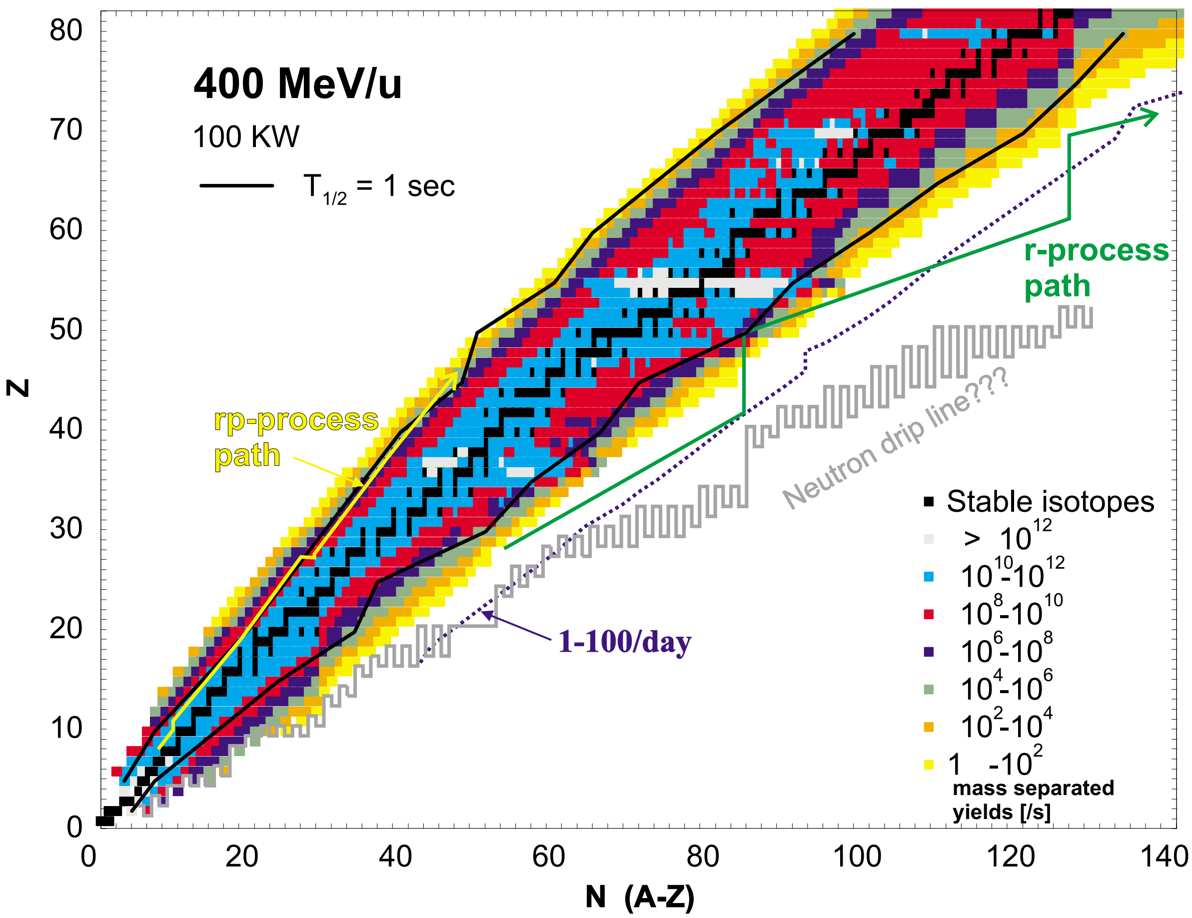

Figure 4. Yields for a Rare-Isotope Accelerator (RIA) facility.

Table 2
Rare-Isotope Accelerator (RIA) Facility Cost Summary
(In $M; includes facilities and R&D during construction)

Front end (source + linac up to 1.5 MeV/nucleon)	20
Driver linac	210
Targets & separator(s)	40
RIB accelerator*	20
Experimental equipment	70
Support facilities	20
Contingency	*120*
Total	**$500M**

* Assumes utilization of ATLAS.

Driver Beam Requirements

RIA beam requirements, driven by the scientific goals, can only be met by a truly new-generation facility. RIA will be unmatched by any of the accelerators now under construction or planned. The optimal maximum beam energy is 400 MeV/nucleon. Operation over a range of energies 200–400 MeV/nucleon is also desirable to maximize yields for some spallation processes. It is important that the driver be capable of accelerating any stable isotope from hydrogen to uranium to the maximum energy. This will allow RIA to utilize both the target and projectile fragmentation approaches. Both light- and heavy-ion beams will be required.

Operation at high beam power is essential to maximize yields of rare species. The minimum requirement is 100 kW, which corresponds to approximately 6×10^{12} ions/s for uranium beams. It is highly desirable that a credible upgrade path exist for operation at up to 400 kW at minimal extra cost.

Beam quality is not a major design issue for the driver and is well within the state of the art for linacs. A transverse full beam emittance of 3 π-mm-mr at 400 MeV/nucleon and a 1 mm beam spot for the projectile fragment production target are adequate. The momentum spread should be within 0.2%.

It is very important that the beam time structure be essentially 100% duty factor. This need is driven by production target heating considerations, the necessity of reducing the instantaneous secondary beam intensity for coincidence experiments, and limitations imposed by ionization in the gas catcher system.

To maximize utilization by a large user community, simultaneous operation with multiple production target stations is essential. This does not present major technical challenges.

The accelerator must be designed and constructed to provide a very high level of reliability and of beam availability. Beam losses must be minimized to facilitate maintenance and repair.

Driver System Description

The focused RIA Driver Working Group studied various design schemes. In summary, the working group found:

- The RIA driver requirements can be most effectively met in a linac design by employing state-of-the-art accelerator technology, including electron cyclotron resonance (ECR) sources, radio-frequency quadrupoles (RFQ), interdigital H-type (IH) structures, SRF accelerating cavities, and superconducting (SC) solenoids.
- 400 kW beam power could be available for most beams immediately, and for the heaviest ions following appropriate ion-source development.
- The rf and cryogenic systems will meet the requirements for reliability.

• Modest accelerator system design studies have already yielded significant cost-reduction steps.
• Because of high leverage on civil construction design and costs, there may be significant advantage to completion of nominal cryomodule design (implying key element prototyping) early in the planning process.

The working group developed a rough benchmark design for the needed SRF linac, together with an associated work breakdown structure. Table 3 presents the accelerating elements of this benchmark linac design.

Table 3
Accelerating Elements of the Benchmark RIA Driver Linac

Section	**Element**	**Beta = *v/c***	**Frequency (MHz)**	**Temp. (K)**	**Number of Elements**	**Section Voltage (MV)**
Source	***ECR***	***(Ions up to uranium at 30+)***			2	
Injector	RFQ	0.004–0.017	58.3	293	1	1.2
Injector	IH	0.017–0.05	58.3	293	4	9
Injector	4-gap	0.05–0.09	58.3	4.5	24	21
Injector	2-gap	0.09–0.16	116.6	4.5	57	71
1st Stripper	***Stripper***	***(Lithium film or carbon wheel)***				
Midsection	2-gap	0.16–0.3	175	4.5	72	111
Midsection	2-gap	0.3–0.4	350	4.5	96	150
2nd Stripper	***Stripper***	***(Carbon wheel)***				
Endsection	6-cell	0.4–0.54	700	2	60	261
Endsection	6-cell	0.54–0.8	700	2	96	684

Superconducting (SC) linac technology has several advantages for this application in addition to enabling cost-effective cw operation. The independent phasing intrinsic to an SC cavity array allows the velocity profile to be varied, and enables higher energies for the lighter ions. For example, the present design for 400 MeV/nucleon uranium can provide 730 MeV protons. The short, high-gradient SC cavities form a linac configured to provide very strong focusing, both transverse and longitudinal, so that the acceptance of the SC linac is large.

Multiple-charge-state beams. SC technology provides a longitudinal acceptance about 250 times larger, and a transverse acceptance about 100 times larger, than the beam emittance expected from the RFQ. Such a large margin for emittance growth makes it entirely feasible to accelerate simultaneously more than one charge state through most of the linac. In this way, the efficiency of charge stripping is greatly enhanced, since virtually all of the stripped beam can be utilized. Multiple-charge-state operation provides not only a substantial increase in the available beam current, typically a factor of 4, but also enables the use of multiple strippers in ways which reduce the size of the linac required for 400 MeV/nucleon beams. An additional benefit of accelerating multiple charge states is a reduction in the amount of beam dumped during charge-state selection at the stripping points, which in turn reduces shielding requirements.

Taking uranium as an example, between the first stripper (12 MeV/nucleon) and second stripper (85 MeV/nucleon) the beam has an average charge state $q_0 = 75$. In this region one can accelerate five charge states, which encompass 80% of the incident beam. After the second stripper, 99% of the beam is in four charge states neighboring $q_0 = 90$, all of which can be accelerated to the end of the linac. Simulations show such operation to be straightforward, with consequent increase of longitudinal and transverse emittance well within the linac acceptance.

With acceleration of multiple-charge-state beams of the heavier ions, the linac described above will be capable of producing intense beams of virtually any stable ion. Some representative examples are listed in Table 4. The beam currents shown in the table are projected from the current state of the art for ECR ion sources and assume sufficient rf power for 400 kW of beam.

Table 4

Projected Driver Output Beams

A/Z	***I* source (pμA)**	**Q_{inject}**	**Q_{strip1}**	**Q_{strip2}**	***I* out (pμA)**	**Beam Energy (MeV/nucleon) 1st Strip**	**2nd Strip**	**Output**	**Power (kW)**
1/1	548	1	1	1	548	51	228	731	400
3/2	218	2	2	2	218	40	173	612	400
2/1	379	1	1	1	379	33	140	528	400
18/8	54	6	8	8	45	26	125	491	400
40/18	24	11	18	18	20	22	125	494	400
86/36	10	17	35*	36	8.5	18	113	460	336
136/54	5	25	50*	54*	3.4	17	104	445	206
238/92	1.5	30	74.5*	90*	1.0	12	87	403	100

* Indicates multiple charge states.

ECR ion source and LEBT. The heavy-ion driver for RIA begins with a high-performance electron cyclotron resonance (ECR) ion source. (One of two such sources will be operated at a time.) This type of source is well matched to the driver's requirements for a cw, high-charge-state ion source capable of ionizing a wide range of elements. The heaviest beam needed for the RIA driver is uranium, which is also the most demanding in terms of ion-source performance. The driver should produce a uranium beam of 100 kW at 400 MeV/nucleon, or 1.05 pμA. The projected efficiency of the driver linac including two stages of stripping is 66% for uranium, so the output of the ECR and LEBT (low-energy beam transport) needs to be 1.6 pμA of U^{30+}. This is a factor 2 greater than the current record intensity with the AECR-U at the Lawrence Berkeley National Laboratory (LBNL). To increase the beam power to 400 kW will require a factor of 8 improvement.

Reaching these higher current levels will require development of a new high-magnetic-field high-frequency ECR ion source coupled to an LEBT capable of handling the high-intensity beams and matching the acceptance of the RFQ. The VENUS ECR ion source currently under construction at LBNL could serve as a prototype for the RIA ECR. It has superconducting solenoid and sextupole coils to enhance the plasma confinement, and it has sufficiently high fields to support ECR operation at 28 GHz. The coils are designed to generate a 4 T axial mirror field at injection, 3 T at extraction, and a radial sextupole field of 2.0 T at the plasma chamber wall.

<u>RFQ component of the injector</u>. A concept has been developed for a cw radio-frequency quadrupole (RFQ) which can operate cw and can accelerate charge states as low as U^{25+} from 5.25 keV/nucleon to 150 keV/nucleon. Using a 58.3 MHz design frequency-matches the SC linac and ensures an adequate transverse acceptance, 1.25 π mm-mrad normalized, for the emittance expected from the ECR ion source. The RFQ incorporates an internal kick buncher and drift, followed by a transition region prior to the acceleration section. This design produces a low-longitudinal-output (full) emittance, 1π keV/nucleon-nsec. Such high beam quality makes multiple-charge-state acceleration further on in the linac straightforward.

The RFQ will be 4 m long with an rf power requirement conservatively less than 60 kW. It will use a modified four-vane configuration with field stabilizers which move the unwanted dipole modes far above the quadrupole mode frequency, reducing assembly tolerances. At 58.3 MHz, 100% duty factor operation is practical, and the wall power loading is low.

<u>Room-temperature IH structures.</u> For an ion energy range from 150 keV/nucleon to about 1.5 MeV/nucleon, interdigital H-type (IH) structures are the most cost-effective acceleration method for cw operation. Excellent performance in cw or high-duty-cycle mode has been proven at Technical Institute Munich, GSI, KEK-Tanashi, and TRIUMF. For IH structures in this velocity range, the optimum frequency is near 60 MHz at 150 keV/nucleon, with a higher frequency desirable at the upper end of the range to increase shunt impedance.

We propose a linac section consisting of four IH tanks with SC solenoids between the tanks. The first two IH tanks will have a frequency of 175/3 = 58.33 MHz, with the last two at 350/3 = 116.7 MHz, the sub-multiples being required to match the beam into the following SC linac sections. The use of SC solenoids between the tanks for transverse focusing will maximize the transverse and longitudinal acceptance of this section. The RF power requirement, less than 20 kW/m, is very modest. Also, the solenoids provide a very short transverse focusing element, only 80 mm long for a 10 T field. This minimizes the phase-focusing required in the IH tanks, and helps to maximize the acceptance of this section of the linac.

<u>The superconducting linac</u>. Currently operating SRF accelerators fall into two classes: velocity-of-light electron linacs and heavy-ion linacs limited to energies at or below 10 MeV/nucleon. Recent development work, however, has demonstrated the feasibility of extending the velocity range of SRF structures to cover the intermediate velocity range required by the RIA driver.

It should be noted that, while feasibility has been established, important aspects of the SRF linac—such as the optimum method of phase control—can be established only by prototyping, including cryomodule tests. The lead time required, more than two years, places this activity on the critical path in determining start of construction.

For ion velocities from 0.05*c* to 0.4*c*, the linac can make use of existing types of low-β SC drift-tube structures, including the 350 MHz spoke-loaded cavities recently demonstrated at Argonne National Laboratory. This portion of the linac has its genesis in the technology of the many SC heavy-ion linacs operating worldwide. The low-β section of the RIA driver linac could comprise 248 SC resonant cavities, of four different types, distributed in 31 cryostat modules. Each module will contain eight SC cavities, with transverse focusing provided by 10 T, 30-mm-bore SC solenoids which will follow each pair of cavities. The frequency of all the cavities in the low-β section will be ≤ 350 MHz. In this frequency range the SC surface resistance is sufficiently low to permit economic operation at 4.5 K.

For ion velocities from 0.4*c* up, the driver linac will make use of the class of foreshortened elliptical-cell cavities recently tested at Jefferson Lab, at Los Alamos National Laboratory, and most notably, at Saclay in France, which last year reported accelerating gradients above 20 MV/m in a $\beta = 0.64$, 700 MHz niobium cavity. Note that nearly three-quarters of the total driver voltage is supplied by similar cavities. The high-β section will consist of 156 SC cavities of two different types, distributed in 39 cryomodules. Each cryomodule will contain four SC cavities. Transverse focusing elements will be placed exterior to the cryostats, in the form either of normal-conducting quad triplets or SC solenoids. Both high-β elliptical-cell cavity types will operate at 700 MHz, and thus require 2 K operation.

Target Concepts for RIA

The RIA facility will use beams from the driver linac to produce rare nuclei via several different reaction mechanisms in a variety of targets. Ion beams will be available with a broad range of masses, as light as protons and as heavy as uranium, and at power levels of 100 kW and higher. To date there are no rare-isotope ISOL (isotope separation on-line) or fragmentation facilities operating at such beam powers. However, engineering concepts exist for high-power targets that are considered viable for both types of exotic beam sources. In the standard ISOL source, the nuclear reaction products formed by protons, neutrons, or light ions from a primary driver machine are brought to rest in a thick refractory target or solid catcher kept at high temperature and connected to an ion source. The species produced are separated from the target bulk and often from other isobaric reaction products via diffusion, effusion, and chemical processes, which permits their transfer into the rare-species ion source.

This method has been successfully used in the last 30 years at several on-line mass separators to produce low-energy radioactive ion beams of some exotic species. The method is tailored to the specific physical and chemical properties of the elements involved. Schemes which yield beams of 70% of the elements have been demonstrated. The crucial dimension is the efficiencies of the transfer and ionization processes which, for long-lived species, are 20% to 100%. For short-lived species with half-lives of the order of 10 ms, however, the efficiency drops typically to 0.1% to 0.01% due to the decay during the transfer process. There is evidence of attractive opportunities to considerably increase these efficiencies as well as the number of available elements if properly addressed in a development program.

Fragmentation sources, by contrast, involve a target in which an incident heavy-ion beam loses roughly 20% of its energy, but produces the rare species of interest as it does so. Following the target must be a fragment separator that removes the residual incident beam as well as any other fragments not of interest to the experiment. The beam out of the fragment separator is then stopped in a gas catcher, from which it is extracted and reaccelerated. The fragmentation-type source has the advantages of chemical independence: it can accelerate any element in the periodic table. It also promises to be especially effective at providing the short-lived nuclei that are so important to the RIA scientific program.

ISOL target: refractory metal foil. Development of one of these concepts has been pursued for the past few years at the Rutherford Appleton Laboratory. This target consists of a stack of many thin tantalum foils with thin spacers to enhance ion effusion. This concept for an ISOL-type target has been tested with internal electron-beam heating to power levels that indicate its viability for use with protons in the 500–1000 MeV energy range at power-levels of 50–100 kW. This concept can be adapted to other refractory-metal target materials and for use with other high-energy, light-ion beams, possibly at somewhat lower beam powers.

ISOL target: compressed powder. Another ISOL-type target concept has been developed for use with porous refractory materials such as UC_x. These target materials tend to have low thermal conductivities that require special geometries to minimize the target's internal temperature. Such geometries include thin, large-area sheets of the target material tilted at a high angle with respect to the incident beam. The tilt increases the target thickness seen by the beam while minimizing the thickness for conduction of heat from the interior of the target. Such targets are appropriate for spallation of heavy target materials with relatively light driver beams, with masses of about 1 to 40. This concept is a variation of a method used routinely in the production of medical isotopes with high-power beams at relatively low beam energies.

Liquid-lithium-cooled two-step ISOL targets. A concept for a high-power two-step production target has also been developed. The two-step concept separates the high power from the secondary target in which the radionuclides are produced. High-energy, light-ion beams such as deuterons or ^{3}He irradiate a primary target such as tungsten to produce secondary neutrons with high multiplicity. The neutrons, in turn, irradiate a thermally decoupled secondary target such as UC_x to produce short-lived, neutron-rich fission fragments. The fission target is geometrically close to the primary target in a coaxial geometry to enhance the radionuclide production rates. The driver beam deposits 50 to 100 kW of power in the primary target. The primary target is cooled via liquid lithium that is flowing in a closed loop through a heat exchanger.

Liquid-lithium targets for heavy-ion fragmentation. One of the unique features of RIA is the availability of high-power heavy-ion beams to produce very exotic isotopes via the beam fragmentation mechanism. In this mode the beam is heavy, e.g., xenon or uranium, and the target is light, e.g., lithium, beryllium, or carbon. With primary beam powers of 100 kW and small beam spots appropriate for matching into the fragment separator, the power density in the target exceeds that feasible with traditional thick-foil solid materials. Thermal and hydraulic analysis of flowing-liquid lithium targets indicates that this is a viable solution. Such targets have been built and tested for potential use in fusion materials test facilities. The liquid-lithium target system tested at Hanford, for example, was sized with a mass flow rate adequate for total beam power of up to 10 MW. Such a system scaled down by a factor of 100 in flow rate to match the 100 kW beams of RIA would operate with lithium temperature rises of less than 100 K.

The liquid-lithium concept is essential for the very high power densities encountered with small-diameter, high-*Z* beams, such as from xenon to uranium. However, for lighter ion beams, such as oxygen, the required thicknesses are much larger and the corresponding power densities lower. Hence, for the lighter beams other concepts may be used, such as liquid-lithium-cooled graphite or rotating graphite target wheels.

In-Flight Isotope Separation

A key feature of the RIA facility is the ability to use in-flight separation to select rare isotopes produced in projectile fragmentation and fission reactions. When this mode of production is used, the heavy-ion beam from the driver is fragmented or undergoes fission induced by a light-element target. The fragments continue forward at high velocity and can be collected by a magnetic system with 50% efficiency for fission fragments and nearly 100% efficiency for projectile fragments. In the process, the isotope of interest can be magnetically separated from the large number of unwanted isotopes. The fragments can be stopped in an optimized catcher system (e.g., an ion-guide isotope separation on-line, or IGISOL-type, helium gas cell where the ions remain singly charged) and quickly extracted. The advantages of this system are chemistry-independent fast separation of the ions (much faster than the isotope half-lives) and separation of the catcher/ion source system from the high power and radiation environment of the production target. The scheme combines the intrinsically advantageous short delay times of in-flight fragmentation with the intrinsically advantageous high-quality, precise-energy beams of the ISOL concept. In addition, at 400 MeV/nucleon, where the nuclear interaction length is comparable to the electronic stopping length for most ions, the in-flight separation scheme can produce yields approaching those of traditional thick-target schemes.

Figure 5 shows the schematic layout of a fragment separator to collect heavy-ion fragmentation products and deliver them to the gas catcher/ion guide system. The key components are the fragment separator and the gas catcher/ion guide system. These components are discussed in detail in the following sections.

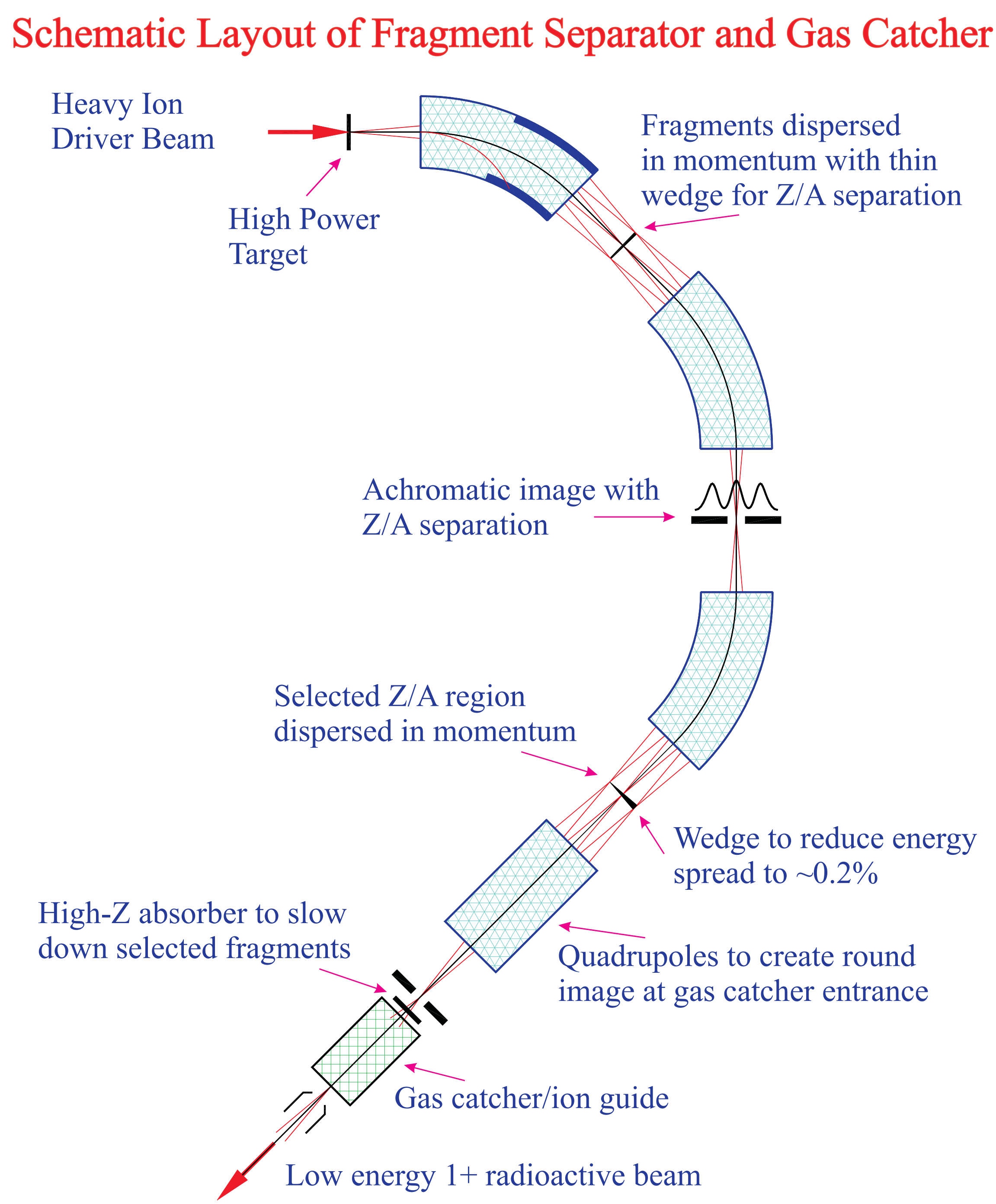

Figure 5. Schematic layout of a fragment separator to collect heavy-ion fragmentation products and deliver them to the gas catcher/ion guide apparatus.

RIA Fragment Separator. The heart of the in-flight separation technique is the so-called fragment separator—an achromatic optical system with two sets of bends. The first set provides a momentum-per-charge selection of the fragments. Degrading material is placed between the segments in order to slow the ions. Different elements lose different amounts of momentum in this degrader, so the second set of bends provides an additional separation that has a different dependence of fragment *A* and *Z* than the first selection. The net result is a system that can select single or perhaps a few isotopic beams, depending on acceptance and resolving power of the system, out of the hundreds or thousands created at the production target.

The main goals of the fragment separator at RIA are to allow the secondary ion yields to be maximized, filter the desired isobars from the transmitted ions, and significantly reduce the number of ions stopped in the gas catcher system. These goals dictate the parameters of the separator. Maximizing fragment yield requires the separator to collect nearly 100% of the fragments produced. This is possible for projectile fragmentation where the angular and momentum spreads of the fragments are about 1 degree and 2%, respectively. Hence, for this mechanism the momentum acceptance of the separator dictates how thick a production target can be used. The optimum momentum acceptance is in the range of 10% to 20%. Acceptances larger than this provide only a marginal gain in fragment yield. Projectile fission, on the other hand, has a larger angular and momentum cone of the fragments. It is still possible to collect about 60% of the fission fragments at 400 MeV/nucleon by a separator of 10 msr solid angle and 20% momentum acceptance. A 10% separator will collect about 35% of the fragments and in addition require a thinner target.

Based on the need for high collection efficiency for fragments from projectile fission, the separator should have a 10 msr solid angle and a 20% momentum acceptance. This large momentum acceptance will have a negative influence on the other goals for the separator. It means the selectivity of the first part of the separator is reduced. Nevertheless, if the fragments are degraded in the wedge to below 200 MeV/nucleon, most of the isobar contamination can be removed and the fragment of interest can be at least 10% of the total stopped rate. If certain applications require reduced impurities, the momentum acceptance of the separator can be reduced and the purity increased at the cost of secondary beam yield.

Preliminary studies indicate that a magnetic system with the desired parameters and a maximum bending power of 8 T-m is feasible. However, research and development are needed in two key areas. First, the quadrupoles near the production target will be in a very high radiation environment. Quadrupoles made out of radiation-hardened materials may have a lifetime on the order of one year. Ultimately, this could be the limiting factor for running the facility at beam powers above the 100 kW level. Thus, a method for construction of compact radiation-hardened quads with longer lifetimes is desirable. The second area requiring research is into techniques for compression of the large (20%) fragment momentum spread before stopping in a gas volume. This can be accomplished by a dispersive system, as shown in Figure 5, with modest resolution and a profiled degrader in front of the gas stopping volume. Higher-momentum ions are passed through more material so that the ions are stopped in the same gas volume. This type of momentum-compression device will have to be implemented in order to reduce the gas stopping volume. Finally, methods using special dipole geometries need to be investigated to allow the primary beam to be caught in a controlled way.

The multiplicity of experiments will be increased if a scheme is devised to allow several of the desirable secondary fragments to be used in experiments simultaneously. It should be possible with a specialized first dipole design to select two sets of magnetic rigidities to be sent to two separate wedge/degrader systems, with one for gas catching and the other perhaps for high-energy nonstopped beam experiments.

Gas catcher/ion guide system. After the fragments are separated, their momentum spread is compensated by a dispersive system and a profiled degrader to give all ions the same final range before implantation into the gas catcher system, as shown in Figure 5**.** The magnetic system serves the important function of ensuring that the primary beam and the majority of other fragments do not enter the gas catcher; otherwise the high ionization density creates a plasma that affects the recoil ions. The transmitted recoils lose most of their energy in a high-*Z* degrader before entering the gas catcher filled with high-purity helium, where they recapture electrons during the final deceleration until they come to rest. The vast majority of them will be in the singly ionized charge state due to the high ionization potential of atomic helium. The effective stopping thickness of helium in the gas catcher must cover the range straggling of the reaction products for the majority of the recoil ions to be stopped in the gas. The range straggling varies for different species, the degrader material used, the energy of the reaction products, and finally how well the momentum dispersion of the reaction products can be canceled. For the parameters of the RIA driver linac and fragment separator, the resulting helium effective thickness will vary from below 0.5 atmosphere-meter for most reaction products above mass 50 amu to about 5 atmosphere-meter for the lightest neutron-rich isotopes. The gas catcher will therefore have a length of about a meter and operate at pressures between 0.5 and 5 atmospheres, depending on the reaction products of interest.

Such a cell is too large to obtain a fast evacuation time just from the gas flow, as is done with standard IGISOL systems. Therefore, to speed up evacuation of the ions from the cell, an electric field gradient along the length of the cell is added. It drags the ions towards the cell exit where a set of concentric electrodes focuses them on the exit hole. At the exit hole, the gas velocity grows rapidly and pulls the ions out. This allows extraction times of the order of a few milliseconds to be attained with the envisioned large cell. The voltage gradients required to extract the ions in that time scale are determined from ion mobility data. The gas cell and a scaled-down 15 cm prototype operating at up to 0.5 atmosphere have been designed using an ion trajectory program developed at Argonne National Laboratory (ANL) in which the effect of the helium gas on the ion trajectories is added by a Monte Carlo method treating individual ion-gas collisions and adjusted to reproduce the known ion mobility data. The scaled-down version of the gas catcher has been constructed at ANL, and measurements performed with reaction products validate the simulations. Figure 6 shows the prototype gas cell used in the demonstration test.

The ions are extracted from the gas cell together with a large flow of helium. The resulting residual pressure of helium after extraction is too large to accelerate the ions directly. They must therefore go through a differential pumping system, an *ion guide* system, where the ions are guided by an rf structure to a region of lower pressure while the gas is pumped away by large roots blowers.

This system carries the ions to a low-pressure region from which they can be accelerated by the post-accelerator. This is a standard technology demonstrated at IGISOL facilities and at ANL. It results in significantly improved emittance for the extracted beam.

Research and development are needed in a few key areas for the gas catcher/ion guide system. The codes used to determine the different components to the range straggling need to be validated in this energy regime. The simulations of the scaling of the gas cell to larger pressures need to be tested experimentally. The ion-guide system will have to handle large currents in RIA, and means to limit the emittance growth for these large currents will have to be investigated. Finally, needing more detailed study is the issue of the ionization in the gas by the contaminant reaction products that will not be rejected by the fragment separator. Preliminary studies indicate that for typical situations this will not be an issue, but this ionization effect may start limiting the efficiency that can be attained in cases where the reaction products might be too close to the primary beam to obtain full rejection of the latter, or with the advent of cases where beam powers up to 400 kW become available.

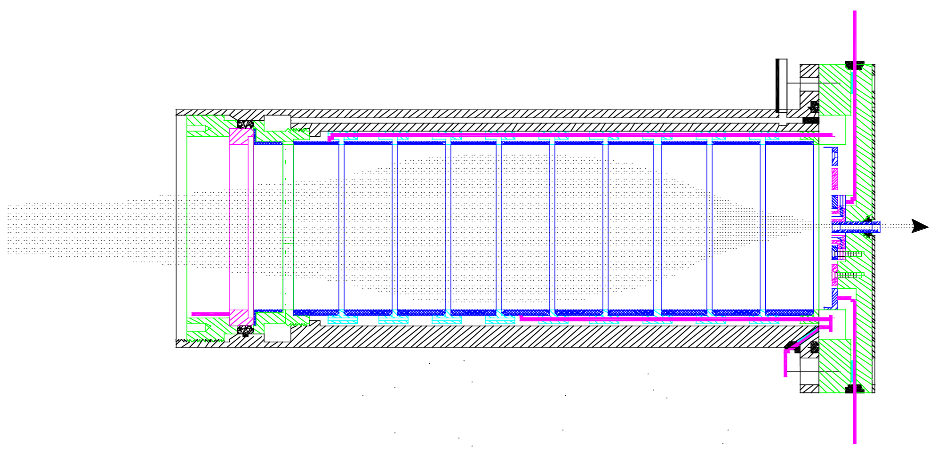

Figure 6. Drawing of the test gas cell used at Argonne National Laboratory to successfully demonstrate the use of rf and dc extraction fields inside the cell to guide the ions to the exit aperture. This is an expanded view of the gas catcher/ion guide at the bottom of Figure 5.

Post-Accelerator

The rare-isotope post-accelerator will be called upon to deliver a wide variety of beams to a wide variety of users. To summarize the demands placed on this element of RIA, it must:

- Provide continuously variable output beam energy.
- Accelerate the full mass range of ions to energies above the Coulomb barrier.
- Provide state-of-the-art beam quality.
- Exhibit high overall efficiency and maximize beam current.
- Accept ions of low charge state.

Almost all of the post-accelerator can be based on current superconducting rf (SRF) technology. Existing superconducting ion linacs consist of arrays of short, independently phased, high-gradient rf cavities closely interspersed with transverse focusing elements and having the following properties:

- Broadly tunable velocity profile, accommodating the complete ion mass range.
- Completely variable output energy.
- Large transverse and longitudinal acceptance.
- State-of-the-art beam quality, providing excellent time and energy resolution.
- High transmission.

In order to utilize the most efficient ion sources, the injector section presents a special requirement for accommodating low charge states. This problem has been studied, and technical solutions have been developed which accommodate even the most difficult case—singly charged uranium—with high efficiency and without compromising beam quality. The following outlines a configuration which would meet all of the above requirements, sized to provide maximum energies of about 8 MV/nucleon for ^{132}Sn, increasing to about 15 MV/nucleon for the lighter ions:

- An injector section mounted on a high-voltage platform, including:
    - A gridded-gap, multiple harmonic buncher.
    - 4 m of 12 MHz, normal-conducting RFQ providing 2 MV of acceleration.
    - An optional thin (non-equilibrium) helium gas stripper.
    - 4 m of low-frequency RFQ providing 2 MV of acceleration.
- A low-charge-state linac section using technology similar to the existing ATLAS positive ion injector, providing 40 MV of acceleration.
- An optional foil stripper.
- A linac very similar to the existing ATLAS ion linac, providing an additional 50 MV of acceleration.

This configuration is highly flexible, and can be set up to optimize performance for a variety of beams and users.

Fast Beams of Rare Isotopes

The direct use of fast beams of rare isotopes, produced without stopping from projectile fragmentation, offers additional physics opportunities. These opportunities fall into two classes:

- Experiments which require projectile energies significantly above 10–20 MeV/nucleon, e.g., studies of giant resonances, charge exchange studies, and spectroscopy with nucleon (and multi-nucleon) knockout reactions.
- Experiments which benefit from the gains in luminosity and/or efficiency that can be realized at higher beam energy. These gains will be most important for studies of the most neutron-rich nuclei where production rates fall below 10^3/s.

Areas of research that may benefit most from fast beams of rare isotopes include the delineation of the neutron drip line, the study of weakly bound extremely neutron-rich nuclei (neutron halos or skins), studies of nuclei along the r-process path, and nuclear-structure studies using knockout reactions, giant-resonance excitation, or Coulomb excitation.

All these topics are elements of the physics justification for RIA. Fast beams of rare isotopes can be separated on microsecond time scales by physical methods and with optimum efficiency. For cases of special scientific merit, it will be possible to identify species produced at the level of one atom/week and to perform reaction spectroscopy with as little as one incident particle per minute. In many applications, thick targets (of the order of g/cm^2) can be used to induce secondary reactions, which leads to gains in luminosity by several orders of magnitude. For medium-mass nuclei, nuclear reaction experiments based on unstopped beams can reach 3 to 4 mass units further out than ISOL-based experiments for the same Z (assuming comparable investments of beam time). Therefore, including the capability to create and exploit fast beams of rare isotopes would enhance a major portion of RIA's mission.

Experimental Equipment

The detection equipment required for RIA to fulfill its scientific potential was discussed at a July 1998 Town Meeting at Berkeley. There it became clear that the required facilities could build on existing concepts, but might require new developments in a few cases. However, these could be carried out, built, and tested well in advance of the completion of RIA.

These devices must be designed to obtain data from even the rarest beams produced. Such weak beams necessitate large, high-efficiency detectors. They must also be able to tolerate the high event rates produced by the background radiation environment from a plethora of unstable background beams. This requires the capability for fast timing to perform the complex coincidences that may be required to separate the nuclei or reaction products of interest from those from background beams. Finally, studies of reactions in inverse kinematics will require detectors with high position resolution to allow angular distributions to be measured and to correct for reaction kinematics.

The major equipment items required for RIA to undertake the wide variety of experiments that are planned for it include:

- Gamma-Ray Detectors. Two types of detectors will be required. One will be used in high-event-rate, low-multiplicity situations, and will consist of small arrays of high-efficiency detectors in close geometry. The other will be used in virtually all studies of high-multiplicity reaction gamma rays, and will consist of a large position-sensitive germanium detector with fine-grained energy-tracking capability.
- Magnetic Spectrographs. Two magnetic spectrographs are envisioned, one with a large momentum acceptance, and the other emphasizing high energy resolution. These will also be used in a variety of RIA experiments.
- Recoil Ion Separators. One of these, to be used in the nuclear astrophysics experiments, will be required to have very high background rejection. Another must have large momentum acceptance. It may also be necessary to have a third separator that emphasizes high energy resolution.
- Particle Detectors. Charged-particle detectors include a large solid-angle array of CsI detectors and an array of Si strip detectors, or possibly even solar cells. Heavy-ion detection will require gas proportional counters. Neutron detection will utilize neutron walls with either solid- or liquid-scintillator neutron detection.
- Detectors for Non-Accelerated Beams. A laser atom trap will be required for parity violation measurements, and an ion trap will be utilized in mass measurements. A beta-gamma coincidence setup will be used for spectroscopic studies. Nuclear orientation and beta-nuclear magnetic resonance facilities will also be used, possibly in condensed matter experiments. An electron beam ion trap will allow study of the heaviest elements.

Radiation Handling

Safety and health issues associated with induced radioactivity can be responsibly and economically handled by addressing the engineering requirements from the very start in the RIA facility design. The costs, although not insignificant, represent only a small fraction of the overall facility cost.

The criteria for safely dealing with radiation in a high-power hadron-accelerator environment are well established from years of experience in laboratories such as LAMPF, PSI, and TRIUMF. RIA will require several types of shielded facilities, as well as a remote handling system with hot cells for dealing with the various sources of radiation. The systems required to handle this radiation will differ in concept according to the nature of the task at hand—prompt radiation, activation, or loose/volatile contamination. The driver accelerator will not need a remote handling system since beam losses in the driver are kept low enough to allow hands-on maintenance of accelerator components. The CERN ISOLDE and the TRIUMF ISAC facilities provide effective solutions to the radiation-handling requirements for ISOL-type targets. The fragmentation target/separator system requires magnets to operate in a high-radiation environment. The secondary beam lines at LAMPF, PSI, and TRIUMF demonstrate that radiation-hardened magnets can be operated and maintained near high-power targets. Nevertheless it is essential, prior to the start of civil construction of the target areas, that an acceptable concept be developed for how these radiation-handling solutions are to be adapted for RIA. In particular an appropriate concept for the fragmentation/separator system is not as well defined as is the concept for the ISOL target systems.

At the controlled beam-loss locations (i.e., collimators, targets, or beam dumps) it is convenient to use local stackable shielding that can be easily removed so that the activated components can be accessed by the remote handling system. For example, at ISAC the remote handling system is based on an overhead crane that is operated remotely from within a shielded room. This crane is used to transport components between the hot cell and the target systems (see Figure 7). In the regions of high radiation, activated components such as targets, ion sources, diagnostics, and ion-beam optical elements are mounted on the bottom of 2-m-long steel modules that fit inside a large evacuated tank. Services and vacuum O-rings for these modules are located near the top where the radiation fields are low enough to permit hands-on servicing, and do not require the use of expensive radiation-hardened magnets. All of the components inside the module are designed so that they can be removed, installed, and aligned inside a hot cell using manipulators.

Experience at ISOLDE shows that in addition to shielding for the prompt and delayed radiation induced in the structures at a rare-isotope production facility, it is also necessary to contain the vapors of non-ionized radioactive species. These vapors escape from the target and ion-source region and propagate along vacuum chambers, vacuum lines, and beam lines, on which the vapors partly condense. To control the risk of contamination from this very loose radioactivity, both ISOLDE and ISAC have taken the approach of enclosing the target/ion source in a containment vessel. At any time the volatile components from the target region are either condensed inside the containment box on the cool surfaces surrounding the target or pumped into sealed storage vessels. The activity is kept in the storage vessels until the contamination is determined to be low enough to be released through monitored air filters. A conventional nuclear exhaust system is required to prevent the accidental release of radioactivity to the environment. Very little modification is required to this modular approach for the spallation-type target stations. A similar, but modified, approach can be envisioned for the fragment-separator system of RIA.

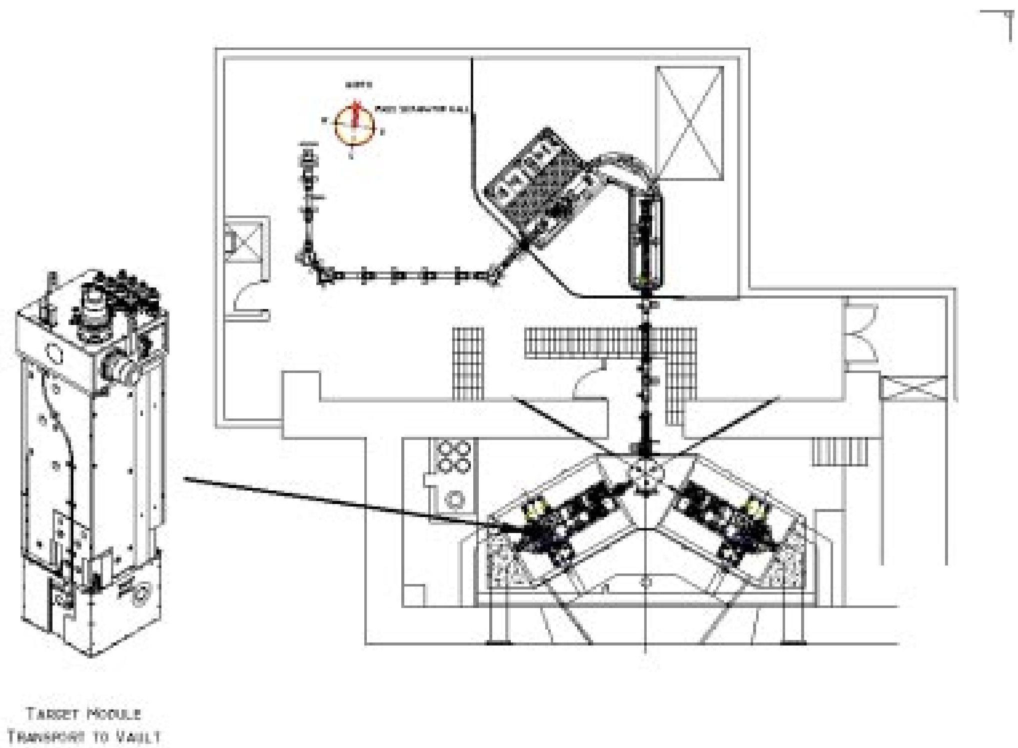

Figure 7. The items having the highest potential residual activity are located in the heavily shielded vault shown in the lower part of this plan view of the ISAC target area. Because the transported activity in the mass separator vault is low, servicing of components does not require a remote handling system. Inside the target vault, two target vacuum tanks each house five modules. An enlarged schematic of the target/ion source module is shown in the left of the figure. The containment box at the bottom confines the products from the target and is used to prevent the spread of loose radioactive contamination to the outside of the module. Nearly 2 m of steel separate the target from the vacuum seals that are all located on the service cap. The modules and the tank housing the modules each have their own separate vacuum system. Each of the modules can be picked up remotely and delivered to a hot cell (not shown) located in the right side of the shielded vault.

The RIA Facility in Worldwide Context

Worldwide, several first-generation ISOL-type facilities currently operate, as do four facilities of the in-flight fragmentation type: the National Superconducting Laboratory (NSCL) at Michigan State University, RIKEN in Japan, GANIL in France, and GSI in Germany. Upgrades of some of these facilities are currently in progress. RIA will build on the pioneering work at all these facilities, advancing the state of the art by several orders of magnitude through a combination of increased intensities and much wider variety of high-quality rare-isotope beams. In the United States there is currently one fragmentation facility, NSCL, and one ISOL facility, the Holifield Radioactive Ion-Beam Facility (HRIBF) at Oak Ridge National Laboratory. Two other facilities also conduct research with accelerated rare-isotope beams, ATLAS at Argonne National Laboratory and the 88-Inch Cyclotron facility at Lawrence Berkeley National Laboratory. Development at these facilities to date and in the years prior to RIA commissioning will provide crucial technological and scientific input.

Particularly significant facility upgrades are in progress at RIKEN and at TRIUMF in Canada. These are described below and compared with RIA.

RIKEN RI Factory vs. RIA

The new RIKEN RI Factory in Japan will accelerate light ions (up to mass 40) to 400 MeV/nucleon and uranium ions to 150 MeV/nucleon. The complex uses an ECR ion source, a linac injector, and a cascade of three cyclotrons.

The 1998 Linac Conference paper of O. Kamigaito, et al., on the RIKEN injector design discusses the ion source/injector/stripping scheme. For uranium ions they plan to use 22+ ions from the source and a single carbon stripper foil at 3.8 MeV/nucleon, with a 12% stripping efficiency. They expect to achieve beam currents of 0.1 pμA for uranium beams at 150 MeV/nucleon, corresponding to 3 kW uranium beam power. The corresponding numbers for uranium at RIA, assuming similar source performance, are 100 kW beam power at 400 MeV/nucleon. The combination of increased energy and current for the uranium beams of RIA implies 300 times more yield of rare isotopes produced via in-flight fission. For lighter ions like oxygen-18, RIA can produce up to 40 times the current at somewhat higher energy, 500 MeV/nucleon vs. 400 MeV/nucleon. The RIKEN RI Factory is designed for 1 pμA of ions in this lower mass range.

At present the RIKEN RI Factory is only proposed as a fragmentation facility. No plans have been announced to stop and reaccelerate fragments, as proposed for RIA. Their emphasis is on doing physics directly with high-energy fragments—a capability that is also recommended for RIA—as well as in storage rings with fixed internal targets and intersecting beams.

ISAC-II vs. RIA

At TRIUMF in Canada, the upgrade of ISAC-I to ISAC-II comprises a major upgrade of the post-accelerator. The ISOL production complex is unaffected. The post-accelerator will have its energy increased from 1.5 to 6.5 MeV/nucleon and the mass range extended to approximately 150 u. It will require the addition of a charge-state booster prior to the RFQ and will still use a carbon foil stripper after the first acceleration stage.

The ISOL production scheme uses the TRIUMF 500 MeV protons at currents on target of up to 100 μA, or about 50 kW of beam power. Hence, they will have excellent yields of isotopes produced via the standard ISOL methods. RIA will be significantly better due to more beam power and higher proton energy (730 MeV). RIA has much more flexibility due to the availability of a wide variety of light-ion beams—for example, 1.8 GeV ^{3}He.

The biggest gain of RIA over ISAC-II comes in the availability of 400–500 MeV/nucleon heavy-ion beams. The use of these beams with the in-flight beam fragmentation mechanism brings with it all the advantages discussed elsewhere in this report—for example, chemical independence of extracted species and very fast extraction for production of very short-lived species.

Preconstruction R&D

The Rare-Isotope Accelerator (RIA) facility will be based principally on moderate extrapolations from proven technologies: superconducting radio-frequency (SRF) accelerating structures, electron cyclotron resonance (ECR) sources, and IGISOL-type (ion-guide isotope separation on-line) gas cells for fragment stopping. No technical showstoppers are identified, and the community is ready to proceed to the conceptual design phase. However, to ensure expeditious construction and commissioning, and to take advantage of potential cost leveraging, a vigorous R&D and prototyping effort should proceed in parallel with the conceptual design process. The Task Force has identified a number of high-leverage and/or long-lead areas where timely funding could have an especially strong impact on the project cost and schedule:

- Gas stopper volume and extraction. A key feature of the RIA concept is the use of intense energetic heavy-ion beams with projectile fragmentation as the production mechanism for beams of short-lived nuclei. This method is based on in-flight separation, with stopping and extraction in a helium gas cell configuration similar to that found in IGISOL systems presently in use. In the RIA context, a longer cell length (1 m) at higher pressures (0.5 to 5 atmospheres, depending on the reaction products) is required. For these long cells, applied electric fields will be necessary for fast extraction. Scaling of the gas cell technology to these pressures, lengths, and applied fields should be modeled and tested experimentally. Secondly, the ion guide system will have to handle large currents in the proposed RIA facility, and techniques to limit emittance growth should be investigated. Finally, although simulations indicate that for typical situations this will not be an issue, for some beams large amounts of reaction products may be transmitted by the fragment separator, and it will be prudent to characterize the ionization effects in this regime.
- Fragment momentum compression preceding the gas stopper. To stop fragments efficiently in the finite gas stopper volume, there must be compensation of the large (20%) fragment momentum spread. The solution takes the form of a dispersive system preceding the gas stopper with a wedge-shaped energy degrader to equalize the range of the exiting particles. Tests of this concept, including straggling, are needed to determine the performance of such systems in a practical design.
- Fragment separators that handle beam spray and allow beam sharing. The main goals of the separator are to allow secondary ion yields to be optimized, to filter isobars from the transmitted ions, and to significantly reduce the number of ions stopped in the buffer gas. Development work on the front end of the separator is required to minimize radiation damage to the magnetic elements, to design the setup to allow simultaneous beam sharing, and to filter driver beam and unwanted fragments to ensure that the driver beam power is dissipated in a controlled way and that ionization effects do not hinder gas cell operation.
- ECR sources producing high intensity, high-charge-state uranium, and LEBT. The driver linac requires ECR ion source performance greater than the current state of the art by a factor of 2 to 8. Improvements in this technology will translate into more intense beams and more robust, reliable operation. The development of very high magnetic field ECR ion sources capable of operation at greater than 18 GHz and 50 kV is needed to produce the required currents of U^{30+}

and other very heavy ions. Laboratory scale gyrotrons (10 kW at 28 GHz) could be used to power such a high-performance ECR. Methods to increase the oven lifetime for high-temperature elements such as uranium also need to be tested. The LEBT (low-energy beam transport) must preserve the source emittance and match into the RFQ. This requires calculations to model the extraction, transport, and charge-state separation as well as emittance measurements on existing ECR ion source/LEBT systems.

- Driver technologies, especially SRF structures. The driver linac will require about a half-dozen distinct rf structures, both superconducting (low and medium velocity) and room-temperature (interdigital-H). Although the specifications for these devices are within or close to performance achieved today, engineering and prototyping (especially for the superconducting systems) will be a significant task and will require a substantial early effort to attain the most economical solution and avoid unnecessary delays in the project.
- High-power targets including liquid lithium for fragmentation and ISOL-type sources with good diffusion and effusion properties. To fully utilize the high beam powers of the RIA driver, for both light and heavy ions, several classes of production targets must be developed. Current concepts for the various types were described earlier. For the standard ISOL method, the concepts include refractory metal foil targets, compressed powders, and liquid-lithium-cooled two-step targets. The development of ISOL-type targets with long lifetimes and fast extraction times at high input beam power is essential for the success of RIA. For in-flight fragmentation and fission, development of a liquid-lithium target, based on technology developed by the fusion community, is required. This type of target is calculated to work at the very high power densities deposited by 1-mm-diameter uranium beams of high intensity. It is imperative that such targets be developed prior to the commissioning of RIA.

Other important tasks will also require focused effort. These include post-acceleration, such as RFQs and very low velocity accelerating structures; detector instrumentation, including gamma ray detectors; and accelerator subsystems optimized for these beams, such as diagnostics, beam dumps, rf, and controls.

Appendix 1: Charge to the Task Force

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

September 24, 1998

Professor Konrad Gelbke
Chairman
DOE/NSF Nuclear Science Advisory Committee
Michigan State University
East Lansing, MI 48824

Dear Professor Gelbke:

This letter requests that the DOE/NSF Nuclear Science Advisory Committee (NSAC) establish a task force to perform a technical study and evaluation of the options for a next-generation facility in the United States for beams of radioactive nuclei, based on the Isotope-Separator-On-Line (ISOL) technique.

The1996 NSAC Long Range Plan identified the scientific opportunities made available by the development of radioactive beam facilities to be very compelling. The plan strongly recommended: (1) the immediate upgrade of the National Superconducting Cyclotron Laboratory at Michigan State University (MSU) and (2) the development of a cost-effective plan for a next-generation ISOL-type facility. The upgrade of the MSU Facility has been approved by the NSF and construction is well underway. With DOE support, considerable progress has been made on the development of possible designs for facilities that could address the scientific opportunities envisioned for a next-generation ISOL facility. The options incorporated into these designs differ significantly. DOE believes that the next step toward a national next-generation ISOL facility is to evaluate the feasibility, cost-effectiveness, and capabilities of the proposed technical options.

The task force should provide a technical analysis of the various options for subsystems of such a new facility for a research program along the lines indicated by the benchmark experiments outlined in the 1997 physics report: "Scientific Opportunities with an Advanced ISOL Facility." It should assess the advantages and disadvantages of these options, utilizing the current state of knowledge around the world. Preferred technologies should be identified, where possible, and, priorities and needs for R&D should be identified. Consideration should be given to the maximum effective use of U.S. accelerator facilities, of major detector facilities, and of technical expertise. The result of this study should point toward the best options for a truly forefront facility that can be constructed and that is likely to produce the optimal scientific returns in a cost-effective manner.

We envision the task force to be operational for approximately one year. However, an interim report is requested after approximately 6 months (April 1999) which will provide some guidance for developing realistic budget projections and time lines for the project. The interim report should include an evaluation of the technical aspects of proposed facility options, identification of areas of maximum technical or cost uncertainty, and a prioritization of R&D areas identified. A final detailed report is expected in October 1999.

Sincerely,

Robert A. Eisenstein

Martha Krebs

Robert Eisenstein
Assistant Director
Mathematical and Physical Sciences
National Science Foundation

Martha A. Krebs
Director
Office of Energy Research
U.S. Department of Energy

MICHIGAN STATE
UNIVERSITY

October 21, 1998

Dr. Hermann A. Grunder
Director
Jefferson Laboratory
Newport News, Virginia 23606

Dear Hermann:

In a letter dated September 24, 1998, NSAC has been charged to establish a task force to perform a technical study and evaluation of the options for a next-generation facility in the United States for beams of radioactive nuclei, based on the Isotope-Separator-On-Line (ISOL) technique.

In response to this charge, NSAC has established an ISOL Task Force with the following membership:

Hermann Grunder, chair (Jefferson Laboratory)
Jim Beene (Oak Ridge National Laboratory)
Dick Boyd (Ohio State University)
Rick Casten (Yale University)
Stan Kowalski (Massachusetts Institute of Technology)
Claude Lyneis (Lawrence Berkeley National Laboratory)
Jay Marx (Lawrence Berkeley National Laboratory)
Jerry Nolen (Argonne National Laboratory)
Helge Ravn (ISOLDE/CERN)
Brad Sherrill (NSCL/Michigan State University)
Paul Schmor (TRIUMF)

The ISOL Task Force is requested to provide a technical analysis of the various options for subsystems of such a new facility for a research program along the lines indicated by the benchmark experiments outlined in the 1997 physics report: "Scientific Opportunities with an Advanced ISOL Facility." It should assess the advantages and disadvantages of these options, identify preferred technologies, and prioritize needs for R&D. Consideration should be given to the maximum effective use of U.S. accelerator facilities, of major detector facilities, and of technical expertise. A copy of the charge letter from NSF and DOE is enclosed.

The ISOL Task Force is requested to provide an interim report by April 1999. The interim report should provide guidance for developing realistic budget projections and project time lines, include an evaluation of the technical

Dr. Claus-Konrad Gelbke
University Distinguished
Professor and Director

NATIONAL
SUPERCONDUCTING
CYCLOTRON
LABORATORY

Michigan State University
East Lansing, Michigan
48824-1321
TEL: 517/333-6300
FAX: 517/353-5967
gelbke@nscl.msu.edu

aspects of proposed facility options, identify areas of maximum technical or cost uncertainty, and prioritize needs for R&D. The final report should be submitted to NSAC no later than mid-September 1999.

On behalf of the Nuclear Science Advisory Committee, I thank all members of the task force to be willing to undertake this very important task.

Sincerely,

Konrad Gelbke

C. Konrad Gelbke
Chairman, DOE/NSF Nuclear Science Advisory Committee (NSAC)

Appendix: DOE/NSF charge to NSAC

CC: Brad Keister, Dennis Kovar, Task Force members

Appendix 2: Task Force Activities and Participants

Activities and meeting topics

<u>In 1998</u>:

October 30, Santa Fe—organization
November 16, ANL—context, required beam specifications, key issues
December 14–16, ANL/Oak Ridge/Knoxville—site visits, beam specifications

<u>In 1999</u>:

January 23–24, JLab—physics, experimental equipment, target challenges
February 21–22, TRIUMF—site visit, radiation, yields
March 25–26, Atlanta—yields, IGISOL method, vision shift
April 23, interim report to NSAC
June 24–25, MSU—system capability, driver specifications
August 11–13, ANL—driver workshop
September 21, Washington, D.C.—driver performance and cost analysis
October 5, Chicago—report refinement

Task Force

Jim Beene— Oak Ridge National Laboratory
Dick Boyd—Ohio State University
Rick Casten—Yale University
C. K. Gelbke, *ex officio*—NSAC, Michigan State University, NSCL
Hermann Grunder— Jefferson Lab
Stanley Kowalski—Massachusetts Institute of Technology
Claude Lyneis—Lawrence Berkeley National Laboratory
Jay Marx—Lawrence Berkeley National Laboratory
Jerry Nolen—Argonne National Laboratory
Helge Ravn—CERN, ISOLDE
Paul Schmor—TRIUMF, Canada
Brad Sherrill— Michigan State University

Driver Working Group

Gerald Alton—Oak Ridge National Laboratory
Joe Bisognano—DOE, Jefferson Lab
Jean Delayen—Jefferson Lab
Stanley Kowalski—Massachusetts Institute of Technology
Y. Y. Lee—Brookhaven National Laboratory
Christoph Leemann—Jefferson Lab
Claude Lyneis—Lawrence Berkeley National Laboratory
Jerry Nolen—Argonne National Laboratory
Charles Reece—Jefferson Lab

Ken Shepard—Argonne National Laboratory
Brad Sherrill—Michigan State University
John Staples—Lawrence Berkeley National Laboratory
Richard York—Michigan State University
Bill Weng— Brookhaven National Laboratory

Observers

Joe Bisognano—DOE, Jefferson Lab
Chip Britt—DOE
Brad Keister—NSF
Dennis Kovar—DOE
Stephen Steadman—DOE

Consultants

Juha Ätstö—University of Jyväskylä
J. R. J. Bennett—Rutherford Appleton Lab
Tony Chargin*—Lawrence Livermore National Laboratory
Marik Dombsky—TRIUMF
Charlie Landram—Lawrence Livermore National Laboratory
I-Y Lee—Lawrence Berkeley National Laboratory
Felix Marti—Michigan State University
P.N. Ostroumov—Argonne National Laboratory
Geoff Pile*— Argonne National Laboratory, Advanced Photon Source
Claus Rode*—Jefferson Lab
Guy Savard—Argonne National Laboratory
Bill Schneider*—Jefferson Lab
Will Talbert—Amparo
John Vincent*— Michigan State University
Antonio Villari—GANIL
Michiharu Wada—RIKEN
Hermann Wollnik—University of Giessen

* Member of driver costing team

Appendix 3: Driver Working Group Process, Findings, and Recommendations

Working Group Composition and Task Definition

Accelerator physicists from a variety of laboratories made up the RIA Driver Working Group:

Christoph Leemann	Jefferson Lab (chairman)
Gerald Alton	Oak Ridge National Laboratory
Joseph Bisognano*	DOE, Jefferson Lab
Jean Delayen	Jefferson Lab
Stanley Kowalski	Massachusetts Institute of Technology
Y. Y. Lee	Brookhaven National Laboratory
Claude Lyneis	Lawrence Berkeley National Laboratory
Jerry Nolen	Argonne National Laboratory
Charles Reece	Jefferson Lab
Ken Shepard	Argonne National Laboratory
Brad Sherrill	Michigan State University
John Staples	Lawrence Berkeley National Laboratory
Bill Weng	Brookhaven National Laboratory
Richard York	Michigan State University

The working group was charged with determining the technically optimal accelerator concept to meet the performance objectives stated below, to develop the concept to the point where a cost estimate could be made of sufficient accuracy to ascertain that the driver will fit within an overall RIA cost of $0.5B, to distinguish significant cost differences between competing approaches, and, if necessary, to determine the derivatives of cost with regard to critical parameters.

The requirements for RIA's driver call for:

- Energy: at least 400 MeV/nucleon for all ions up to uranium.
- Current: sufficient for 100 kW beam power for all ions, ~1 pμA for uranium; meeting the uranium goals is central to the facility's objectives.
- cw operation; considered an essential requirement.
- Normalized emittance < 10 μm; critical to the separation process.
- No obstacles to 400 kW beam power (with source development); i.e., there should not be any limitations intrinsic to a proposed approach.
- Cost: less than $300M.

Beyond these strict requirements are two "desiderata," features considered valuable but not so essential as to justify high additional cost. Both have to do with energy:

- Partial energies between 200 and 400 MeV/nucleon accessible.
- Energies higher than 400 MeV/nucleon for lighter ions.

In its evaluation process, the working group considered any approach meeting the criteria a solution, but defined the capability of achieving the desiderata within the cost envelope as superior performance.

---

* Now at the University of Wisconsin.

Process Used by the Working Group

Working group members worked both together and independently. The group met formally on three occasions in 1999: June 24 and 25 at Michigan State University (MSU), August 11–13 at Argonne National Laboratory (ANL), and September 21 at the Washington, D.C., offices of the Lawrence Berkeley National Laboratory.

Based on the establishment of a shared understanding of the requirements—the underlying physics, such as stripper performance as a function of energy and atomic number—the working group began its process simply by listing all of the conceivable approaches. The induction linac was never seriously considered, but four other approaches were initially discussed: the room-temperature linac, the rapid-cycling synchrotron in conjunction with a stretcher ring, the isochronous cyclotron, and the cw SRF full-energy linac. First, these were considered based on general, high-level arguments. Second, example sets of the most crucial parameters of initial design concepts were considered. The group intended, as a third step, to arrive at one chosen solution and to focus on that solution the development of further analysis concerning design and costing. However, as reported below, two "finalist" concepts received substantial consideration. The somewhat competitive nature of the ensuing analysis enhanced the process of uncovering performance enhancers and cost savers.

<u>Key outcomes at the MSU meeting</u>. At MSU the working group received the requirements from the Task Force, reached agreement on the formulae to be used in all comparisons of stripper performance, and adopted a baseline source performance figure. The group discarded the room-temperature linac within a few minutes of discussion simply because of its enormous power consumption. For three reasons, the group also discarded the synchrotron approach on the basis of a sketch by Y. Y. Lee and Bill Weng. The three reasons were:

- The marginal emittance resulting from space charge that is intrinsic to the approach.
- The usual issues of RCS: big magnet power supplies and vacuum chamber issues.
- Concern about sufficiently smooth extraction from the stretcher ring to meet the cw requirement.

In sum, at MSU in June the working group recognized the cyclotron and the SRF linac as potent "finalist" contenders, and adopted a two-track approach toward the August meeting at ANL.

<u>Key outcomes at the ANL workshop</u>. At ANL the working group, together with additional experts and a special costing team, held a workshop. (The costing team is listed in Appendix 2.) The participants refined descriptions of performance and systems for both driver concepts and created the Work Breakdown Structure (WBS) to be used by the costing team. For both concepts, the two-level (in a few cases, three-level) WBS covers 40 elements including the prerequisite prototyping. The table below summarizes the high-level description of the two finalist concepts that emerged.

SRF Linac vs. Cyclotron

	Linac	Cyclotron
Ion source	ECR	ECR
Acceleration to 1 MeV/nucleon	RFQ, IH	RFQ, IH
Low-beta section	4 types of cavities	3 types of cavities
High-beta sections	2 types elliptical cavities	Cyclotron
	Multiple charge states	Single charge state
U performance (source as is now)	0.6 pμA	< 0.1 pμA
All ions	Yes	Yes
400 kW	possible	possible
Intermediate energies	Yes, easily	Yes, energy loss
Energy of lighter ions	> 400 MeV/nucleon	= 400 MeV/nucleon
	(^{3}He @ 1.8 GeV)	(^{3}He @ 1.2 GeV)

Key outcomes at the Washington meeting. At Washington in September, the working group further refined descriptions of systems and the resulting performance for the two finalist concepts. The costing team reported its findings, and consensus was reached on the findings and recommendations made just below in the present report. The costing team focused on capital cost estimates. It is important to note that the next level of refinement will have to come from the team that develops the conceptual design report (CDR). Operating costs were deferred to an operations review at a later time, and were addressed only insofar as was necessary to establish that there was no significant cost difference between the two approaches. It could be argued that the cyclotron, by needing fewer staff, might save of the order of $3 million per year.

Findings and Recommendations

Findings

1. A full-energy SRF linac of the sort described in "Driver System Description" in the main report comes close to meeting the full requirements (needs modest ECR source development for full uranium current), and is a solid solution within the present state of the art.
2. The cyclotron is a solution contingent on an order-of-magnitude improvement in injector current through ion-source improvement and/or possible three-charge-state operation of the RFQ.
3. The SRF linac will always have the performance edge, since it could automatically incorporate any improvement to the cyclotron front end.
4. The cyclotron has a likely capital cost advantage of 3–10% of the driver total.
5. No significant schedule difference between the two approaches could be identified.

Recommendations

The RIA Driver Working Group consensus recommendations:

1. The SRF linac should be pursued as the preferred option.
2. R&D should begin in the immediate future on cavity, cryostat, and rf control, and on advancing the conceptual design to the point where civil construction planning and design can start.

Appendix 4: Driver Beam Energy Choice for RIA

Introduction

This appendix addresses issues relevant to the choice of beam energy for the driver accelerator of RIA. Because the nuclear science to be pursued at RIA is very broad in scope, there is no simple benchmark experiment that can be identified on which to make the decision. The real breakthrough in capability made possible by the proposed concept is the great increase in both the intensities and variety of rare isotopic beams. The facility will use both the standard ISOL techniques and in-flight fragmentation or fission of heavy ions to achieve this goal. Figure 1 is a chart of the nuclides color-coded to indicate which production technique is optimal for a given isotope, with extrapolation and interpolation from current understanding.

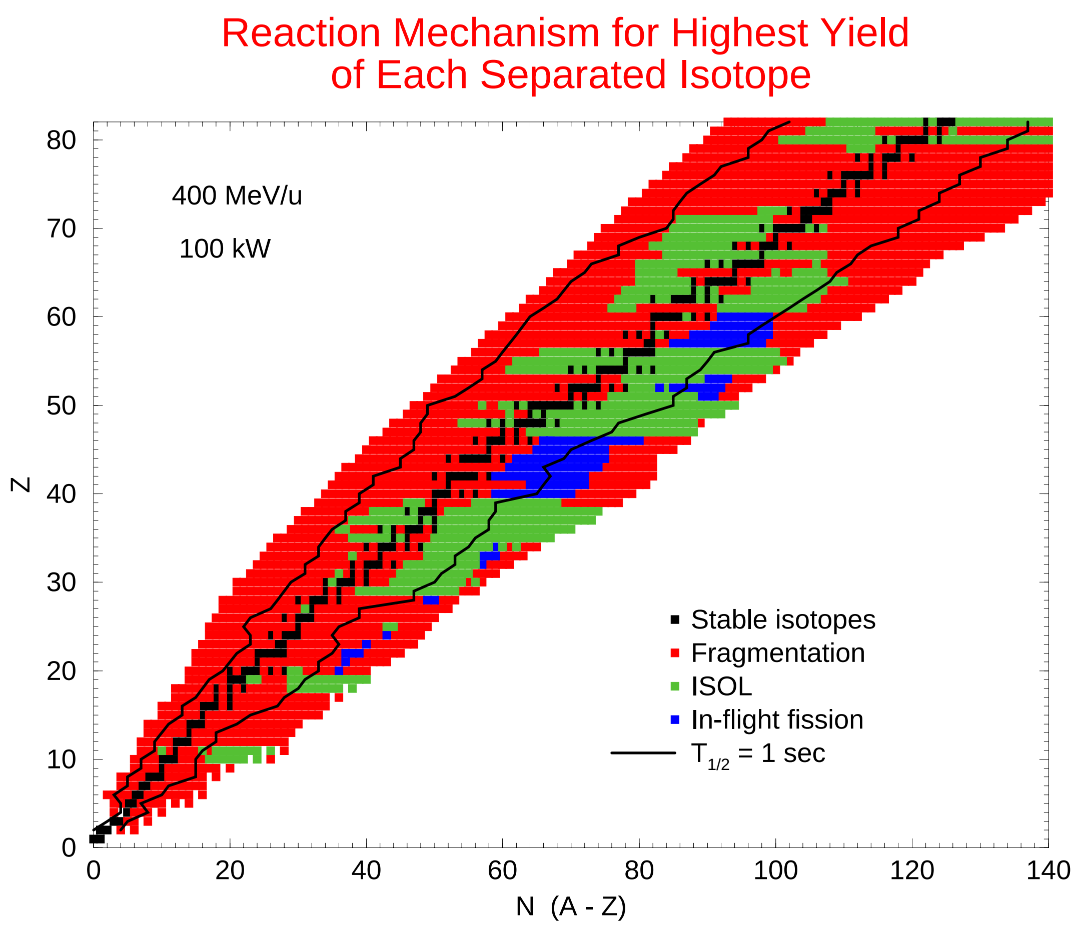

Figure 1. This chart indicates which production mechanism gives the highest yields for each isotope. All ISOL target configurations are shown in green, in-flight fragmentation in red, and in-flight fission of uranium beams in blue. For the lower mass region of this diagram the edges are determined by reaching the limits of particle stability. For the heavier masses, the limits of particle stability are generally reached on the proton rich side, but not the neutron rich side. For the neutron rich heavier isotopes the chart cuts off at predicted rates of about 1 per hour. The lifetimes of the isotopes at this limit are currently totally unknown, but are predicted to be between 0.01 and 0.1 seconds. For such short life-times, the fragmentation mechanism will probably have the highest yields.

The standard ISOL methods involve the irradiation of heavy target materials with high-power light-ion beams such as protons, deuterons, or ^{3}He, or intense secondary fluxes of neutrons. This method is very effective for specific elements, especially the alkalis and noble gases. The in-flight-produced rare isotopes, from either fragmentation or fission, are separated magnetically, slowed down in solid absorbers, and finally stopped as 1+ ions in helium gas. The fast ions could also be used directly for high-energy experiments without slowing or stopping. The in-flight separation methods enable the use of high-quality beams of very short-lived rare isotopes without regard to their chemical properties. With optimal application of the various production mechanisms, RIA will provide beams for research at intensities varying from ~10^{12}/second for moderately exotic species to ~1/day for extremely rare, short-lived isotopes. The science case for RIA has identified important needs for such beams of rare isotopes all around the chart of the nuclides, from very light to very heavy and from very proton-rich to very neutron-rich nuclei. While important science can be done with rare beams of any intensity, the variety of studies that are possible expands with increasing intensity, as does the extent from stability of the nuclides that are produced. And, in general, the production rates of rare isotopes increase monotonically with the energies of the primary beams. The optimal energy for the RIA driver accelerator is a balance between the gains in yields at higher energies and the increased facility costs that the higher energies entail.

Energy Dependence of the Yields of Rare Isotopes

The predicted yields for a few specific isotopes at RIA are plotted as a function of the driver beam energy in Figs. 2 and 3, with Figure 2 showing the absolute yields after mass separation and Figure 3 showing the relative yields. These yields are the net results from all of the contributing factors discussed below. The net yield of any specific isotope at RIA is the product of the primary beam intensity, the cross section for the reaction producing that isotope, the effective target thickness, the release or collection efficiency, the survival fraction of short-lived species, and the ionization or transport efficiency.

Cross Sections

For most nuclear reactions the total cross section increases with beam energy until it saturates at a limiting value. For protons on heavy targets this energy is about 2.5 GeV. For the fragmentation of heavy-ion beams on heavy-ion targets this limiting total cross section is already reached at energies about 100 MeV per nucleon where the ion energies are above a few GeV. For a given total cross section the fractional yields of specific isotopes are determined by the relative probabilities of losing the required number of protons and neutrons from the primary beam or target nucleus. For energies above the saturation value this branching pattern for various beam/target combinations is well described by a computer code, EPAX2, that was developed at GSI. For the in-flight fission of uranium there are recent data from GSI, and another computer code, ABRABLA, was developed to systematically describe that data. Both of these empirical codes were developed to fit the cross sections for known isotopes and are now being used to make extrapolations further from stability. For light ions such as protons, deuterons, and ^{3}He the total energies are somewhat below the saturated regime, so there is significant energy dependence of the cross sections. For this reaction mechanism, generally called spallation, the cross sections of isotopes not too far from the target nucleus peak at relatively low primary beam energies, while those far from the target generally increase with beam energy until saturation is reached. There are several models to describe this mechanism that are in good enough agreement to be used for the present estimates of the energy dependence of specific cross sections.

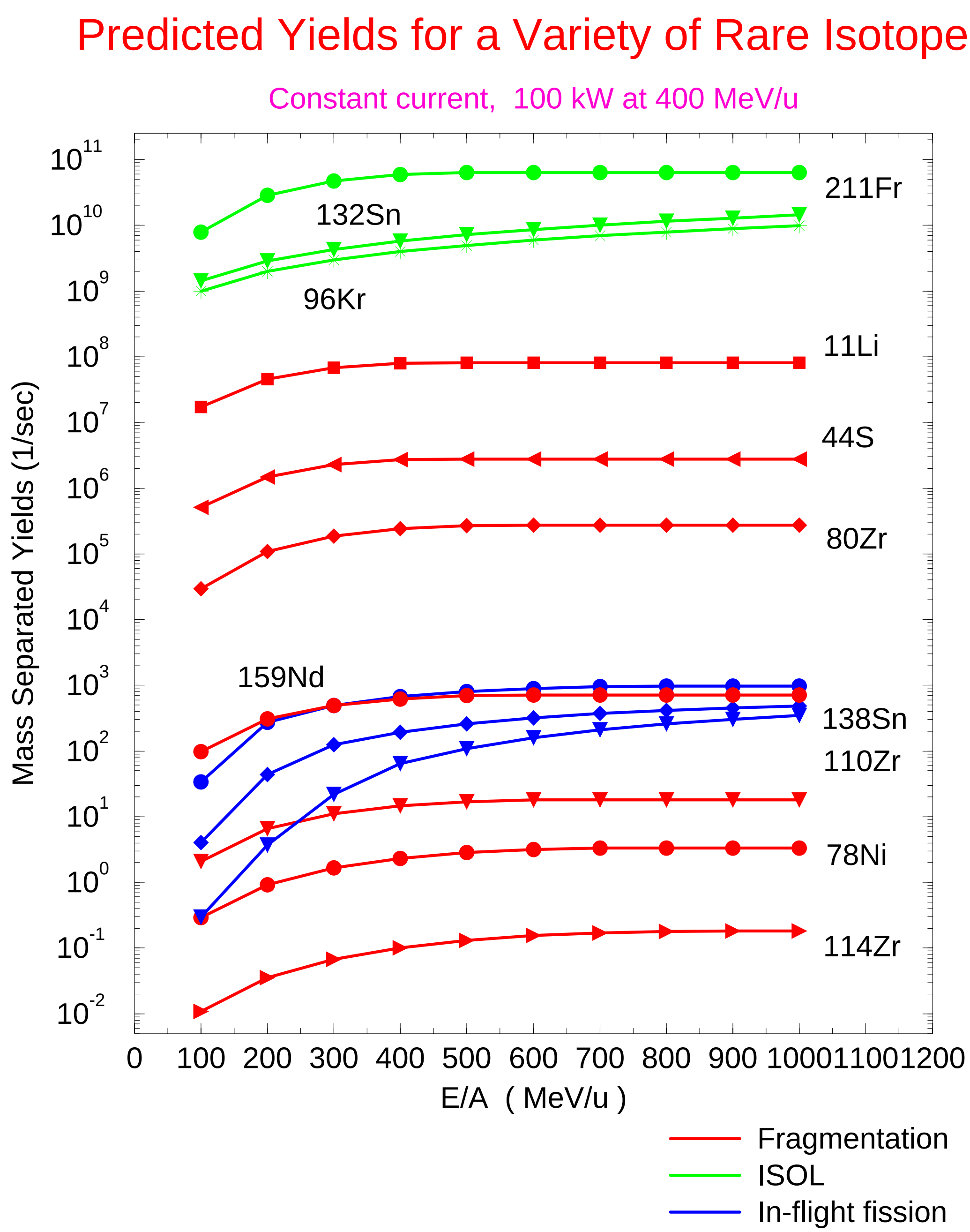

Figure 2. The predicted mass-separated yields of a few specific isotopes as a function of the driver-beam energy. The absolute yields are for beam currents that correspond to 100 kW of beam power at 400 MeV per nucleon.

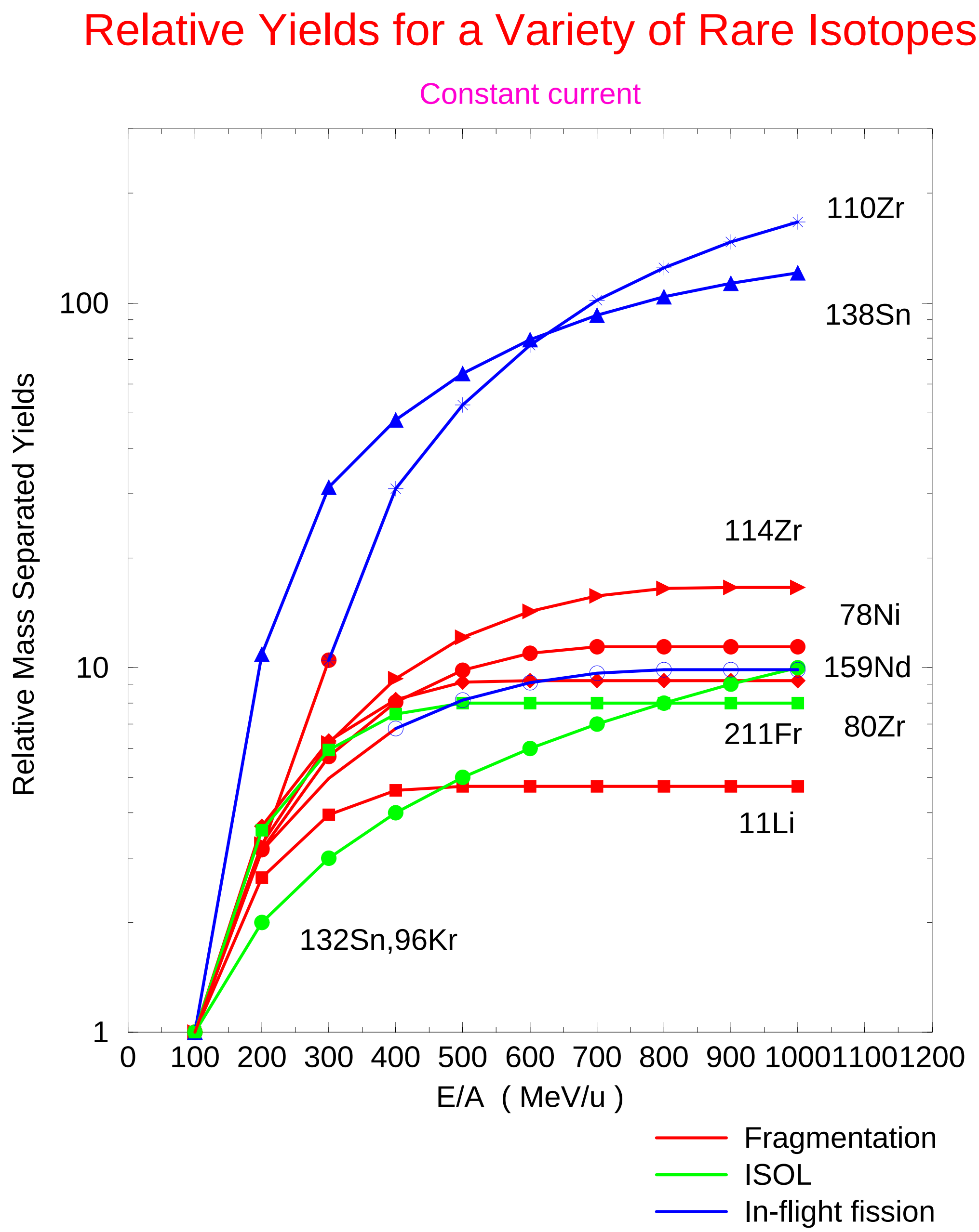

Figure 3. The relative mass-separated yields of a few specific isotopes as a function of the driver beam energy, assuming constant beam current, and normalized to the yields at 100 MeV per nucleon.

Target Thickness

Another parameter that is significantly energy-dependent is the useful target thickness. At low energies the range of the beam in the target is determined by the electromagnetic energy loss and increases approximately quadratically with energy. At energies above ~200 MeV per nucleon, nuclear attenuation of the primary beam and the secondary particles becomes significant. Hence, targets over about a mole per square centimeter can actually decrease the net yields.

Two-Step, Neutron-Generator Geometries

The two-step target geometry proposed in the body of this report uses neutrons produced in a well-cooled primary target to produce large quantities of neutron-rich fission products in a secondary uranium target. In this case the neutron multiplicity, i.e. number of neutrons produced per primary beam particle, increases rapidly with energy until the total cross section saturates. Hence, the net yields per beam particle increase rapidly at first and then more slowly at higher energies. For this target configuration the processes were simulated via Monte Carlo methods using the LAHET/MCNP code package from Los Alamos. The yields of specific fission products were estimated from the existing databases of fission branching ratios at the appropriate neutron energies.

Kinematic Acceptance of the Fragment Separator

For the in-flight fission and fragmentation mechanisms there is variation in the acceptance of the magnetic fragment separator due to the reaction kinematics. The acceptance of the separator increases rapidly with energy at first and then levels off as the acceptance approaches 100%. The leveling-off occurs at ~200 MeV/u for fragmentation and at ~400 MeV/u for in-flight fission.

Energy Dependence of Charge-State Fractionation

For the in-flight fission and fragmentation mechanisms that use the magnetic separator to select specific rare isotopes, there is an additional energy-dependent effect that is not included in Figs. 2 and 3. At energies above 1 GeV per nucleon all beams, even as heavy as uranium, are nearly fully stripped by solid materials. At lower velocities there are varying degrees of charge-state fractionation. The transmission of the fragment separator for specific isotopes is reduced by the square of the peak charge-state fraction, one factor from the primary target and another from the intermediate absorber used for isobar separation. (See Figure 5 of the body of this report.) For RIA this effect reduces the yields of heavy isotopes (Z~60) by a factor of 2 at 400 MeV per nucleon and a factor of 4 at 100 MeV per nucleon. For light isotopes the effect is much smaller because they are already essentially fully stripped in this energy range.

Summary

The choice of 400 MeV per nucleon proposed by this task force is based on the rapidly increasing yields up to that energy and the decreasing slope above that point. The net yield increase of typical rare isotopes in going from 100 MeV/u to 400 MeV/u is in the range of a factor of 5 to 100, whereas the additional relative gains at higher energy are much less.

Acronym List

AECR-U	operating ECR source at LBNL
ANL	Argonne National Laboratory
ATLAS	a heavy-ion linac at ANL
ECR	electron cyclotron resonance
GANIL	nuclear physics laboratory in France
GSI	nuclear physics laboratory in Germany
HRIBF	Holifield Radioactive Ion-Beam Facility (at ORNL)
IGISOL	ion-guide isotope separation on-line
ISAC	Isotope Separator and ACcelerator at TRIUMF
ISOL	isotope separation on-line
ISOLDE	ISOL facility at CERN
JLab	Jefferson Lab (Thomas Jefferson National Accelerator Facility)
KEK-Tanashi	Japanese unstable nuclear beam facility
LAMPF	Los Alamos Meson Physics Facility
LBNL	Lawrence Berkeley National Laboratory
LEBT	low-energy beam transport
MSU	Michigan State University
NSCL	National Superconducting Cyclotron Laboratory (at MSU)
ORNL	Oak Ridge National Laboratory (Tennessee)
PSI	Paul Scherrer Institute in Switzerland
RFQ	radio-frequency quadrupole
RIA	Rare-Isotope Accelerator
RIKEN	Japanese rare-isotope beam factory
SC	superconducting
SRF	superconducting radio-frequency
TRIUMF	a Canadian nuclear physics accelerator laboratory, Vancouver, B.C.
VENUS	an ECR ion source under construction at LBNL