Eur. Phys. J. A **15**, 105–108 (2002)
DOI 10.1140/epja/i2001-10235-7

THE EUROPEAN
PHYSICAL JOURNAL A

# Production of low- and high-energy radioactive-ion beams by fragmentation

D.J. Morrissey[a]

Department of Chemistry and National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

Received: 21 March 2002 /

**Abstract.** The physics opportunities made possible by beams of rare isotopes are among the richest available in nuclear science. The rare-isotope accelerator (RIA) now under development is an innovative accelerator that will define the state of the art for all such facilities. A novel aspect of the RIA project is the conversion of the most intense high-energy heavy-ion beams into both fast and reaccelerated exotic beams. Along with target fragmentation in next-generation high-power ISOL targets, RIA will use projectile fragmentation in a high-energy separator/gas-filled ion collector system to provide an extensive range of thermalized ions for reacceleration. In addition, a second high-energy separator will provide the same or larger range of ions for high-energy experiments. A brief overview of the RIA accelerator concept, the layout of the facility, and production techniques will be given along with information on the present R&D efforts in gaseous-ion collection.

**PACS.** 29.25.Rm Sources of radioactive nuclei – 29.30.-h Spectrometers and spectroscopic techniques

## 1 Introduction

The rare-isotope accelerator (RIA) is an innovative, large-scale facility that will define the state of the art for the production and use of exotic nuclei. The RIA facility will employ the best features of both projectile fragmentation (in-flight techniques) and target fragmentation (ISOL techniques) to provide the widest possible range of exotic nuclei to the nuclear-physics community. The project to develop RIA is very big with conceptual design, research, and development studies going on in many laboratories across the United States. Significant contributions have been made by a very large number of people that, unfortunately, cannot be adequately covered in the present short presentation. In this contribution I will present a brief overview of the RIA facility with an emphasis on the new capabilities of fast-ion beams, and the present situation for thermalization and collection of fast ions in gases will be reported.

Until recently all of the designs for the next-generation exotic-beam facility in the US were based (solely) on the ISOL concept of target fragmentation by light-ion beams (*e.g.*, Nolen [1]). Three important facts emerged during the initial consideration of possible facilities. A) Very sensitive techniques were developed to study nuclear structure with low-intensity fast beams, B) the limitations from ion-source chemistry on the range of shortest-lived and most exotic nuclei available from ISOL systems were not overcome, C) most importantly, the IGISOL concept [2] used to thermalization and collection low-energy reaction products is being extended to fast projectile fragments [3, 4]. Thus, the scope of the RIA project was increased significantly so that a new paradigm for facility operation can be applied. The optimum production method will be used to produce each secondary beam rather than obtaining those secondary beams available from one technique. This new approach requires the primary or driver accelerator to provide very intense beams of light ions to next-generation ISOL targets as well as intense beams of all heavier stable nuclei to projectile fragment separators. Low-energy, target fragment ions will be extracted from the ISOL targets and accelerated to low energies in the usual way. The high-energy projectile fragments will be delivered to a high-energy experimental arena as well as to a new low-energy "ion source" based on new concept for the thermalization and reacceleration of projectile fragments. Thus, there will be three different target areas for the primary beam: a pair of high-power ISOL targets feeding an isobar separator system and the low-energy accelerator, a high-intensity projectile fragmentation target with a high-resolution fragment separator, and another high-intensity projectile fragmentation target with a high-acceptance fragment separator connected through a gaseous-ion collector to the low-energy accelerator. The

---

[a] e-mail: `morrissey@nscl.msu.edu`

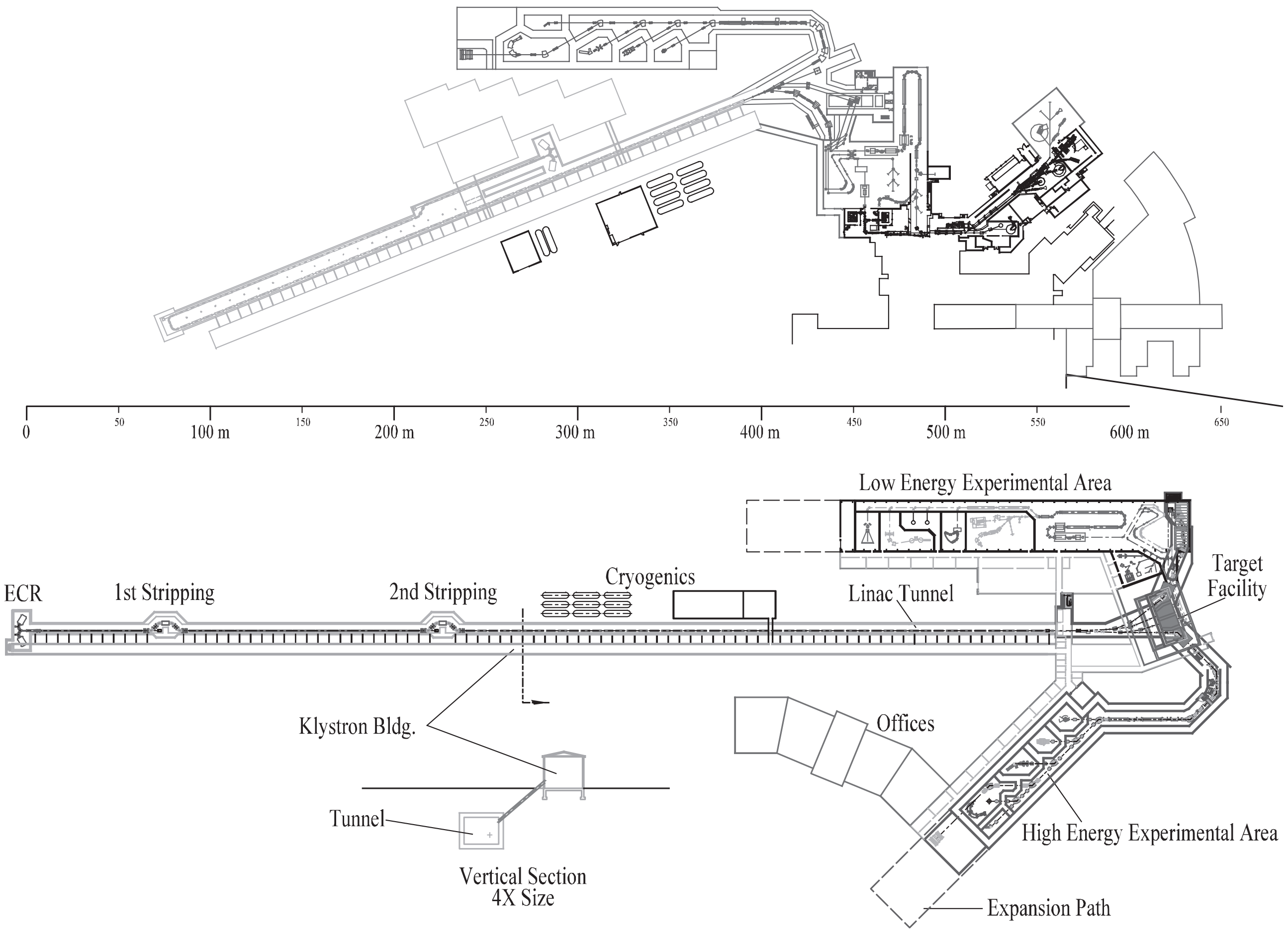

**Fig. 1.** A comparison of the schematic layout of the RIA facility at Argonne (above) and at Michigan State (below).

resulting exotic nuclei will be available at four separate experimental regions (ion-source energy, below Coulomb barrier, near Coulomb barrier, and high energy) in order to service a large and diverse user community.

The design goals and concepts for the RIA accelerator were selected by a subcommittee of the Nuclear Science Advisory Committee (NSAC) chaired by Herman Grunder in 1999. The technical details of the ion sources, accelerator, target systems, fragment separators, and gas catchers are being worked out in a variety of laboratories around the US with specific funds from the DoE for research and development. Preliminary designs for the complete RIA facility have been prepared by the NSCL at Michigan State University and by Argonne National Lab. An independent bottoms-up cost analysis has been reviewed by another subcommittee of NSAC at the end of 2000. The schematic layouts of these facilities can be compared in fig. 1. Both layouts are dominated by the primary linear accelerator that can provide beams with $E/A \sim 500$ MeV at 400 kW up to $A \sim 40$ and uranium with $E/A \sim 400$ MeV at 150 kW. Ken Shepard and collaborators at Argonne have suggested and have recently shown that a Linac can simultaneously accelerate an isotope in multiple charge states which provides very high intensities of the heaviest elements. One difference between the two designs is that the existing ATLAS accelerator is incorporated into the Argonne layout, whereas the MSU is a "green field" layout. The initial requirements for the experimental facilities and equipment have been prepared by the community [5,6] and have been incorporated into the designs.

## 2 High-energy fragmentation

As indicated above, projectile fragmentation will probably be the predominant mechanism for producing exotic beams at RIA. The intense primary beams will have to be fragmented in a windowless liquid-metal target due to the high-power density, of order 100 kW in a 1 mm diameter beam spot. Such targets are under development in an Argonne-MSU collaboration lead by Jerry Nolen. The first-generation prototype target consists of flowing liquid-lithium metal between beryllium windows that will absorb 1 kW beam power. This target is in the final stages of design and will be tested and used at the NSCL in 2002.

The projectile fragments will be separated from the unreacted primary beam with two different separators, a high-resolution device to prepare secondary beams for the high-energy research arena and a high-acceptance device to prepare the beams for thermalization in a gaseous-

**Table 1.** Selected properties of the two RIA projectile fragment separators compared to existing devices that use superconducting magnets, see the text.

| | $\Delta p/p$ (%) | $d\Omega$ (msr) | $B\rho$ (Tm) | Resolving power | Fig. of merit |
|---|---|---|---|---|---|
| A1200 | ±1.5 | 0.8 | 5.4 | 2400 | 0.5 |
| A1900 | ±2.5 | 8 | 6 | 2900 | 10.2 |
| High res. | ±3 | 10 | 8 | 3000 | 14.3 |
| High accpt. | ±9 | 10 | 8 | 1000 | 14.3 |

ion collector. Fragment separators have developed significantly over the past decade, see for example [7], and both of the devices planned for RIA will be next-generation superconducting fragment separators that go well beyond the best present-day machines. For comparison, the resolving power and a figure of merit for the A1200 (now retired) and A1900 (just completed) separators at the NSCL can be compared to the specifications of RIA separators in table 1. The resolving power is the dispersion divided by the product of the beam spots size and the magnification in the same coordinate ($x$). The dimensionless "figure of merit" used to categorize the separators is the product of the relative solid angle ($d\Omega/4\pi$), the momentum acceptance ($\Delta p/p$), and the resolving power. The RIA separators will be made up of large-scale superconducting quadrupoles and dipoles based on those recently constructed for the NSCL facility.

The new approach for the production of thermalized exotic ions for nuclear-structure studies has been pioneered at Argonne and at RIKEN, where moderate and fast, respectively, nuclear-reaction products are stopped in large high-purity helium gas cells and extracted as singly charged ions through the application of drift fields and gas flow. Once ejected from the high-pressure region, the ions pass through the differential pumping stages in rf-multipole ion-guides. The combination of physical separation with thermalization in a buffer gas avoids the limitations of thermal diffusion in a solid matrix in ISOL-type ion sources.

One of the important ingredients of the new concept is the incorporation of an energy-focusing ion-optical device that can compensate for the large-momentum distribution of the projectile fragments. Such devices consist of a dispersive magnetic dipole stage and slowing-down of the fragments in specially shaped energy degraders ([8] and references therein). A schematic drawing of the ion-optical layout of such a system is shown in fig. 2. The feasibility of momentum compensation, also called range bunching, has been recently demonstrated at the GSI-FRS, where the range distribution of 360 MeV/u $^{56}$Ni fragments with a relative momentum spread of ±0.45% were slowed-down in a quartz degrader and stopped in a chamber filled with P10 gas (90% Ar, 10% methane) at ambient pressure. Calculations have shown that the longitudinal range straggling of typical projectile fragments can be brought down to the level of the intrinsic straggling width of an equivalent monoenergetic beam which is, nonetheless, on the order of tens of centimeters of helium gas at 1 bar.

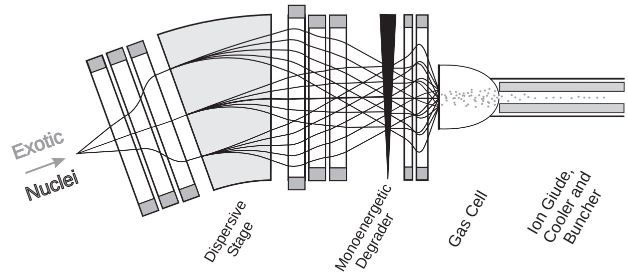

**Fig. 2.** A representation of the ion-optics necessary to compensate for the large-momentum spread of a secondary beam produced by a projectile fragment separator prior to stopping in a gaseous-ion collector, taken from H. Weick *et al.* [8]. The thermalized ions are carried through a supersonic nozzle and captured by a ion-guide system.

The crucial component of the gaseous-ion collection is a large gas cell located behind a fragment separator and an energy bunching system (see table 2). The size of the cell has to be on the order of ~ 25 L, about three orders of magnitude larger than the IGISOL gas cells [2]. The throughput of the gas nozzles are limited by pumps so that the evacuation times for the large chamber will be about three orders of magnitude longer than for IGISOL gas cells. Rapid extraction of the ions from such large gas volumes require drifting the ions to the exit aperture of the cell as in ion-mobility spectrometry and in ion-funnel devices used in analytical chemistry. Rapid drifting of the ions to the extraction nozzle can be ready accomplished with modest DC electric fields. A combination of DC and rf-electric fields inside the high-pressure region have been shown to work for collection of ions in the Canadian Penning trap injection system at ATLAS [4,9] and at RIKEN [3]. The purity of the buffer gas and unwanted ion-molecule reactions have large effects on the efficiency of IGISOL systems as has been shown by the Leuven group [10]. These neutralization and the many possible effects from ionization of the buffer gas will have to be understood for efficient operation of large-scale gas cells. It has been reported at this conference that the system operating at Argonne obtained an efficiency of close to 50% and extraction times below 10 milliseconds are routinely attained [9]. The ions can be captured and transported with a very high efficiency in an rf-multipole placed after the exit of the gas cell [11,12]. The collection and bunching of singly charged ions in linear Paul traps and

**Table 2.** Some properties of gaseous-ion collector systems under development.

| | Gas | Cell length (cm) | Pressure (mbar) | $E/A$ (MeV) |
|---|---|---|---|---|
| IGISOL (typical) | He or Ar | ~ 2 | 500 | ~ 1 |
| ANL [4] | He | ~ 20 | 150 | ~ 3 |
| SHIPtrap [13] | He or Ar | ~ 15–20 | 150 | ~ 5 |
| RIKEN [3] | He | ~ 200 | 150 | ~ 50 |
| NSCL [14] | He | ~ 50 | 1000 | ~ 100 |

rf-multipoles (at low pressures after extraction from the gas cell) are very well understood.

## 3 Conclusion

The need for a next-generation facility to provide beams of exotic nuclei in the US has grown over the past decade and an innovative concept for the next-generation facility has been put forward. The nuclear-science community as a whole has given the highest priority for new construction to the RIA project. This presentation focused on the projectile fragmentation parts of the facility. Some developments will be needed to provide target systems that will be capable of withstanding the very intense heavy-ion beams. Conceptual designs have been prepared for the fragment separators that are based on extrapolations of recently constructed devices, especially the A1900 at MSU. A preliminary layout for the high-energy arena has been prepared with input from the community. The new aspect of the RIA facility is the thermalization and collection of the fast exotic beams in a buffer gas cell. This novel approach requires the combination of several different ion manipulation techniques, all of which are known or being studied. The largest uncertainty lies in the manipulation of the ions in the high-pressure buffer gas and in neutralization reactions with any gaseous impurities.

## References

1. J.A. Nolen, in *ENAM98*, edited by B.M. Sherrill, D.J. Morrissey, C.N. Davids, AIP Conf. Proc. **455**, 952 (1998).
2. P. Dendooven *et al.*, Nucl. Instrum. Methods B **126**, 182 (1997).
3. M. Wada *et al.*, RIKEN Review No. 31 (December, 1999) p. 56, unpublished.
4. G. Savard *et al.*, in *Proceedings the 2nd Euroconference on Atomic Physics at Accelerators: Mass Spectroscopy (APAC2000)*, Hyperfine Interact. **132**, 221 (2001).
5. I.Y. Lee (Editor), *Proceeding of the Workshop on the Experimental Equipment for an Advanced ISOL Facility*, LBNL-42138, 1998, `http://srfsrv.jlab.org/ISOL/ExpEquipWkShop.pdf`.
6. M.R. Thoennessen (Editor), *Scientific Opportunities with Fast Fragmentation Beams from RIA* NSCL, Michigan State University, 2000, `http://www.nscl.msu.edu/research/ria/whitepaper.pdf`.
7. D.J. Morrissey, B.M. Sherrill, Philos. Trans. R. Soc. London, Ser. A **356** 1985 (1998).
8. H. Weick *et al.*, Nucl. Instrum. Methods B **164-5**, 168 (2000).
9. J.A. Clark *et al.*, *Mass measurements of proton-rich nuclides using the Canadian Penning trap mass spectrometer*, to be published in *Exotic Nuclei and Atomic Masses* (Springer-Verlag, Heidelberg, 2002).
10. Y. Kudryavtsev, Rev. Sci. Instrum. **69**, 738 (1998).
11. H.J. Xu, M. Wada *et al.*, Nucl. Instrum. Methods A **333**, 274 (1993).
12. P. Van den Bergh *et al.*, Nucl. Instrum. Methods B **126**, 194 (1997).
13. J. Dilling *et al.*, Hyperfine Interact. **127**, 491 (2000).
14. P.A. Lofy *et al.*, National Superconducting Cyclotron Laboratory Annual Report (2000) unpublished.